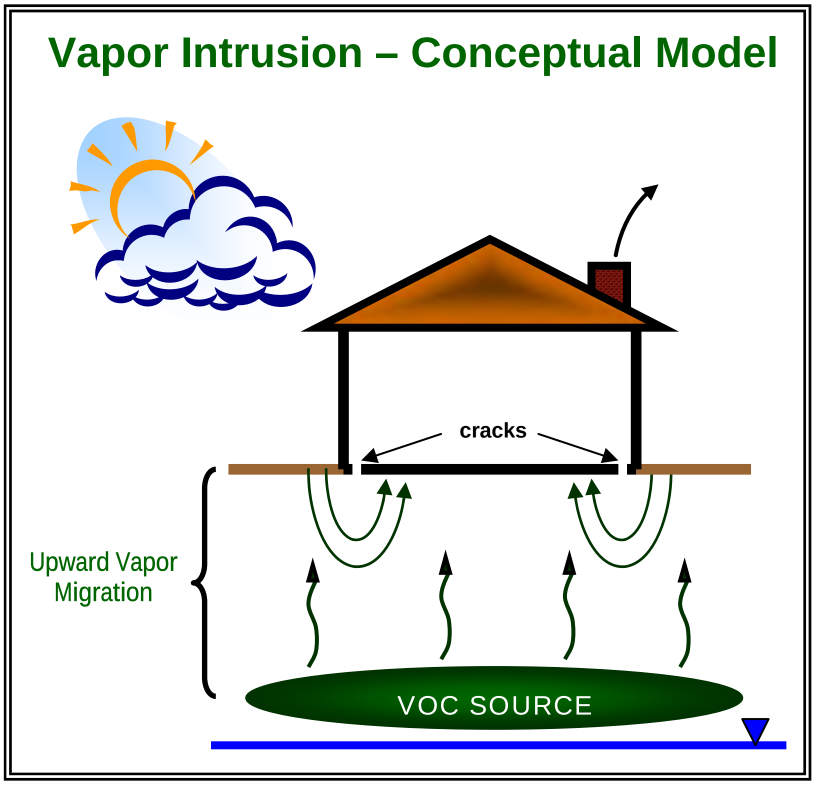
FINAL

GUIDANCE FOR THE EVALUATION AND MITIGATION OF SUBSURFACE VAPOR INTRUSION TO INDOOR AIR (VAPOR INTRUSION GUIDANCE)



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More than 370 public comments on the interim final Guidance were received. Every comment was considered and the Guidance has been revised in response to those comments. The Guidance has also been revised to address recent developments in the field of vapor intrusion. DTSC thanks all commenters for their efforts. The Guidance is much improved because of their thoughtful observations. Also, William Bosan, Barbara Renzi, Lorraine Larson-Hallock, Dot Lofstrom, Kate Burger, Peter Wong and Christine Papagni of DTSC, along with Elizabeth Allen of the SFBRWQCB (now with USEPA Region 10) and Alana Lee of USEPA Region 9, provided invaluable assistance in the revision of this document.

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EXECUTIVE SUMMARY

The intrusion of subsurface vapors into buildings is one of many exposure pathways to be considered in assessing the risk posed by releases of hazardous chemicals into the environment. The Department of Toxic Substances Control (DTSC) in this Guidance recommends an approach for evaluating vapor intrusion into buildings and its subsequent impact on indoor air quality. DTSC anticipates that this Guidance will be used by regulators, responsible parties, environmental consultants, community groups, and property developers.

Step-Wise Approach

If volatile chemicals are present in the subsurface at a site, vapor intrusion should be evaluated along with the exposure pathways identified in other guidance (DTSC's Preliminary Endangerment Assessment (PEA) Guidance Manual, and United States Environmental Protection Agency's (USEPA) Risk Assessment Guidance for Superfund (RAGS), Volume 1 Human Health Evaluation Manual, Part A). This Guidance is appropriate to any site or facility where volatile chemicals are detected in the subsurface. Due to the complexity of vapor intrusion, many professional disciplines may be needed to evaluate and mitigate human exposure. Accordingly, an appropriate project team should be gathered for all vapor intrusion investigations.

DTSC recommends an approach as discussed below and depicted in Figure 1 for the evaluation of vapor intrusion. For sites with existing buildings, Steps 1 through 11 apply. For sites with proposed buildings, Steps 1 through 3, 5, 6, 7, and 11 apply.

- *Step 1* – Identify all spills and releases.
- *Step 2* – Characterize the site, including subsurface features such as utility corridors.
- *Step 3* – Identify the site as one where vapor intrusion may represent a complete exposure pathway (volatile chemicals are detected in the subsurface).
- *Step 4* – For an existing building, determine if an imminent hazard exists from vapors migrating into indoor air. If an imminent hazard is identified, proceed to Step 11a.
- *Step 5* – Perform a screening evaluation using the provided default vapor attenuation factors. If a potential risk exists, proceed to either Step 6 or Step 8, as appropriate.
- *Step 6* – Collect additional site data.
- *Step 7* – Perform an evaluation using site-specific physical parameters and building parameters as appropriate. If the calculated risk is still significant, proceed to the next applicable step.
- *Step 8* – For an existing building, prepare an indoor air sampling work plan, develop a contingency plan for appropriate response actions, and conduct appropriate public outreach with the affected community.
- *Step 9* – For an existing building, conduct indoor air sampling.
- *Step 10* – For an existing building, evaluate the data to determine if the indoor air concentrations are acceptable. If they are not, proceed to Step 11.
- *Step 11a* – For an existing building, mitigate indoor air exposure, implement engineering controls, and remediate the volatile chemical contamination as appropriate.
- *Step 11b* – If no building exists on the site, remediate subsurface volatile chemical contamination or implement institutional controls to ensure that potential exposure is reduced or prevented.
- *Step 11c* – For both circumstances, institute long-term monitoring at the site.

Steps 1, 2 and 3 – Identifying Spills and Releases, Characterizing the Site, and Evaluating if the Vapor Intrusion Exposure Pathway is Complete

Steps 1 and 2 are common to all site investigations, and guidance is only provided for performing these steps when volatile chemicals have been found in the subsurface. With respect to Step 3, the site should be considered as one where the vapor intrusion exposure pathway may be complete if volatile chemicals are detected in the subsurface near or adjacent to existing or proposed buildings. Public outreach should begin as soon as volatile chemicals are detected in the subsurface near existing or proposed buildings. See DTSC's Vapor Intrusion Public Participation Advisory for guidance on public outreach during this step.

Step 4 – For an Existing, Occupied Building, Identifying an Imminent Hazard from Volatile Chemicals Migrating into Indoor Air from the Subsurface

The identification of an imminent hazard is based on the presence of odors in the building under investigation or observing illnesses in building occupants, such as headache, eye irritation, nausea, and dizziness, that may be linked to inhaling hazardous vapors indoors. If any of these circumstances exist, it may be necessary to consider the evacuation of the building. See DTSC's Vapor Intrusion Public Participation Advisory for guidance on public outreach during this step.

Step 5 – Performing a Preliminary Screening Evaluation for Vapor Intrusion

The preliminary evaluation of vapor intrusion utilizes attenuation factors provided by DTSC in this Guidance. With the subsurface contaminant concentrations and default attenuation factors, the associated contaminant concentrations in indoor air can be estimated. Default attenuation factors are provided for the following building scenarios (see Table 2):

- Existing residential slab-on-grade buildings
- Existing residential buildings with crawl spaces
- Existing commercial buildings
- Future residential slab-on-grade buildings
- Future residential buildings with crawl spaces
- Future commercial buildings

The following conditions apply to preliminary screening evaluations:

- Subsurface data should be representative of site conditions.
- Multiple lines of evidence, such as soil gas, soil matrix and groundwater data, should be used.
- Maximum contaminant concentrations should be used.
- Fractured bedrock or other preferential pathways should not exist at the site.
- California and USEPA inhalation toxicity factors should be used according to DTSC recommendations.
- Cumulative health effects should be calculated.

The screening evaluation for vapor intrusion should be included as part of the PEA for a site or facility. As discussed by USEPA in its risk assessment guidance (USEPA, 1989), the risks from each chemical and from all applicable exposure pathways should be summed to obtain the overall screening level risk posed by chemicals detected at the site.

Pursuant to Senate Bill 32 (SB 32, Stats. 2001, Ch. 764), the California Land Environmental Restoration and Reuse Act, the Office of Environmental Health Hazard Assessment (OEHHA) published a list of screening numbers, called the California Human Health Screening Levels (CHHSLs). The CHHSLs are contaminant concentrations in soil or soil gas that may be used to screen for potential impacts to human health. Numerous exposure pathways were evaluated in calculating the CHHSLs, including the vapor intrusion pathway. The CHHSLs can be used to evaluate sites for vapor intrusion but only with an understanding of the underlying assumptions and limitations, as indicated in OEHHA's Advisory Document (California Environmental Protection Agency [Cal/EPA], 2005a) and its associated User's Guide (Cal/EPA, 2005b). Toxicity criteria used for the CHHSLs should be reviewed prior to use and adjusted as necessary based on regulatory updates. The current list of CHHSLs can be found on the Cal/EPA website (www.oehha.ca.gov/soil.html) along with a spreadsheet calculator.

Occupational Safety and Health Act (OSHA) permissible exposure limits (PELs) are not appropriate exposure endpoints in occupational settings for indoor air degraded by subsurface contamination.

Steps 6 and 7 – Collecting Additional Site Data and Performing a Site-Specific Vapor Intrusion Evaluation

If a potentially significant risk is calculated in the preliminary screening evaluation, further investigation can be conducted, as follows:

- Collecting soil samples to define site-specific soil physical and chemical parameters using recommended test methods.
- Measuring in-situ soil effective diffusion coefficient and soil air permeability.
- Collecting subslab soil gas samples or crawl space samples at an existing building.
- Statistically evaluating the environmental media data to derive the appropriate contaminant concentration to be used in a site-specific risk assessment.

Public outreach will be necessary prior to sampling beneath existing occupied buildings (see DTSC's Vapor Intrusion Public Participation Advisory).

With additional information and data, the risk associated with vapor intrusion can be evaluated with the USEPA Vapor Intrusion Model. Multiple lines of evidence are needed to reasonably estimate the level of risk posed by the vapor intrusion. As appropriate, Steps 6 and 7 can be skipped and investigators can proceed directly to indoor sampling (Step 8) or building mitigation (Step 11).

Steps 8, 9 and 10 – Conducting Building Survey, Collecting Indoor Air Samples and Determining if Indoor Air Concentrations are Acceptable (Existing Buildings)

If the site-specific evaluation shows that buildings are subject to vapor intrusion, the owners and occupants of these buildings must be notified. During the notification process, information concerning the buildings should be collected, such as occupancy, preferential migration pathways, consumer product usage, and building characteristics. After the notification process, indoor air samples should be collected and the health risk evaluated. Buildings should be sampled twice to evaluate seasonal variability before a final risk determination is conducted. See DTSC's Vapor Intrusion Public Participation Advisory for detailed guidance on public outreach during these steps.

Step 11 – Mitigating Indoor Air Exposure and Conducting Long-Term Monitoring

If the health risk evaluation of indoor air data indicates a significant risk or hazard, vapor intrusion should be mitigated. These remedies should be considered where vapor intrusion poses a health risk:

- Removing volatile chemical contamination through site remediation (cleanup).
- Installing a vapor intrusion mitigation system.

During mitigation, long-term monitoring of soil gas and indoor air may be necessary. The frequency of sampling and the duration of monitoring will depend upon site-specific conditions and the degree of volatile chemical contamination.

The goal of a vapor intrusion mitigation system is to eliminate subsurface vapor contaminant entry into the building until the subsurface contamination source is remediated or no longer poses a significant risk to human health. Remediation and mitigation are complementary components of a response action for volatile chemical contamination. At some sites, removal of all volatile chemicals from the subsurface will not be possible and institutional controls and engineering measures will be necessary to prevent potential exposure to subsurface vapors. Land use covenants will be required in these cases, which should include the following:

- A description of the potential cause of the unacceptable risk.
- A prohibition against construction without removal or treatment of contamination to approved risk-based concentrations.
- The implementation and monitoring of appropriate engineered remedies to prevent vapor intrusion until risk-based cleanup levels have been met.

This documentation should be recorded at the local County Recorder's Office. Additionally, land use covenants must include notification requirements to utility workers or contractors that may have contact with contaminated soil or groundwater while installing utilities or undertaking construction activities. Detailed information on mitigation strategies may be found in DTSC's Vapor Intrusion Mitigation Advisory. Public outreach continues during vapor intrusion mitigation and long-term monitoring (see DTSC's Vapor Intrusion Public Participation Advisory).

TABLE OF CONTENTS

FIGURES

TABLES

APPENDICES

ACRONYMS AND ABBREVIATIONS

α	alpha, attenuation factor
AB 422	Assembly Bill 422
ARAR	applicable or relevant and appropriate requirement
ASTM	ASTM International (formerly known as the American Society of Testing and Materials)
BTEX	benzene, toluene, ethyl benzene, xylene
Cal/EPA	California Environmental Protection Agency
CEC	California Energy Commission
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CHHSL	California Human Health Screening Level
COPC	chemical of potential concern
CSIA	compound-specific isotope analysis
CSM	conceptual site model
DQO	data quality objective
DTSC	Department of Toxic Substances Control
GC/MS	gas chromatography / mass spectrometry
HI	hazard index
HVAC	heating, ventilation, and air conditioning
J&E	Johnson and Ettinger
LARWQCB	Los Angeles Regional Water Quality Control Board
MFSD	multi-functional sampling device
MSDS	material safety data sheet
NAPL	non-aqueous phase liquid
OEHHA	Office of Environmental Health Hazard Assessment
OSHA	Occupational Safety and Health Act
PCB	polychlorinated biphenyl
PCE	tetrachloroethylene
PEA	Preliminary Endangerment Assessment
PEL	Permissible Exposure Limit
PTFE	polytetrafluoroethylene
Q_{soil}	soil gas advection rate
RAGS	USEPA Risk Assessment Guidance for Superfund
RWQCB	Regional Water Quality Control Board
SB 32	Senate Bill 32
SFBRWQCB	San Francisco Bay Regional Water Quality Control Board
SIM	selective ion mode
SVE	soil vapor extraction
SWRCB	State Water Resources Control Board
TAGA	trace atmospheric gas analyzer
TPH	total petroleum hydrocarbon
$\mu g/m^3$	microgram per cubic meter
USEPA	United States Environmental Protection Agency
VOA	volatile organic analysis
VOC	volatile organic compound

INTRODUCTION

Volatile chemicals in the subsurface, whether in soil or groundwater, can migrate upward through the soil and enter into buildings, causing unacceptable chemical exposure for building occupants. The California Department of Toxic Substances Control (DTSC) requires that the human health risk be evaluated at sites under its oversight and, if volatile chemicals are present, exposure from vapor intrusion should be included in the human health risk evaluation. Evaluation of the indoor air exposure pathway involves characterizing the nature and extent of subsurface volatile chemical contamination, obtaining appropriate environmental data, using fate and transport models to predict indoor air concentrations from vapor intrusion, and conducting indoor air sampling, if necessary. This Guidance outlines the technical aspects of evaluating this exposure pathway and provides recommendations on elements that should be included in a site investigation. Due to the complexity of vapor intrusion, many professional disciplines may be needed to evaluate and mitigate exposure. Accordingly, a multi-disciplinary project team should be gathered to provide professional and sound scientific judgment when evaluating vapor intrusion issues and to make decisions concerning potential human exposure.

DTSC anticipates that this Guidance will be used by regulators, responsible parties, environmental consultants, community groups, and property developers. The intent of this Guidance is to help stakeholders understand and evaluate the vapor intrusion exposure pathway. Use of the Guidance is optional, as other technically sound approaches may be available. If local regulators or Certified Unified Program Agencies need assistance with vapor intrusion issues, DTSC, Regional Water Quality Control Boards (RWQCBs), and the Office of Environmental Health Hazard Assessment (OEHHA) are available for consultation. Because vapor intrusion is a developing field, it is anticipated that many of the procedures and practices within this Guidance will change as our understanding of vapor intrusion progresses. DTSC will update this document as needed to accommodate refinements and advances in our understanding.

SCOPE

This Guidance, along with the vapor intrusion guidance from the United States Environmental Protection Agency (USEPA, 2002a), describes technically defensible and consistent approaches for evaluating vapor intrusion, based upon the current understanding of this exposure pathway. This Guidance is not a regulation and does not impose any requirements or obligations on the regulated community, but provides a technical framework for evaluating vapor intrusion. Other technically equivalent procedures may exist. This Guidance is not intended to exclude alternate approaches or methodologies for evaluating exposure nor is it intended to provide prescriptive or inflexible requirements.

This Guidance addresses the following questions:

- What sites are candidates for vapor intrusion?
- What site characterization data are needed to conduct a vapor intrusion evaluation?
- What are the data requirements for an evaluation of indoor air exposure?
- What sites pose an imminent threat and warrant immediate action due to vapor intrusion?
- What is the estimated human health risk associated with vapor intrusion?
- When should indoor air sampling be conducted?
- When are long-term soil gas and indoor air monitoring required?
- What are the available remedies to alleviate vapor intrusion exposure?

This Guidance only addresses the single exposure pathway of vapor intrusion. However, when evaluating the human and ecological risk associated with releases of hazardous chemicals to the environment, all potential exposure pathways should be evaluated and the results reported to the appropriate oversight agency, such as DTSC. In addition to the inhalation of vapors intruding indoors, potential exposure pathways include the incidental ingestion of soil contaminated with hazardous chemicals, dermal contact with such soils, inhalation of contaminated soil particles, and inhalation of vapors diffusing from soil to outdoor air. The impact of vadose zone contamination on groundwater quality should also be evaluated. This latter exposure pathway is known as the soil to groundwater pathway. Remedies that eliminate contaminant exposure must be conducted with an understanding of all exposure pathways, not just the vapor intrusion pathway. As such, this Guidance supplements DTSC's Preliminary Endangerment Assessment (PEA) Guidance Manual and USEPA's Risk Assessment Guidance for Superfund (RAGS; USEPA, 1989).

Assembly Bill 422 (AB 422) amended Section 25356.1.5 of the California Health and Safety Code and added Section 13304.2 to the Water Code. AB 422 requires that human and ecological exposure assessments prepared in conjunction with a response action, or approved pursuant to the "California Superfund Act", include reasonable maximum estimates of exposure to volatile chemicals that may enter existing or proposed buildings due to vapor intrusion.

VAPOR INTRUSION ASSESSMENT OVERVIEW

Figure 1 shows the step-wise approach for evaluating vapor intrusion and these steps are described in the following text. DTSC recommends that a team of technical professionals be assembled when evaluating this exposure pathway. The core team may include environmental scientists, geologists, toxicologists, and engineers, as needed. Consultation with other experts such as analytical chemists may also be necessary. The team can provide technical and management judgment when encountering unusual or complex issues outside the scope of this Guidance. The step-wise approach in this Guidance document is meant to be flexible and may be tailored to site-specific circumstances.

If volatile chemicals do not enter the building, the exposure pathway from the subsurface contaminant source to the building occupant (receptor) is deemed incomplete, and the receptors cannot be considered at risk for vapor intrusion, even though volatile chemicals may be present in the subsurface beneath the building. Likewise, subsurface vapors may enter the building but be present at such low concentrations that the risk is negligible. Figure 2 provides a simplified conceptual diagram and description of vapor intrusion.

The use of a single line of scientific evidence to determine whether vapor intrusion is occurring is challenging due to the complexity of the exposure pathway. In many cases, multiple lines of evidence may be advisable to avoid potential biases inherent in any single line. Multiple lines of evidence are one way to reduce the uncertainties imposed by spatial and temporal variability of data. For this reason, this Guidance attempts to provide investigators with many different approaches for evaluating vapor intrusion.

Methane is not specifically addressed in this Guidance, although some of the procedures described may apply to its evaluation and mitigation. See DTSC's Advisory on Methane Assessment and Common Remedies at School Sites and DTSC's forthcoming guidance, Evaluation of Biogenic Methane, for more information concerning methane.

VAPOR INTRUSION ASSESSMENT

For sites with existing buildings, DTSC recommends that Steps 1 – 11 be followed. For sites where no buildings exist but may potentially be built, DTSC recommends that Steps 1 – 3, 5, 6, 7, and 11 be followed (Figure 1). While the assessment process is presented in a step-wise fashion, the vapor intrusion pathway may be evaluated in an iterative manner.

Step 1: Site History and Identification of Spills and/or Releases

A comprehensive evaluation of the current and historical features, structures, and activities at a site should be conducted. Compilation of complete site information is essential for identifying all exposure pathways. All historical documents should also be reviewed to identify the potential locations of releases of the hazardous chemicals to the environment. These documents include, but are not limited to:

- Regulatory Agency Files. Agency files contain information on hazardous chemical releases to the environment. Relevant agencies to contact are DTSC, USEPA, State Water Resources Control Board (SWRCB), RWQCBs, county environmental health departments, air quality management agencies, sewerage agencies, city environmental health departments, and local fire departments.

- Site Owner and Operator Records. Site records are the primary source of information concerning the handling of hazardous chemicals. Owner/operator files may include such records as product purchase invoices, waste manifests, permits, material safety data sheets (MSDS), safety plans, spill prevention plans, regulatory violations, and product inventory reports.

- Maps and Photographs. Maps and photographs should be reviewed to determine the physical setting of a site and to identify prior property uses. Aerial photographs, historical photographs, and insurance maps should be checked to determine prior site use.

Site visits should be conducted to locate areas where chemicals were potentially released into the environment. The site visit should include a walk-through of all known and potential areas of operation. Observations during the site visit should focus on identifying hazardous materials and wastes, associated handling and storage areas, and possible discharge locations. Some of the physical features that are indicative of chemical releases are:

- Storage tanks and storage areas
- Areas with odors or stressed vegetation
- Waste piles
- Pools of liquid
- Electrical or hydraulic equipment
- Unidentified containers
- Drains and sumps
- Stained soil and pavement
- Degraded floors and walls
- Pits, ponds, and lagoons
- Dry wells and injection wells
- Wash racks and oil/water separators
- Septic systems

- Loading docks or waste transfer areas
- Waste processing areas
- Solvent dipping tanks and spray booths
- Production lines

All physical features that are unique to the vapor intrusion pathway should be noted in characterization reports. All buildings at a site should be inventoried along with their foundation types (basement, slab-on-grade, crawl space, or earthen floor) and foundation condition. For commercial buildings, office space within the structure should be differentiated from non-office space. The building dimensions should be noted along with the building construction date. All potential preferential pathways for vapor migration should be documented. Examples of preferential pathways include piping and utility corridors, floor drains, foundation construction joints, and elevator shafts. Uses of adjacent properties should be determined in order to evaluate potential exposure associated with offsite migration of subsurface contamination. Additional guidance on the evaluation of site history and the identification of spill and releases can be found in the DTSC PEA Guidance Manual.

Step 2: Site Characterization

Subsurface contamination warrants three-dimensional characterization so that the impact to human health and the environment can be evaluated. Subsurface sampling activities should define contaminant source concentrations and identify potential contaminant migration pathways pursuant to the conceptual site model (CSM) for the project. Typically, these subsurface sampling activities include the collection of soil matrix, soil gas, and groundwater samples. Multiple lines of evidence should be used, along with professional judgment, to render technically sound risk-based decisions concerning vapor intrusion. Considering multiple sources of data and information together rather than relying on a single dataset will yield a more comprehensive understanding of vapor intrusion. The following are some lines of evidence to consider, listed in no particular order:

- Open field soil gas data
- Subslab soil gas data
- Passive soil gas data
- Groundwater data
- Soil matrix data
- Spatial and temporal variability of data
- Site-specific fate and transport modeling
- Building construction configuration
- Crawl space air data
- Indoor air data
- Outdoor air data
- Radon data
- Comparison of constituent ratios in soil gas and indoor air

Not all of these lines of evidence are needed to make site management decisions, but it is important to obtain multiple lines of evidence to evaluate vapor intrusion exposure. Lines of evidence may be weighted differently, depending on its nature and quality. In general, the closer the sampled medium is to the receptor, the more relevant the data are for estimating exposure and greater its weight of evidence. Some lines of evidence may conflict with others and this should be anticipated in the project planning process. Ideally, if the contaminant concentrations in the affected media (such as soil gas and groundwater) are in equilibrium, the estimated vapor intrusion risk associated with different contaminated media should be approximately the same. If not, a reasonable risk management decision should be made based on an interpretation of the data and the CSM. All lines of evidence should be considered in the decision-making process.

The magnitude of any sampling effort is determined by site-specific conditions. Under certain conditions, site characterization activities can be less rigorous with available resources allotted to mitigation and remediation to alleviate human exposure. When evaluating exposure to subsurface contamination, a CSM should be developed and submitted to the oversight agency for approval. Site characterization data needed for vapor intrusion evaluation and the associated CSM are described below.

Public outreach should begin as soon as volatile chemicals are detected in the subsurface at locations near or adjacent to existing or proposed buildings. See DTSC's Vapor Intrusion Public Participation Advisory for guidance on public outreach during this step.

Conceptual Site Model

The CSM is a component of all site investigations. A CSM provides a conceptual understanding of the potential for exposure to contamination at a site and should include a diagrammatic or schematic presentation that relates the source of contamination to human receptors and identifies all the potential sources of contamination, the potentially contaminated media, and exposure pathways. The CSM organizes and communicates information about the site characteristics and is a necessary component of any health risk assessment. If volatile chemicals have been released to environmental media at the site, the vapor intrusion pathway should be included as part of the overall site-specific CSM. DTSC recommends that the following items related to the vapor intrusion pathway be included in a CSM (see the DTSC PEA Guidance Manual and USEPA RAGS Part A for other contaminants and exposure pathways):

- Primary Sources of Contamination. For each potential contaminant source, describe the industrial settings or other site activities that potentially caused the contamination and provide a list of chemicals possibly released into the environment for all such settings.

- Primary Release Mechanism. For each potential contaminant source, describe the means by which the release, or suspected release, is thought to have occurred.

- Secondary Sources of Contamination. Include all the environmental media potentially contaminated by the primary sources, such as surface soil, subsurface soil, and groundwater. Areas contaminated with non-aqueous phase liquid (NAPL) should be identified. Include contaminated building materials, such as concrete floors and foundations, which can also be a source for vapors in indoor air.

- Contaminant Transport Mechanisms. For each potentially contaminated medium, describe the transport mechanisms to indoor air, which are usually advection and diffusion through the vadose zone. Include a description of the physical characteristics of the subsurface through which the contaminants must move.

- Environmental Exposure Media and Exposure Routes. At sites where buildings exist, describe the buildings where vapors may migrate and any preferential contaminant migration pathways associated with the buildings, such as foundation seams or cracks, voids, utility ports, pipes, elevator shafts, sumps, and drain holes. All subsurface volatile chemicals should be evaluated for vapor intrusion. Ambient air data are not used as the basis for excluding contaminants from the indoor air pathway analysis but help guide the risk management decisions to determine if a response action is warranted. If subsurface data indicate an unacceptable human health risk, then indoor air should be sampled at least twice to evaluate the seasonality of vapor migration, concentrations in indoor air, and resulting exposure.

- Potential Receptors. List all the current and future receptors that could potentially contact contaminated media.

In documenting current site conditions, a CSM should be supported by maps, subsurface cross sections, foundation details, and site diagrams. The narrative description should clearly describe known site conditions and state what assumptions were made to generate the CSM. The narrative should include a description of ambient sources and nearby potential sources of volatile chemicals. As additional data are collected and analyzed for vapor intrusion, the CSM should be updated and distributed to interested parties. The CSM should be an essential decision-making and communication tool for all interested parties. Additional information on the development of a CSM can be found in USEPA (1996), USEPA (2008a), and DTSC (2008a). Also, the CSM for the behavior of chlorinated volatile organic compounds (VOCs) in the subsurface can be found in Appendix A of DTSC (2010).

Data Quality Objective Process

The scope and objectives of all sampling should be established before the field work is conducted and documented in an appropriate work plan. The data quality objective (DQO) process is a planning method that establishes the basis for collecting data of sufficient quality and quantity to support project goals and decision-making. The DQOs are qualitative and quantitative statements that:

- Define the problem or hypothesis.
- Clarify the study objective.
- Identify chemicals of potential concern (COPCs).
- Define the type, quantity, and quality of data for the study.
- Identify the type of data as qualitative or quantitative information.
- Define how each sample will be used to determine if vapors are intruding into buildings.
- Determine the most appropriate locations, sampling method, and sampling duration for data collection.
- Describe how sources of uncertainty will be addressed.
- Specify how the data will be used to test the exposure hypothesis.

While DQOs are developed prior to commencement of field sampling, the process is flexible to allow for field contingencies or phased investigations. All vapor intrusion projects should have site-specific DQOs. Additional information on the DQO process can be found in USEPA (2006).

Soil Gas

Soil gas data represent a direct measurement of the contamination that may intrude into indoor air. For sites subject to vapor intrusion, permanent vadose monitoring points for sample collection should be installed to evaluate the long-term behavior of contaminated soil gas. Soil gas may need to be monitored through time, in a fashion similar to groundwater, to ascertain representative subsurface concentrations, to detect seasonal variations and other temporal changes, and to determine long-term stability of contaminant concentrations. California Environmental Protection Agency's (Cal/EPA) Active Soil Gas Investigation Advisory provides procedures for obtaining high-quality soil gas samples for use in risk assessments. Conditions warranting the installation of long-term soil gas monitoring wells may include the following:

- Shallow groundwater conditions make the collection of soil gas samples from a temporary well difficult.
- Barometric pressure fluctuations influence the vadose zone. Barometric pumping can be significant when groundwater is deep and when soils have high air permeability.
- Soil gas concentrations indicate vapor intrusion may pose a human health risk approaching one-in-a-million risk (1×10^{-6}).
- Contamination has not reached steady-state conditions in the subsurface.
- Soil gas samples from temporary wells produce an irregular distribution of subsurface contamination.
- Contamination has migrated offsite under occupied structures.
- Soil matrix sampling indicates a large mass of volatile chemicals in the subsurface.
- Groundwater is influenced by tides (Erskine, 1991).

Soil gas samples should be collected to delineate the lateral and vertical extent of the subsurface contamination. Contaminant source areas at sites should be sampled first, and the sampling should continue towards buildings as indicated by the field data. When contaminated soil gas is encountered near buildings, soil gas samples should be collected around the perimeter of the building, as close as possible to the foundation. Soil gas samples from preferential pathways, such as utility corridors and geological discontinuities (fault zones, sand channels, etc.) should also be collected. Characterization should continue until the extent of VOC contamination has been delineated in the subsurface, both laterally and vertically, to analytical detection limits. The DQO process might establish that contaminant characterization to risk-based concentrations or other criteria, rather than to detection limits, is adequate for the project. For example, if adjusted for updated toxicity criteria and for cumulative health effects from multiple contaminants and exposure pathways, CHHSLs might be used to delineate subsurface soil gas plumes.[2] Soil gas samples should be analyzed using the methods discussed in the Cal/EPA's Active Soil Gas Investigation Advisory. Volatile chemicals known or likely to be present in the subsurface, whether determined through direct measurement, historical records review, or possible chemical transformation, should be evaluated for vapor intrusion.

Sampling soil gas immediately adjacent to a building's foundation may be a viable option for assessing vapor intrusion if the samples are collected near the contaminant source. Shallow soil gas measurements collected at five feet below grade rather than immediately above the contaminant source may result in risk that is biased low when using the Johnson and Ettinger

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[2] This approach may not be appropriate for sites with multiple exposure pathways. For example, risk-based concentrations for vapor intrusion characterization may not be protective of groundwater quality.

(1991) model. Soil gas samples collected immediately above the source of contamination are more likely to be representative of what may be in contact with the building's foundation (Hers et al., 2006; DiGiulio and Cody, 2006; Wertz, 2006). Numerical modeling also suggests this relationship where soil vapor concentrations under a building may be higher than soil vapor concentrations beside a building at the same depth (Abreu and Johnson, 2005; Abreu et al., 2006). Therefore, DTSC recommends the collection of soil gas samples near contaminant sources for vapor intrusion modeling. The source of subsurface contamination should be determined by collecting soil gas samples with depth. Ideally, numerous vertical profiles of soil gas and stratigraphy should be developed to accurately locate subsurface sources at the site. Once located, soil gas collection can be targeted at these depth intervals sitewide, as appropriate. Typically, the areas of highest soil gas concentrations are adjacent to contaminant sources.

The density and frequency of soil gas collection should be based on site-specific conditions. The following should be considered when collecting soil gas samples:

1) Sampling Density. For sites seeking regulatory closure with unrestricted land use, the residual concentrations of volatile chemicals in the subsurface should be protective of residential receptors. Therefore, soil gas sampling locations should be sufficiently dense to effectively evaluate residential building scenarios. Ideally, there should be a soil gas sample location for every potential future residential building. The parcel size for most residential housing tracts in California is approximately one-eighth to one-quarter acre. Hence, the density of soil gas collection for future residential developments should be based on this type of spacing. Soil gas samples should be collected until the soil gas contaminant plume is fully delineated and a 100-foot buffer zone beyond the extent of the soil gas plume is demonstrated (see Step 3, Criterion Two). This 100-foot buffer is warranted due to uncertainty about future soil gas migration upon redevelopment. For sites where future building size will be restricted by a land use covenant, the soil gas sampling density can be increased as a function of the size of the future buildings.

2) Sampling Frequency. Soil gas may need to be monitored through time to ascertain representative subsurface concentrations, to detect seasonal variations and other temporal changes, and to determine long-term stability of contaminant concentrations. After vapor well installation, DTSC recommends that samples be collected quarterly for the first year and sampling thereafter should be based on site-specific conditions.

3) Analytical Detection Limits. Analytical detection limits for the soil gas samples should be sufficiently low to adequately evaluate potential health risks associated with the vapor intrusion pathway. At a minimum, the method reporting limits should be lower than health protective levels as corrected for cumulative health effects.

4) Low Flow Conditions. Even when low flow conditions are encountered, such as sites underlain with clay-rich soil or with a saturated vadose zone due to a shallow water table, soil gas samples can usually be collected. Permanent soil gas wells should be installed and sampled using the low flow protocols described in Cal/EPA's Active Soil Gas Investigation Advisory.

5) Soil Matrix Sampling. If soil gas samples cannot be obtained by active methods, then passive soil gas samples should be collected, along with soil matrix samples using USEPA Method 5035 (see Step 2, Soil Matrix Section). The vapor intrusion pathway should then be evaluated using soil matrix data along with groundwater, subslab, and passive soil gas

data, as appropriate. Furthermore, during routine soil gas sampling, it may be appropriate to collect soil matrix samples to determine the physical character of the subsurface, such as total porosity, soil moisture, and dry bulk density (see Step 6 - Additional Site Characterization), and for the evaluating other exposure pathways (dermal contact, soil ingestion, soil leaching to groundwater, etc.).

6) Encountering Groundwater. If groundwater is encountered during the collection of soil gas samples and it appears that the soil contamination is in close proximity to the water table, groundwater grab samples should be collected pursuant to USEPA (1997a) to evaluate the potential contaminant impact to the aquifer. If groundwater contamination exists at a site as documented by groundwater grab samples, the installation and sampling of permanent groundwater monitoring wells may be required by the oversight agency.

7) Soil Gas Samples from Groundwater Monitoring Wells. Water table monitoring wells are often installed with screened intervals that extend above the static water level to allow for water table fluctuations. Due to the open screen within the vadose zone, these wells can be an inexpensive alternative to deep soil gas well installation. When sampling, the applied vacuum of the sampling purge pump should be sufficiently low to avoid significant upwelling of the water table that might cover the screen available for sampling. See Cal/EPA's Active Soil Gas Investigation Advisory for more information about sampling protocols.

Groundwater

Only the uppermost water bearing zone encountered in the subsurface has the potential to produce a vapor intrusion risk. While deeper water bearing zones might be contaminated, potential upward volatile chemical migration from these units is potentially blocked by shallower water bearing zones. Hence, characterization activities associated with vapor intrusion should focus on the shallowest groundwater in the subsurface at the site.

When buildings exist over or near contaminated groundwater, the risk associated with emissions of volatile chemicals from groundwater into the vapor phase should be evaluated. Soil gas samples should be collected over areas of the contaminated groundwater, and the vapor intrusion risk associated with the contaminated soil gas should be estimated, along with the vapor intrusion risk from the contamination in the groundwater itself. Quantification of risks from both media is a method of evaluating which contaminated media, soil gas or groundwater, provides the greater health threat. If the media are in equilibrium, the associated vapor intrusion risk should be approximately the same.

Cal/EPA (1995), DTSC (2008b) and USEPA (2002b) provide procedures for the installation of groundwater monitoring wells and the acquisition of groundwater samples that are representative of aquifer conditions. Some of the recommendations for data acquisition are:

1) Screen Placement. Contaminants at the top of the water table are responsible for causing potential vapor intrusion problems rather than contaminants present at deeper intervals. Hence, monitoring wells used to collect groundwater samples for vapor intrusion evaluations should be screened across the saturated/unsaturated interface.

2) Screen Lengths. Monitoring wells with long well screens should not be used to make vapor intrusion evaluations, regardless of screen placement. When sampling from wells with long screens, clean water entering the well screen at depth may dilute the contaminated groundwater near the top of the screen, biasing the sampling results and the associated

risk determination. Hence, short screen lengths are preferred for monitoring wells that will be used to make vapor intrusion evaluations. Ideally, the saturated thickness in a well screen should be 10 feet or less.

3) Well Installation. Monitoring wells should be designed and installed to yield representative samples of groundwater conditions. Monitoring wells should have proper filter packs, slot sizes, and annular seals.

4) Well Development. Monitoring wells should be developed to create an effective filter pack around the well screen, rectifying damage to the formation caused by drilling, optimizing the hydraulic communication between the formation and well screen, and assisting in the restoration of natural water quality of the aquifer near the well.

5) Well Purging. If applicable to the selected sampling approach, prior to sampling, monitoring wells should be purged to remove stagnant casing water from the well that is not representative of aquifer conditions. Wells can be purged by removing the traditional three casing volumes prior to sampling or the well can be purged with low flow techniques. For low flow purging and other sampling techniques, DTSC (2008b) should be followed.

6) Well Sampling. DTSC prefers bladder pumps or submersible pumps to sample groundwater for vapor intrusion evaluation. These pumps minimize the loss of volatile chemicals during sample collection and handling. Likewise, groundwater can be sampled with diffusion bags or low flow techniques to evaluate contaminant concentrations near the top of the well screen. See DTSC (2008b) for more information about these methods.

Groundwater grab samples should not be used to evaluate vapor intrusion due to the inability to place the sampler at the top of the water table and the inability to establish temporal contaminant trends with such data. Groundwater grab samples are qualitative samples, typically used to determine the location of permanent monitoring wells. Permanent monitoring wells should be sampled at a regular frequency to determine representative contaminant concentrations that may be used in a vapor intrusion risk assessment. Accordingly, groundwater grab sampling is typically an interim characterization step.

Soil Matrix

When characterizing subsurface contamination at a site, both soil gas and soil matrix sampling may be warranted for assessing human exposure. Soil gas samples provide data needed for evaluating the risk associated with vapor intrusion, but these samples cannot be used to estimate the human health risk associated with other exposure pathways, such as dermal and ingestion exposure to soil. To evaluate these other exposure pathways, soil matrix sampling is necessary.

The presence of very shallow groundwater can make the collection of soil gas samples difficult. Where groundwater is less than five feet below grade, and when there is a large capillary fringe associated with the water table, no-flow conditions for soil gas may be encountered. In this instance, at a minimum, both groundwater and soil matrix sampling would be warranted. Other lines of evidence should be applied as needed. The risk associated with both media (groundwater and soil matrix) should be estimated and compared to evaluate contaminant equilibrium. If the risk from both media diverge significantly, a risk management decision should be made based on the weight of evidence. Subslab sampling or passive soil gas sampling may be warranted as an additional line of evidence. Soil matrix sampling also may be needed to characterize co-contamination that can affect the behavior of volatile chemicals.

The USEPA vapor intrusion guidance document (USEPA, 2002a) does not provide soil matrix screening concentrations. USEPA (2002a) specifically addresses soil matrix samples, stating that "soil (as opposed to soil gas) sampling and analysis is not currently recommended for assessing whether or not the vapor intrusion pathway is complete". Soil matrix data are less than ideal for evaluating vapor intrusion risk because of the uncertainty associated with using partitioning equations and the potential loss of volatile chemicals during sample collection. However, in some cases, as described above, there may be no alternative. Interested parties should be cognizant of these factors when evaluating vapor intrusion with soil matrix samples. Soil matrix data, as a sole line of evidence, are not recommended for evaluating risk from vapor intrusion. However, soil matrix data may be valuable for determining the location and nature of the contaminant source and, thus, may be necessary for site characterization purposes.

When sampling soil for volatile chemicals, the soil samples should be collected using the procedures with SW-846 Method 5035A (USEPA, 2002c). DTSC has augmented USEPA Method 5035A procedures with additional guidance (DTSC, 2004) which summarizes all the available soil sampling options. Both USEPA (2002c) and DTSC (2004) provide the minimum requirements and minimum standards to prevent loss of volatile chemicals during sample collection and handling. DTSC encourages interested parties to read and understand both documents before implementing Method 5035A in the field.

Generally, the options available for soil matrix sampling pursuant to Method 5035A are:

1) <u>Chemical Preservation in the Field.</u> Tared and labeled volatile organic analysis (VOA) vials with polytetrafluoroethylene (PTFE)-lined septum caps with appropriate chemical preservatives are taken into the field. The VOA vials with preservative are weighed in the field before sampling activities to verify no preservative loss. Soil subcores are obtained from sampling locations using a field coring device. The soil subcores are placed into the VOA vials in the field and capped, forming an airtight seal. The vials are re-weighed in the field to determine the sample weight. At the laboratory, the capped VOA vials are re-weighed to verify no preservative loss. The samples are prepared and analyzed with the caps in-place. All preservatives, surrogates, internal standards, and matrix spikes are introduced through the PTFE-lined septum caps (either manually or mechanically) and analyzed with a closed-system purge-and-trap process.

2) <u>Soil Sampling with Multi-Functional Sampling Devices.</u> Multi-functional sampling devices (MFSDs) act as both a coring tool and airtight storage container. An example of a MFSD is the EnCore™ Sampler and the Core N' One™ Sampler[3]. With MFSDs, a small subcore of soil (from soil core or soil surface) is collected directly into the volumetric storage chamber of the MFSD, filling it completely with zero headspace. The storage chamber is then capped to form an airtight seal. The intact MFSDs are sealed in a plastic bag for transport to the laboratory at 4 ± 2°C.

3) <u>Empty Vial Technique in the Field.</u> Empty, tared and labeled VOA vials with a PTFE-lined septum caps are taken into the field. The VOA vials do not contain chemical preservatives. Soil cores are placed into the VOA vials in the field and capped, forming an airtight seal. At

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[3] The mention of trade names or commercial products in this Guidance is for illustrative purposes only, and does not constitute an endorsement or exclusive recommendation for use at DTSC sites. Equipment other than that listed may be used, provided that the resulting performance meets the project DQOs.

> the laboratory, the capped VOA vials are re-weighed to obtain the weight of the soil samples. The samples are prepared and analyzed with the caps in-place within 48 hours of sample collection. Otherwise, the vials should be frozen upon receipt at the laboratory and analyzed within seven days of sample collection. All preservatives, surrogates, internal standards, and matrix spikes are introduced through the PTFE-lined septum caps (either manually or mechanically) and analyzed with a closed-system purge-and-trap process.

Soil samples should not be collected in large bottles, wide-mouthed jars, acetate liners, or brass sleeves. These are not appropriate containers under Method 5035A and are not appropriate sample collection devices for risk assessment purposes.

Passive Soil Gas

Passive soil gas sampling is a qualitative tool that provides a line of evidence for evaluating vapor intrusion. Sampling devices containing an adsorbent material are placed in the subsurface and left to collect vapors over a time period of 10 to 15 days, dependent on site conditions. Contaminant vapors encounter the sampling device and are passively amassed onto the adsorbent material. The sampling devices are then retrieved and analyzed.

Passive soil gas sampling can be an effective tool in understanding the vapor intrusion pathway. The composition of subsurface soil gases can be determined from passive soil samples and the location of subsurface plumes can be mapped. This approach is particularly useful for mapping plume edges in order to determine if contamination is near existing or future buildings. Passive soil gas sampling methods can also be used to collect soil gas from low-permeability and high-moisture settings, and are capable of detecting compounds present in very low concentrations. Likewise, passive soil gas samplers can be placed into potential preferential pathways for soil gas migration, such as utility corridors, to determine if these pathways could affect indoor air quality. However, passive soil gas samples cannot be used to measure the contaminant concentration in soil gas or be used to determine the flux of contaminants over a given area. The concentration of volatile chemicals on the adsorbent material in a passive soil gas sampler, though yielding a contaminant mass value, cannot be directly equated to soil gas concentration. Hence, passive samplers should only be used with this understanding.

Utility Corridor Assessment

Vapor intrusion site investigations should include an evaluation of utility corridors. Vapors and free product liquids in utility corridors can potentially migrate long distances, longer than predicted with conventional fate and transport models. This is especially true for utility corridors where the native soil is of lower permeability than backfill material. Vapors can migrate in any direction along the corridor, while free product liquids will migrate in a downslope direction along the bottom of the corridor trench. Vapors or free product liquids in a corridor could migrate toward buildings that are serviced by or connected to the utility.

Figure 3 provides a utility corridor decision tree to assist investigators in evaluating these features. The first step is collecting information to determine if utility corridors (sewer, electrical, fiber optic, cable, water, etc.) are present and if these conduits lead from subsurface contamination to occupied buildings. Facility and public records showing the spatial locations of utility corridors should be reviewed. Such records include utility maps, historical use maps, building "as-built" diagrams, building construction specifications, and utility hotlines. The locations of all utilities within, or adjacent to, subsurface contamination should be identified, regardless of whether the contamination is currently limited to property boundaries. If records show utility corridors might provide a conduit for contaminant migration, collection of active or passive soil gas samples is necessary to determine whether the backfill material of the conduit or adjacent soil is contaminated. The investigation of the corridor should continue until the extent of the contamination is delineated. If utility corridors are contaminated, monitoring the corridors with permanently installed vapor wells may be necessary. Utility corridors with contamination may require immediate remedial action to stop further transport of vapors along these preferential pathways.

If utility corridor sampling is warranted, the corridor location should be accurately identified at the ground surface by a qualified locator service. Representative soil gas samples should be collected from the backfill material or native soil of the utility corridor. To accomplish this and to avoid utility damage, the sampling locations should be hand-dug to verify placement of the sampling device. Vapor wells should then be installed and sampled pursuant to the procedures in the Cal/EPA Active Soil Gas Investigation Advisory.

Flux Chambers

Emission isolation flux chambers (USEPA, 1986) have been used for vapor intrusion risk determination by directly measuring the flux of VOCs from the ground surface. Ground surface flux measurements have been used to estimate indoor air concentrations in structures with a “standard box model”, typically by assuming an infiltration ratio of 0.01 (Bjorklund et al., 2002; Schmidt et al., 2004; Copeland and Van de Water, 2004; Sager et al., 1997). However, no field studies have validated this approach. Furthermore, the flux chamber does not measure contaminant migration into buildings by structure depressurization. USEPA (1992a) recognized this limitation and stated that “flux chambers. . . may give significantly negatively biased results if building underpressurization is exerting an effect on soil gas flow rates”. Likewise, existing literature identifies several difficulties associated with obtaining representative data using the flux chamber. These challenges are largely associated with flux chamber operation, atmospheric influences, and variability of emissions from soil. Appendix A contains additional information on flux chambers.

Step 3: Evaluate Whether the Exposure Pathway is Complete

To evaluate whether or not a site is a candidate for vapor intrusion, two primary criteria are considered: 1) the nature of the subsurface contaminants, and 2) the proximity of existing or future buildings to subsurface contaminants.

Criterion One: The chemicals in the subsurface must be volatile and toxic to present a vapor intrusion risk.

The chemicals in Table 1 are volatile and toxic enough to pose an indoor air risk. If a site contains any of the chemicals listed in Table 1, the site should be evaluated for vapor intrusion. The chemicals in Table 1 were taken from USEPA (2002a), with the addition of fuel oxygenates and two volatile polychlorinated biphenyl (PCB) congeners, monochlorobiphenyl and dichlorobiphenyl (Davis et al., 2002; Davis and Wade, 2003).

Soil gas, soil matrix, and groundwater should be tested for all COPCs at a site. Vapor intrusion is one exposure pathway so soil matrix and groundwater sampling may be warranted to evaluate other exposure pathways. All potentially complete exposure pathways and multiple exposure media must be evaluated in any health risk assessment. If the chemicals listed in Table 1 are not present at a site, the vapor intrusion pathway needs no further consideration.

Criterion Two: The existing or future buildings at a site must be close to subsurface contamination so that vapor migration into indoor air is possible.

Existing buildings within 100 feet of subsurface contamination may be considered at risk for vapor intrusion (USEPA, 2002a). Accordingly, buildings within 100 feet of soil gas or groundwater plumes should be evaluated for vapor intrusion. Buildings greater than 100 feet from a plume boundary are deemed to not be at risk if preferential pathways, either natural or anthropogenic, do not exist in the subsurface that link the buildings with the contaminant plume. In some instances, for screening purposes, the 100-foot distance may not be appropriate due to site-specific conditions. When determining site-specific distances for the existing building scenario, the approaches from Lowell and Eklund (2004) and Abreu and Johnson (2005) can be used. However, the determination of a site-specific distance criterion must be made with caution and only used when soil gas migration has reached steady-state conditions. The two- and three-dimensional modeling, as indicated by Lowell and Eklund (2004) and Abreu and Johnson (2005), respectively, has not been extensively field validated. Hence, the determination of site-specific offsets is best documented with field data.

For future buildings at sites where unacceptable contaminant levels are left in the subsurface, engineering controls would be needed unless buildings are at least 100 feet from contamination. The uncertainty associated with plume migration upon brownfields redevelopment warrants these engineering controls. The guideline of 100 feet assumes that preferential pathways do not exist in the subsurface. Development activities that include new utility corridors or covering large areas of the site with pavement may significantly alter vapor migration and concentrations.

Evaluations of building distance from contaminant plumes should only be conducted if the subsurface contamination has reached steady-state conditions. Steady-state conditions are reached when that the maximum migration potential of the subsurface plumes have been achieved. If contaminant plumes (whether in soil or groundwater) are increasing in extent, the 100-foot guideline is not an appropriate distance between buildings and plumes for evaluating vapor intrusion. For groundwater, the migration potential can be evaluated with data from routine sampling of groundwater monitoring wells. If temporal contaminant trends from the monitoring wells indicate stable or decreasing trends, steady-state conditions for groundwater has probably occurred. For soil gas, a similar evaluation can be conducted if routine temporal sampling data are available from permanent or temporary sampling points, provided sampling has occurred over a sufficient period of time. If there are minimal temporal soil gas data, the length of time to reach steady-state conditions should be estimated from the date that the chemical releases ceased at the site. The timeframe to reach steady-state conditions can be calculated using the methods in Johnson and others (1999).

In some situations, the 100-foot separation distance between subsurface plumes and buildings might not sufficient. For instance:

- When a continuous low permeability surface (such as pavement or surface clay layers) covers the ground between the contamination and the building, soil gas discharge to the atmosphere is restricted, thus enhancing migration toward the building.

- When the vadose zone has very high gas permeability due to fracturing, soil gas contaminants can follow fractures for distances exceeding 100 feet without substantial concentration attenuation.

- When soil gas is under pressure, the 100-foot rule should not be used. This is typically seen at landfills, where methane gas (often containing volatile chemicals) can travel much farther than 100 feet.

Step 4: Evaluation of Acute Hazard in an Existing Building

If a site is a candidate for vapor intrusion pursuant to Step 3, the site should be evaluated to determine if immediate action is necessary to verify and abate acute threats to human health. See DTSC's Vapor Intrusion Public Participation Advisory for guidance on public outreach during this step. Some indicators of acute threats are described below. Other suitable indicators may also exist.

- Odors. Odors reported by building occupants may be an indication of vapor intrusion. The presence of odors does not necessarily correspond to adverse health effects or safety concerns, but it is prudent to investigate any reports of odors because odor thresholds for many chemicals exceed their respective risk concentrations.

- Physiological Effects. Exposure to vapors may cause headaches, nausea, eye and respiratory irritation, vomiting, and confusion. Exposure sensitivity can vary greatly from one person to the next. Individuals most affected by vapors are children, the elderly, and people with pre-existing respiratory conditions such as asthma or bronchitis. These physiological effects may or may not be attributable to vapor intrusion but should be evaluated. In all cases involving physiological effects, individuals should consult their physician.

- Wet Basements. Buildings with basements over shallow groundwater are very prone to vapor intrusion. Basements with evidence of shallow groundwater, such as frequent flooding and wet walls during the rainy season, should be scrutinized closely for potential acute health threats. This is especially true for sites with significant subsurface contamination, such as the occurrence of NAPL on the water table.

- Fire and Explosive Conditions. The potential for fire and explosion from vapor intrusion should be evaluated. Fire and explosion concern is often raised with petroleum vapors. The lower explosive limit for gasoline vapor is 1.4 percent (approximately 50,000 times higher than its corresponding odor threshold), thus making it an easily identifiable threat at petroleum release sites. Fire and explosion hazards related to chlorinated solvent vapor intrusion are also easily identifiable. Flammable levels for chlorinated solvent are approximately 1,000 times higher than their odor threshold. Nonetheless, however unlikely an explosion or fire might be, it should be evaluated, particularly if the odors are strong within a building. Also, methane may be present as a constituent at petroleum release sites or as a by-product of contaminant breakdown and should be considered when evaluating buildings for imminent threat.

Buildings with odors, occupants with physiological effects, and/or wet basements should be evaluated and the indoor air sampled as soon as possible using procedures outlined in Step 9 of this Guidance. The results of the indoor air sampling should be evaluated pursuant to Step 10 and, if needed, the measures within Step 11 should be implemented to mitigate the vapor intrusion risk.

DTSC recommends immediate evacuation of buildings with potential fire and explosive conditions. The local fire department should be contacted about the threat. DTSC does not currently have any policy or procedures for emergency response relocation. USEPA (2002d) is the best available guidance for use in such situations. Re-occupancy of the buildings should only be granted with concurrence of the local fire department. After re-occupancy, Step 8, 9, and 10 should be followed as appropriate to evaluate vapor intrusion.

For sites that have potential methane intrusion issues, DTSC's guidance on methane should be consulted and, as appropriate, followed in conjunction with this Guidance.

Step 5: Preliminary Screening Evaluation

If evaluation of a site pursuant to Steps 1 - 4 indicates a potential vapor intrusion problem, a preliminary health risk screening evaluation should be conducted using the available subsurface data to estimate vapor migration into the building. The California Human Health Screening Levels (CHHSLs) can be used as a mechanism to evaluate sites subject to vapor intrusion (see below for additional information).

Attenuation Factors for Preliminary Screening Evaluations

To evaluate vapor intrusion with subsurface contaminant data, the attenuation factor (alpha or α) for a given building should be determined. The attenuation factor represents the ratio between indoor air concentration and soil gas concentration, as follows:

$$\alpha = \frac{C_{\text{indoor}}}{C_{\text{soil gas}}}$$

where:

C_{indoor} = Indoor air concentration (µg/m^3)
$C_{\text{soil gas}}$ = Soil gas concentration (µg/m^3)

DTSC recommends that the default attenuation factors in Table 2 be used along with the maximum subsurface concentrations for preliminary screening evaluations. Default attenuation factors are provided for three sampling locations relative to building foundation: contaminant source, subslab, and crawl space. Appendix B provides the derivation of the default attenuation factors. These default attenuation factors reflect reasonably protective assumptions for conditions in California for the contamination of indoor air due to vapor intrusion. Hence, after lateral and vertical delineation of subsurface contamination and determination of all COPCs at the site, a preliminary evaluation for vapor intrusion can be conducted with subsurface concentration data and default attenuation factors. For soil gas data, the concentrations can be used directly in the above equation for evaluating vapor intrusion. For soil matrix and groundwater data, the associated soil gas concentrations should be estimated using partitioning equations (see below). The associated cumulative health risk can be estimated by using the procedures described in Appendix C.

The default attenuation factors assume the following conditions for their use in evaluating an existing or future building:

- The subsurface is reasonably homogeneous (uniform).
- No fractures exist in the subsurface.
- Fluctuations of the groundwater surface are minimal.
- Preferential pathways (utility corridors) do not exist.
- Biodegradation of vapors is not occurring.

- Contaminants are homogeneously distributed.
- Contaminant vapors enter a building primarily through cracks or seams in the foundation and walls.
- Building ventilation rates and the indoor-outdoor pressure differentials are constant.
- Model assumptions are representative of site conditions.

All lines of evidence should be considered when estimating human exposure. Some lines of evidence may be conflicting. Hence, a reasonable risk management decision should be made as compelled by the interpretation of all the data. If the evaluation of the subject building with default attenuation factors results in an acceptable cumulative human health risk, no further consideration is needed for this exposure pathway. However, if potentially significant risks are indicated, DTSC recommends proceeding to Step 6 and conducting a site-specific screening evaluation.

OEHHA's 2004 guidance for school site risk assessment should be followed when conducting human health risk assessments at existing or proposed schools.

Use of Soil Gas Data

Soil gas data for evaluating vapor intrusion should meet the following requirements:

- Soil gas data used for screening should be collected near contaminant sources.
- Permanent or semi-permanent wells should be used for collecting samples.
- Soil gas concentrations should represent steady-state conditions.
- Soil gas sample collection should follow Cal/EPA's Active Soil Gas Investigation Advisory.
- The method reporting limits should be sufficiently low to adequately conduct a screening evaluation of human health risk.
- The density of soil gas sampling should be sufficient to accurately extrapolate isoconcentration contours throughout the area of interest.

Use of Soil Matrix Data

As an additional line of evidence, soil matrix samples can be used to evaluate vapor intrusion in conjunction with soil gas and groundwater data. Soil matrix samples should be collected using the procedures in USEPA Method 5035A. The contaminant concentration in soil gas can be estimated from the soil matrix data by using the partitioning calculation procedures in Appendix E. Estimating soil vapor concentrations and human health risk from soil matrix samples may yield results that are biased low due to inherent volatile chemical escape during sample collection. Under no circumstances should soil matrix data be used as a sole line of evidence for evaluating vapor intrusion.

Use of Groundwater Data

When performing preliminary vapor intrusion evaluations with groundwater data, the associated soil gas originating from contaminated groundwater should be determined, as follows:

$$C_{\text{soil gas}} = C_{\text{groundwater}} * H_c * C_f$$

where:

$C_{\text{soil gas}}$ = Soil gas concentration (µg/m^3)

$C_{groundwater}$ = Groundwater concentration (µg/L)
H_c = Henry's law constant (unitless)
C_f = Conversion factor (1000 L/m^3)

Groundwater data for the evaluation of vapor intrusion should meet the following requirements:

- The groundwater monitoring wells are properly drilled, constructed and developed, and the wells are screened across the water table (see Step 2 - Groundwater).
- The well screen lengths are sufficiently short (≤10 feet) to yield representative samples of the uppermost portion of the water table.
- The groundwater samples collected for analysis are representative of aquifer conditions.
- The contaminant trends in individual groundwater monitoring wells are adequately established with an appropriate amount of temporal sampling. The intent of establishing contaminant trends within monitoring wells prior to screening groundwater for vapor intrusion is two-fold. First, the degree of natural temporal variability of the volatile chemical contamination can be established so that an appropriate contaminant input concentration can be used for risk assessment purposes. Second, the stability of the plume should be determined to ensure that the risk to receptors does not unexpectedly increase as a result of plume migration.
- The method reporting limits for the groundwater samples are sufficiently low to adequately conduct a screening evaluation.
- The density of the groundwater monitoring network is sufficient to accurately extrapolate groundwater isoconcentration contours throughout the area of interest.

Use of Soil Gas Screening Numbers

Pursuant to SB 32, the California Land Environmental Restoration and Reuse Act (codified in the California Health & Safety Code), OEHHA published a list of screening numbers for specific contaminants (CHHSLs). A screening number is defined in SB 32 as the concentration of a contaminant published by an agency as an advisory number that is protective of public health and safety. The screening numbers required by SB 32 are not intended as mandatory cleanup standards for use by regulatory agencies that have authority to require remediation of contaminated soil. The pertinent part of SB 32, in Health and Safety Code Section 57008(a)(3), states the following:

> *A screening number is solely an advisory number, and has no regulatory effect, and is published solely as a reference value that may be used by citizen groups, community organizations, property owners, developers, and local government officials to estimate the degree of effort that may be necessary to remediate a contaminated property. A screening number may not be construed as, and may not serve as, a level that can be used to require an agency to determine that no further action is required or a substitute for the cleanup level that is required to be achieved for a contaminant on a contaminated property. The public agency with jurisdiction over the remediation of a contaminated site shall establish the cleanup level for a contaminant pursuant to the requirements and the procedures of the applicable laws and regulations that govern the remediation of that*

> *contaminated property and the cleanup level may be higher or lower than a published screening number.*

Numerous exposure pathways were evaluated in calculating the CHHSLs, including vapor intrusion. Hence, OEHHA developed soil gas CHHSLs for vapor intrusion for many of the volatile chemicals found in Table 1, and these CHHSLs may be used to evaluate the vapor intrusion pathway in a preliminary screening evaluation. CHHSLS are intended to be conservative and, under most circumstances, correspond to concentrations that are assumed to not pose a significant health risk to people who are subject to indoor vapor exposure. The presence of a chemical in soil gas at concentrations greater than its respective CHHSL does not necessarily indicate that adverse human health effects are occurring. It simply indicates that a potential for adverse risk may exist and that additional evaluation may be warranted. The need for additional investigation and possible cleanup of affected areas may then proceed on a more site-specific basis. This step-wise approach can help expedite judgments about the degree of effort necessary to remediate contaminated properties and restore the properties to productive use. The screening numbers can also be used to assist in the prioritization of work.

Interested parties should read and understand the OEHHA Advisory Document (Cal/EPA, 2005a), along with its associated User's Guide (Cal/EPA, 2005b), before using CHHSLs at a particular site. The CHHSLs should be used with an understanding of the underlying assumptions and limitations, as discussed below.

- The CHHSLs for volatile chemicals only address the single exposure pathway of vapor intrusion. When evaluating the human and ecological risk associated with releases of hazardous substances to the environment, all potential exposure pathways should be evaluated. Mitigation of contaminant exposure should be conducted with an understanding of all exposure pathways, not just the vapor intrusion pathway.

- The CHHSL for a single volatile chemical in soil gas represents a carcinogenic risk of 1×10^{-6} or a hazard quotient of 1.0. For sites with a release of a single chemical into the environment, the screening number can be easily used to evaluate potential impacts to human health. However, human health risks are cumulative and should be calculated for sites with multiple contaminants.

- The use of CHHSLs for screening evaluations is entirely voluntary on the part of the responsible party and subject to the approval by the oversight agency. At sites where cleanup of contaminated soils to meet the SB 32 levels would be very costly, the time and effort to develop more site-specific, and presumably less stringent, cleanup levels is usually warranted.

- CHHSLs should not be used to determine when impacts at a site should be reported to a regulatory agency. All releases of hazardous substances to the environment should be reported to the appropriate regulatory agency in accordance with governing regulations.

Toxicity criteria used for the CHHSLs should be reviewed prior to use and adjusted as necessary based on regulatory updates. The current list of CHHSLs can be found on the Cal/EPA website (www.oehha.ca.gov/soil.html) along with a spreadsheet calculator. Other screening levels can be used for the preliminary evaluation of vapor intrusion if the levels are reasonable and scientifically based.

Use of Occupational Safety and Health Act (OSHA) Standards

Pursuant to the California Health and Safety Code, OSHA Permissible Exposure Limits (PELs) are not appropriate criteria for evaluating the risk associated with vapor intrusion. OSHA intended the PELs to regulate an employee's exposure to workplace air contaminants and not environmental air contaminants originating from the subsurface. Hence, for vapor intrusion sites, potential adverse effects to humans should be evaluated in terms of acceptable exposure based upon risk, rather than upon comparison to OSHA PEL endpoints. Appendix F provides further discussion of the use of OSHA PELs.

At sites subject to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), cleanup levels are determined either by Applicable or Relevant and Appropriate Requirements (ARARs) or the risk assessment process. OSHA standards are not ARARs under CERCLA statute and regulations, and, therefore, are not applied to CERCLA site activities.

When a Preliminary Screening Evaluation Indicates an Unacceptable Risk

If the preliminary screening evaluation indicates that the risk due to vapor intrusion is unacceptable, one or more of the following options are available:

- Conduct an evaluation of vapor intrusion with site-specific data (Steps 6 and 7);
- Collect indoor air samples to substantiate exposure from vapor intrusion as indicated by the preliminary evaluation (Steps 8 - 10);
- Remediate the subsurface contaminants to levels as determined by the preliminary screening evaluation process (Step 11);
- Institute engineering controls at the building to mitigate the exposure (Step 11).

Step 6: Additional Site Characterization

For a site that does not pass a preliminary screening evaluation, a site-specific evaluation of vapor intrusion may be warranted. Three options are available in this step: 1) collection of additional subsurface data, 2) subslab sampling, and 3) crawl space sampling. Additional site characterization may be needed to better understand the physical nature of subsurface conditions. This data would be used to determine site-specific attenuation factors. For sites with existing buildings, one can sample the soil gas directly under the building foundation (subslab) or sample the air in the area of the raised foundation (crawl space). The collection of subslab or crawl space data does not require site-specific attenuation factors for the estimation of risk. Each option is discussed separately below. At this stage of a vapor intrusion evaluation, the nature and extent of the subsurface volatile contaminant plume should be adequately characterized.

When conducting either subslab or crawl space sampling, public outreach should be conducted (see DTSC's Vapor Intrusion Public Participation Advisory).

Physical Characteristics of the Subsurface

Data on the physical character of the subsurface can be collected for the determination of site-specific attenuation factors. Subsurface samples should be representative of site conditions and sufficient number should be collected so the data can be approximated statistically. Soil cores can be submitted to a geotechnical laboratory for site-specific determination of bulk density, grain density, total porosity, grain size, volumetric moisture content, and fraction of organic carbon, as appropriate. Appendix H describes recommended methods for laboratory analysis.

Direct field measurement of a soil's effective diffusion coefficient and air permeability are recommended over determination of these fate and transport parameters by other means. Typically, the effective diffusion coefficient is derived from the soil's porosity and moisture content using the method described by Millington and Quirk (1961). To reduce uncertainty about scale effects and soil sample representativeness, investigators should consider measuring the effective diffusion coefficient in the field. Appendix I describes the method for determining the effective diffusion coefficient during the collection of the soil gas samples.

The air permeability of the vadose zone, if needed for modeling purposes, should be determined from in-situ measurements rather than from laboratory measurements. At the laboratory, core analysis for soil air permeability usually involves subjecting the soil core to a confining pressure which may bias the results low by potentially reducing the pore space within the soil core. In-situ measurements of soil air permeability should be conducted at the depth interval in the vadose zone subject to advection by building-driven depressurization. This depth interval is typically less than one meter below surface grade. Appendix J describes the method for determining soil air permeability in the field during the collection of the soil gas samples. In-situ soil air permeability measurements may not be necessary if default values for the volumetric flow rate of soil gas into the building (Q_{soil}) are used instead of calculations based on near surface soil permeability.

For existing buildings, information on the subsurface soil and engineered fill directly underneath the foundation can be obtained from the building's geotechnical report. Reports usually contain geotechnical laboratory and engineering data for the native soil and fill material, along with fill thicknesses.

Subslab Soil Gas Sampling

Subslab soil gas sampling directly below the building foundation should be considered for additional site characterization. Subslab soil gas data indicate whether contaminants are present directly under the building and thus have the potential to degrade indoor air quality. Monitoring subslab soil gas is potentially less costly than monitoring indoor air quality. However, to use subslab soil gas concentrations to evaluate vapor intrusion, contaminant attenuation over the foundation slab must be known to determine the associated indoor air concentrations. If the attenuation factor associated with the building slab is unknown or cannot be determined, an attenuation factor of 0.05 should be used (see Appendix B). When collecting subslab samples, the method reporting limits should be appropriately low to effectively evaluate the indoor air risk.

If proceeding directly to subslab sampling after preliminary screening, further characterization of the subsurface soil gas around the building, determination of the physical character of the vadose zone through geotechnical testing, and site-specific vapor intrusion modeling may not be necessary. Proceeding with subslab sampling may shorten the timeframe for evaluation of the exposure pathway and may help reduce the overall cost of a vapor intrusion evaluation. However, in addition to subslab samples, further characterization of subsurface physical properties and contamination may be needed to: (1) evaluate more complex sites, (2) predict long-term conditions and potential exposure, and, (3) if mitigation and remediation are anticipated, support planning and design.

Appendix G describes the methods and procedures for collecting subslab samples. Subslab sampling can be invasive to building occupants because it requires the removal of floor coverings and drilling of the foundation slab. Permanent sampling points should be installed and an appropriate number of sampling events should be conducted to characterize the temporal variability of subslab concentrations. At least two subslab probes should be installed at each residential structure, with one probe installed in the center of the building's foundation. The probes should be installed in inconspicuous areas, such as utility closets or beneath stairs. Subslab sampling should not be conducted near the edges of the foundation due to the effects of wind on the representativeness of contaminant concentrations (Luo et al., 2009). For buildings larger than a typical residential structure, additional subslab probes should be installed to adequately characterize the foundation area.

Crawl Space Sampling

Air within a crawl space can be sampled as a method to evaluate vapor intrusion. Crawl space air should be less affected than indoor air by lifestyle choices of the building's occupants, such as household product use and smoking. Hence, the results of crawl space air sampling should be easier to interpret than indoor air sampling results. To use contaminant concentrations in crawl space air for evaluating vapor intrusion, an attenuation factor of 1.0 should be used, which is consistent with USEPA guidance (USEPA, 2002a). Thus, for evaluation purposes, the contaminant concentration in indoor air is assumed to be equal to the concentration in crawl space air.

Step 7: Site-Specific Screening Evaluations

If evaluation of a site pursuant to Steps 1 - 5 indicates a potential vapor intrusion problem, a site-specific evaluation may be conducted using the physical parameter data collected in Step 6. DTSC recommends use of the California version of USEPA's Johnson and Ettinger (J&E) model (USEPA, 2004a). DTSC created the California version of the USEPA Vapor Intrusion Model by including California-specific chemical toxicity factors. The USEPA Vapor Intrusion Model should be used to simulate site conditions with reasonable site-specific input parameters. Other fate and transport models addressing vapor intrusion may be available and acceptable for use after agency review.

Use of USEPA Vapor Intrusion Model Spreadsheets

The J&E model (Johnson and Ettinger, 1991) is a fate and transport model that simulates the transport of soil vapors in the subsurface by both diffusion and advection into indoor air. The model calculates an attenuation factor, alpha (α), which represents the ratio of predicted indoor air concentrations to subsurface soil gas concentrations. Hence, by inputting subsurface data, the model estimates an indoor air concentration. In September 1998, USEPA programmed the J&E model into Microsoft EXCEL™ and added a health risk component that calculates the risk from inhaling a specific chemical at the concentration estimated in indoor air (USEPA, 2004a).

Individual spreadsheets were generated for different contaminated environmental media: soil gas, soil matrix, and groundwater. Model results are provided as a risk-based soil, soil gas, or groundwater concentration protective of human health, or as an estimate of the incremental risk associated with user-defined initial contaminant concentrations.

DTSC has modified two USEPA Vapor Intrusion Model spreadsheets, the models for soil gas and for groundwater, by including Cal/EPA OEHHA toxicity factors and California-specific building properties. The spreadsheets can be downloaded from DTSC's website and are recommended for site-specific evaluations. Appendix C provides information on human exposure factors used in the model. The collection and use of geotechnical input parameters for the model can be found in Appendix D. Before conducting any modeling for vapor intrusion, DTSC strongly encourages all users of these spreadsheets to review not only this Guidance but also USEPA's User's Guide for the spreadsheets (USEPA, 2004a).

Maximum contaminant concentrations should be used for modeling. However, if extensive environmental media data have been collected, the input value for contaminant concentration into the J&E model may be a statistical approximation of the dataset. A robust dataset is needed for statistical approximation, which usually implies the collection of at least eight samples (USEPA, 1992b). Collecting as many as eight subsurface samples for a single building, even a large commercial building, both spatially and temporally, is rarely done. Hence, DTSC envisions the use of statistics only at sites with large existing or future commercial buildings where at least eight samples have been collected within the building's footprint.

Attenuation Factors for Site-Specific Evaluations

In certain situations, the USEPA Vapor Intrusion Model can yield very low attenuation factors, exceeding reasonable values. DTSC does not anticipate that many sites will have attenuation factors of less than 0.0002 for shallow soil gas as indicated by the empirical data in USEPA's database (USEPA, 2008b). Hence, when using the USEPA Vapor Intrusion Model in site-specific evaluations, particularly for brownfields redevelopment, the attenuation factors are expected to range from 0.002 to 0.0002. The use of attenuation factors less than 0.0002 should be fully explained and justified using site-specific information and a weight of evidence approach.

Existing Buildings

Site-specific evaluations with the USEPA Vapor Intrusion Model should be conducted using the site data obtained in Step 6 – Additional Site Characterization. A site-specific evaluation should be conducted only after lateral and vertical delineation of the subsurface contamination and identification of all COPCs at the site. Table 3 summarizes the input parameters for site-specific USEPA Vapor Intrusion Model evaluations for California and the default input parameters specific for California. Appendix D contains information on the use of the USEPA Vapor Intrusion Model in California. Appendix D should be read before conducting fate and transport modeling with the USEPA Vapor Intrusion Model. Information about the critical input parameters into the USEPA Vapor Intrusion Model can be found in Johnson (2005).

Building-specific attenuation factors and air exchange rates can be determined as follows:

- Tracer Studies for Attenuation. Measurement of a conservative tracer injected below a structure can allow for the calculation of a site-specific attenuation factor. The tracer-observed attenuation factor can then be used as an additional line of evidence for evaluating risk. Likewise, naturally-occurring radon can also be used to determine a building-specific attenuation factor (McHugh et al., 2008). Radon should be measured in the subslab area concurrent with indoor air measurements.

- Tracer Studies for Air Exchange Rate. The actual air exchange rate in a building can be determined by tracer studies. ASTM Method E741-00 (2006) describes a number of techniques for measuring ventilation rates using gaseous tracers such as helium or sulfur hexafluoride. Measurements of site-specific air exchange rates should be representative of long-term building behavior.

Building pressure measurements should not be used as single line of evidence for negating the possibility of vapor intrusion. Even though numerous foundation measurements may indicate positive building pressurization, overpressurization within a building is usually non-uniform, allowing for vapor intrusion. While DTSC does not discourage the collection of differential pressure measurements over a building's foundation, the data should only be used with other lines of evidence for evaluating vapor intrusion.

Future Buildings

Making a reasonable prediction for vapor intrusion into future buildings is challenging. Construction activity may alter subsurface vapor concentrations and the physical character of the subsurface. The soil air permeability may be altered due to activities associated with new building construction, significantly increasing the potential for vapor intrusion. Likewise, the moisture content of the vadose zone directly under a future building may decrease with time due to the inability of rainwater to infiltrate under the building (Tillman and Weaver, 2007). Accordingly, DTSC recommends that modeling approaches for future buildings be sufficiently conservative to protect public health, as follows:

- Subsurface plumes should be delineated three-dimensionally.

- Fate and transport modeling should be conducted with concentration data from contaminant source zones.

- Maximum subsurface concentration data should be used for modeling purposes. Statistical approximation of contamination should only be done if a robust dataset is available for each individual building footprint.

- Data should be collected to demonstrate that the soil gas and groundwater plumes are stable.

- When calculating attenuation factors, a default value of 5 liters per minute for the soil gas advection rate (Q_{soil}) should be used, as proportionally corrected for building size. Hence, buildings covering an area larger than 100 square meters will have, for modeling purposes, a soil gas advection rate of greater than 5 liters per minute.

- The crack-to-total area ratio of 0.005 (unitless) should be used for modeling purposes, regardless of the proposed foundation design.

- Human health risk should be estimated and characterized using multiple lines of evidence.

Step 8: Building Survey and Work Plan Development

This step describes the preparatory activities that should be completed prior to indoor air sampling. The step includes the building survey, work plan development, and completion of building screening. This preparation ensures that the objective of the indoor air sampling, to establish the relationship between the subsurface and the indoor air, can be achieved. Indoor air sampling is typically conducted in a later phase of a vapor intrusion investigation due to the complexity in evaluating indoor air data. When indoor air sampling is anticipated, a work plan should be submitted to the lead oversight agency for review and approval. The work plan should include the following:

- Conceptual site model (CSM)
- Site map showing onsite and offsite buildings, and utility corridors
- Sampling methodology
    - Data quality objectives (DQOs)
    - Number and type of samples
    - Rationale for each sampling location
    - Duration of air sample collection
    - Laboratory analytical methods and detection limits
- Procedures for risk assessment
- Contingency plan for response actions
- Public outreach activities

The indoor air sampling work plan should be sufficiently detailed so that building occupants, owners, and the sampling team have a clear understanding of the activities that will take place. The work plan should include an updated CSM, site history, a summary of all investigations preceding the indoor air sampling, and an explanation and justification for indoor air sampling. Additional information on CSM preparation can be found in Step 2.

Building Inventory

Prior to preparation of an indoor air sampling work plan, a site visit should be conducted to inventory and survey all the buildings potentially subject to vapor intrusion. The building information should be added to the CSM, specifying the location of the building, type of building construction, building use, building occupancy, and type of foundation. A recent aerial photograph of the site and the surrounding area is a good evaluation tool. Also, the aerial photograph can be used to display the results of the subsurface investigation and the lateral dimensions of the contaminant plumes.

Detailed plot maps should be prepared from the information collected during the onsite and offsite building inventory. The plot maps should include all buildings, building addresses, street names, outdoor air sample locations, monitoring well locations, soil gas sampling locations, utility corridors, and predominant wind direction. Businesses and land use in the area that could influence the indoor air sampling results, such as gasoline stations, oil production facilities, factories, dry cleaners, parking lots, and heavily used roadways, should be noted on the maps. Information on the types of industry in the neighborhood is used when selecting outdoor sample locations and for interpreting the air data. The local air district should be contacted regarding air permits issued in the surrounding area. The local air district can also provide data from nearby ambient air monitoring stations.

In the work plan, the location of all environmental treatment systems, such as for soil vapor extraction and groundwater extraction, should be denoted on plot maps because system discharges to the air may impact outdoor air sampling results. Ideally, these systems should be shutdown during indoor and outdoor air sampling to minimize bias on the sampling results.

Sampling Methodology

Because concentrations of volatile chemicals in the air environment are variable, collecting enough data to thoroughly understand and predict the temporal and spatial distribution can be too resource-intensive to be fully achieved. Air sampling should be conducted with an understanding of this variability and uncertainty. Because of contaminant variability and potential indoor sources of contamination, the completion of the Building Survey Form (see Appendix L) will aid in interpreting the indoor air sampling results. To compensate for these inherent uncertainties, indoor air sampling should target locations and conditions under which maximum vapor intrusion is expected.

Work plans should specify the number of sampling events, number of sampling locations, sampling equipment, and sampling duration. Given the resources required and sometimes invasive nature of indoor air sampling investigations, sampling is often limited to a few locations within a building. Typically, for each sampling event, two to three samples are collected in a residence and a minimum of three samples are collected from outdoor locations. At least two sampling events should be conducted to evaluate the seasonality of vapor migration into the building.

The work plan should specify the analytical methods, analytes, method reporting limits, and method detection limits. For indoor air investigations, the analytical methods must be appropriate and sufficiently comprehensive to ensure that all COPCs, including possible transformation products, are analyzed. Detection limits should be sufficiently sensitive to ensure that data quality objectives can be met. Consultation with the analytical laboratory as part of the work plan development is recommended, particularly for volatile chemicals that may require adjustment or modification in the analytical procedures. See Step 9 for further discussion.

Data Evaluation and Risk Assessment Procedures

The work plan should describe procedures for data evaluation and interpretation of sampling results. For the health risk assessment, the work plan should describe the procedures for estimating contaminant concentrations for exposure assessment, and provide the exposure assumptions, toxicity criteria, and risk equations to be used for estimating cancer risk and hazard. If risk-based screening concentrations will be used for evaluating risks, the chemical-specific concentrations should be provided and the source of the criteria should be described.

To compute statistical estimates for most environmental data, a minimum of eight samples is generally necessary, depending on the coefficient of variation and the underlying statistical distribution of the data. Indoor air data sets are typically too limited to compute reasonable statistical estimates of contaminant concentration. In these cases, DTSC recommends that the maximum observed concentration of each identified contaminant be used to estimate human health risks.

Contingency Planning

Prior to initiating indoor air sampling, a contingency plan should be generated for responding to the indoor air sampling results. Indoor air sampling data is an important line of evidence in the characterization of potential human health risks from vapor intrusion and for determining appropriate response actions for managing those risks. The specific responses are determined on a case-by-case basis upon interpretation of at least two indoor air sampling events, along with consideration of all other lines of evidence and characterization of the risks. Additional sampling events may be necessary if indoor air data indicate large spatial or temporal variations in contaminant concentrations. The contingency plan should identify response actions for risk management, such as no further action, monitoring, mitigation, and/or source remediation, based on the weight of evidence. See Step 10 for further discussion.

Public Notification

The public should be notified well in advance of indoor air sampling. Sensitivity to building occupants is essential due to heightened concerns about potential exposure and disruption of daily routines. Individual letters, fact sheets, and other appropriate materials should be mailed to occupants stating that indoor air testing is pending. About two weeks prior to indoor air sampling, each occupant should be contacted in person to schedule the testing and to explain the testing procedures. Also, written instructions should be provided. The instructions should state that use of certain consumer products is discouraged due to potential biasing of the sampling results. Then, at the time of sampling, the occupant should again be asked about consumer products. Hence, at least two opportunities to discuss the use of consumer products with occupants prior to the indoor air sampling should take place. See DTSC's Vapor Intrusion Public Participation Advisory for detailed guidance on public outreach during this step.

To the extent feasible, appointments are scheduled at the convenience of the building occupants. Therefore, for residences, it is not uncommon to schedule appointments and initiate sampling in the evening after people return home from work.

Building Screening and Indoor Air Sampling Preparation

At the time of sampling, the Building Survey Form (Appendix L) should be completed and the building and indoor air should be screened as described below. A floor diagram should be generated, illustrating the floor layout, chemical storage areas, garages, doorways, stairways, basement sumps, utility conduits, elevator shafts, and any other pertinent information (see Appendix L).

Indoor sources of contamination should be identified and, if possible, removed from buildings prior to indoor air sampling. Common household items, such as cleaners, glues, fingernail polish remover, aerosol sprays, paint, dry-cleaned clothes, and tap water can offgas and interfere with sampling results. The presence of these interfering sources may bias indoor air sample results or preclude detection of vapors from the subsurface. Commercial and household products should be inventoried every time indoor air is sampled so their potential contribution to indoor air contamination can be evaluated. Each room in the building should be inspected, and products that contain volatile chemicals should be listed on the Building Screening Form (Appendix M) along with the volatile ingredients of each product.

As appropriate, indoor contaminant sources can be located with portable field instruments that have detection limits in the parts per billion by volume range. A properly calibrated portable gas chromatograph/mass spectrometer (GC/MS) can yield reliable measurements in this range. Other instruments may be available to achieve these detection limits, such as photo-ionization detectors and the USEPA's trace atmospheric gas analyzer (TAGA). Once field instruments identify indoor sources of contamination, these sources can be either removed or sealed prior to indoor air sampling. Removing these sources prior to testing is the most effective means of reducing bias and eliminating confounding factors. Sealing containers rather than removal may be acceptable, but the containers should be tested with a field instrument to demonstrate that the seal is tight. Once these interfering conditions are corrected, ventilation may be needed before sampling to eliminate residual contamination.

When deploying or retrieving indoor air sampling devices, portable field instruments can also be used to determine the entry points of contaminated soil gas into the structure through the collection of measurements in the following areas:

- Foundation-wall joints
- Foundation cracks and concrete control joints
- Building utility entry ways
- Elevator shafts
- Floor drains
- Fixtures and seams around bathtubs and showers

A barometer or differential pressure meter capable of measuring small increments of pressure (e.g., 0.03 inches of mercury) may be used to measure the difference in pressure between indoor and outdoor locations. These measurements allow determination as to whether (1) a building is under or overpressurized and (2) pressure differences are present between locations within a building. All indoor air screening and other measurements collected with field equipment should be annotated on building plot plans (Appendix L) and included in indoor air assessment reports.

Step 9: Indoor Air Sampling

Indoor air sampling is conducted because subsurface contaminant concentrations pose a potential risk as determined by vapor intrusion modeling and risk assessment or by comparison with preliminary or site-specific risk-based screening levels. Interpreting indoor air sampling results to assess the risk from vapor intrusion is challenging. DTSC recommends that this step be undertaken after the subsurface has been completely characterized. However, there may be site-specific circumstances when indoor air sampling may be conducted prior to full subsurface characterization, particularly to address public concerns. As in other steps of this Guidance, public outreach is an essential component of any indoor air sampling work plan.

Site Visits and Documentation

Each indoor air sampling event may require numerous visits to the building potentially subject to vapor intrusion, as follows:

- Meeting with building occupants to explain vapor intrusion investigation and schedule building screening and air sampling
- Deployment and retrieval of air sampling equipment
- Discussion of sampling results with building occupants

When scheduling the sampling, usually about two weeks prior to the field event, the intent of the data collection is explained to building occupants and written information (fact sheets and instructions) is provided. Upon deployment of the sampling equipment, the Building Survey Form (Appendix L) is completed to denote the time, date, sample location, sample identification number, and weather conditions. As appropriate, the building should be screened with a field instrument to locate VOC-emitting household products. A photograph of each sampling device can assist in the documentation of the sampling activities and should be considered on a site-by-site basis. Upon sampling device retrieval, any changes in the building condition should be recorded and the occupants should be asked if any consumer products were used or brought into the building. Regulatory staff should be present during all building visits, and sampling technicians are advised to conduct indoor air sampling in pairs.

An operating industrial facility with processes or activities that use or produce the same chemicals that are contaminants in the subsurface presents a challenge for evaluation of vapor intrusion and risk. Chemical releases to the environment should be characterized and mitigated based upon the risks to human and ecological receptors resulting from the release. Because the chemicals in the industrial process are likely to confound indoor air sampling results, indoor air sampling may not be a viable option to further document the health risks associated with vapor intrusion. Accordingly, the response action for subsurface contamination would proceed without the benefit of indoor air testing. However, indoor air data for chemicals present in the subsurface, but not currently used or produced by the facility, may provide evidence of vapor intrusion. Empirical attenuation factors developed for these subsurface co-contaminants may be extrapolated to the chemicals used in the facility process so that indoor air concentrations attributable to vapor intrusion can be estimated.

Indoor Air Sampling

Indoor air sampling should be conducted under conservative conditions. In general, the windows of the building should be closed. However, certain exceptions may be necessary if sampling is done in the summer in a building that is not air conditioned. Likewise, ingress and egress activities should be minimized. Heating, ventilation, and air conditioning (HVAC) systems should be operated normally for the season and time of day. During colder months, heating systems should be operating for at least twenty-four hours prior to the scheduled sampling event to maintain normal indoor temperatures above 65°F before and during sampling.

DTSC recommends the following when conducting indoor air sampling:

1) Sampling Duration. For the first sampling event, indoor air samples should be collected over a 24-hour period to ensure diurnal fluctuations in vapor intrusion and indoor air concentrations are included in the sampling period. After vapor intrusion is confirmed, sampling events should be conducted to produce representative concentrations of the monitored compounds over the anticipated daily exposure period for building occupants. Hence, air samples should be collected over a 24-hour period for residential structures, over an 8-hour period for non-residential structures, and over a typical school day for students. When feasible, 24-hour and 8-hour sampling may be conducted during the same sampling event. In some cases, indoor air samples may be collected with passive samplers for longer sampling periods (see Appendix K).

2) Number of Sampling Events. One indoor air sampling event is not representative of continuous long-term exposure within a building. Multiple sampling events should be conducted to characterize exposure over the long-term. Numerous sampling events may

be required within a building before DTSC would consider “no further action” for the exposure pathway. At a minimum, sampling data should be obtained over two seasons; late summer/early autumn and late winter/early spring. The data evaluation and contingency plan for the site should guide decisions regarding the objective and number of sampling events.

3) Number of Samples and Locations. All floors of a residential structure potentially subject to vapor intrusion should be sampled for indoor air quality. All occupied areas, as well as basements, should be sampled. Based on site-specific conditions, it may be necessary to sample all units of an apartment building. Sampling devices should be located in the breathing zone, approximately 3 to 5 feet off the ground for adults and at lower sampling heights if the receptors of concern are children as in a daycare center or school. Samples should be collected in the center of the room, away from doors. At a minimum, it is recommended that sampling points include the primary living area and likely locations for subsurface vapor entry (typically the bathroom or kitchen). For multi-storied residential buildings, at least one sample should be collected on each floor. When sampling an office building, the number and locations of samples should be based on site-specific conditions. In office buildings, samples should be collected from primary work areas and near the points of vapor entry (such as sumps, elevator shafts or floor drains) to help define the potential routes of entry.

4) Sampling Equipment. When sampling indoor air with evacuated canisters, extra canisters, pressure gauges, and flow regulators should be taken into the field in case the integrity of some of the canisters is compromised or if some flow regulators and pressure gauges malfunction. Each sampling canister should have a dedicated vacuum gauge. The gauge is needed to verify the canister is properly evacuated prior to initiation of sampling and to demonstrate that the canister is slightly depressurized upon completion of the sampling. Likewise, the gauge will indicate whether the canister’s flow regulator is functioning properly during sample collection. Flow regulators should be configured to produce a constant sampling rate. Sampling canisters, along with all flow regulators and pressure gauges, should be certified clean to the laboratory’s method reporting limit.

   Collecting air samples in canisters is currently the predominant sampling method used for indoor air investigations. Canisters provide quantitative analytical data and achieve the low detection limits needed to support risk assessments. USEPA Region 9 is currently evaluating the use of passive air samplers for indoor air investigations by conducting comparison studies with canisters at several sites in California (Lee et al., 2010). Other researchers have also conducted comparison studies (Coyne et al., 2009; Bruno et al., 2008; Odencrantz et al., 2009). Passive samplers offer several advantages over canisters, including lower cost, simplicity and versatility of use, small size, unobtrusive appearance, and potential to collect samples over longer time periods than canister samplers. At present, passive samplers appear to have potential as a reliable alternative to canister sampling in certain applications, particularly as a screening tool for identifying structures for further indoor air evaluation. The use of passive samplers for screening or as a supplement to canister sampling should be based on the contaminants, site conditions, and project DQOs. As passive sampler technology becomes further developed, and high quality, quantitatively accurate results for contaminant concentrations in indoor air can be achieved, data from passive samplers may be used in quantitative risk assessments. See Appendix K for more information.

5) Analyte List. Indoor air should be analyzed for all known and potential subsurface contaminants so that contaminants in the subsurface and indoor air can be correlated in the evaluation of vapor intrusion and the cumulative health risks associated with vapor intrusion can be characterized. Limiting the indoor air testing to a few target analytes is not recommended, particularly for initial sampling events. Subsequent to the initial sampling event, limiting target analytes might be justified on a case-by-case basis for sites that are fully characterized and all contaminants are known with certainty. Analyzing air samples for a large suite of analytes may detect vapor intrusion-derived contaminants not previously detected in the subsurface. Contaminants may not have been detected in the subsurface for various reasons, including but not limited to, a) elevated detection limits resulting from high concentrations of co-contaminants, b) sampling and analytical errors, c) temporal and spatial variation, d) inappropriate sampling locations and depths, and e) generation of unanticipated degradation and transformation products. Multiple lines of evidence should be used to determine vapor intrusion-derived contaminants (see Step 10). Data for indoor sources may indicate a potential background risk that should be communicated to occupants and considered in risk management decisions concerning the subsurface contamination.

It is generally desirable to conduct concurrent sampling of other media, such as sub-slab soil gas, and/or groundwater, when sampling indoor air. Sampling all media concurrently will give a more accurate representation of contaminant migration and reduce the uncertainty associated with the temporal variability in contaminant concentration data.

Ambient (Outdoor) Air Samples

Site-specific ambient (outdoor) air samples should be collected when indoor air sampling is conducted, with the realization that indoor and outdoor air samples will always have detectable concentrations of common air pollutants. While local ambient air monitoring station data may be available, the data should be used with caution. Ambient air station data are reported as basin-wide results and are not typically useful when evaluating vapor intrusion. However, ambient data from the local air district or the Air Resources Board can be included in the final indoor air assessment report. When conducting a vapor intrusion assessment, site-specific ambient air data are used to interpret the measured indoor air concentrations, not to adjust the indoor air concentrations for risk assessment purposes.

Ambient air samples should be collected at locations that are not influenced by subsurface contamination. Therefore, ambient air samplers should be located upwind of subsurface plumes. In addition, information on the types of industry in the neighborhood should be used when selecting ambient sample locations and interpreting the air data. The ambient air data can be used as a qualitative tool to provide information regarding outside influences on indoor air quality.

The following should be considered when collecting ambient air samples:

- Sampling devices should be located approximately six feet off the ground.
- Ambient sampling should be conducted concurrent with the indoor air sampling.
- Ambient samples should be collected in upwind locations.

- Ambient samples should be located away from gasoline stations, automobiles, gasoline-powered engines, fuel and oil storage tanks, chemical storage areas, and dry cleaners.

- Sampling devices should be placed at least 10 feet beyond a tree's drip line.

- Ambient air samples should be collected on the upwind side of a building at a distance equal to twice the height of the building.

- Three ambient samples, at a minimum, should be collected with each indoor air sampling event.

Air Sampling Analytical Methods

When sampling indoor air, analytical methods should include all contaminants of potential concern identified in the subsurface. The goal of indoor air sampling is to measure volatile chemicals at levels lower than risk-based concentrations. Therefore, the samples should be analyzed by methods that can achieve a method reporting limit of at least 0.025 µg/m^3. Some chemicals may require lower reporting limits, such as 1,2-dibromo-3-chloropropane, 1,2-dibromoethane, 1,2,3-trichloropropane, and 1,3-butadiene. Prior to choosing an analytical method, the laboratory should verify that it can achieve the minimum reporting limits for the target compounds as indicated by the project DQOs.

The recommended laboratory analytical methods for specific volatile chemicals are listed in Table 1. Detailed descriptions of these analytical methods are given in Cal/EPA's Active Soil Gas Investigation Advisory and are briefly summarized here. The analytical methods for air analysis that are capable of achieving appropriate detection limits are TO-14A (non-polar compounds only) and TO-15 (polar and non-polar compounds). TO-10A and TO-13A are the suggested methods for the analysis of pesticides, herbicides, and PCBs.

The analytical mode (i.e., full scan or selective ion mode [SIM]) should be dictated by the DQOs of the sampling event. Generally, DTSC recommends analyzing air samples in full scan mode. The full scan mode will provide a more accurate identification of the analytes and corresponding concentrations in the sample. Further, in full scan mode, all compounds can be confirmed by a mass spectral library. SIM can achieve lower detection limits for contaminants and should be used when a known contaminant must be detected at relatively low concentrations. Project DQOs might require analysis of a subset of samples by SIM, such as those expected to have lower concentrations. The analysis of the remaining samples should be done in full scan mode. Both SIM and full scan analysis can be performed on the same sample if a sufficient sample volume is collected.

Quality Assurance/Quality Control

Only certified clean sampling devices should be used for air sampling. Precautions should be taken to avoid sample interference such as fueling vehicles used to transport air sampling equipment or using solvent-based permanent marking pens in the field. Once the samples are collected, they should be stored according to the method protocol and delivered to the analytical laboratory as soon as possible. Sampling canisters subject to air travel should have vacuum measurements before and after transit to verify canister integrity. Samples should not exceed recommended holding times. To check the precision of the sampling, DTSC recommends collection of at least one duplicate per laboratory per field day. Chain-of-custody protocols should be followed. A trip blank is considered unnecessary when sampling with passivated canisters. Field blanks are necessary for USEPA Method TO-17 for sorbent tubes and should be submitted and analyzed with the samples.

Post-Sampling Notification of Building Occupants

Communicating indoor air sampling results to property owners and building occupants can be difficult because detectable concentrations of subsurface contaminants are often encountered, even if vapor intrusion is not transpiring at the building in question. The means by which the results are conveyed is a project-specific decision, and should be identified prior to the indoor air sampling event, typically in the indoor air sampling work plan. The results should be conveyed to property owners and building occupants individually or in small groups (because of privacy considerations) in a timely fashion. In addition to any verbal discussion, the project team should consider providing an individualized letter about the sampling results, accompanied by additional explanatory information, as appropriate. Refer to DTSC's Vapor Intrusion Public Participation Advisory for additional discussion regarding the communication of indoor air sampling results to building occupants and owners.

Privacy Rights

The privacy rights of property owners and building occupants should be protected during the indoor air investigation and associated risk evaluation. In general, personal information should not be released to the public if the release constitutes an unwarranted invasion of privacy. Any privacy concerns should be addressed during the investigation-related activities (such as in the development of the public communication strategy, public participation actions, incidental communications with interested community members, and responses to press inquiries and Public Records Act Requests).

Information regarding investigation and response actions on private property and within private buildings should be handled in a discrete manner, both to maintain privacy and to address any privacy concerns that the property owners or building occupants may have. To the extent allowable by law, privacy concerns could be accommodated by providing the property owners and building occupants with the sampling results in a private letter while providing a general summary of the sampling results for public use. The privacy rights of the property owners and building occupants have to be balanced against the public's right to know. The balancing test should be used on a case-by-case basis, in consultation with legal counsel.

DTSC's Vapor Intrusion Public Participation Advisory provides further discussion regarding privacy considerations.

Step 10: Evaluation of Indoor Air Sampling Results and Response Actions

DTSC recommends a minimum of two indoor air sampling events before making a risk management decision for a building. Investigators must be cognizant that short-term measurements rarely represent long-term conditions (Schuver and Mosley, 2009). Discrete samples collected in most indoor air investigations may not adequately address temporal variation in contaminant concentration. Also, it is usually not possible to collect enough samples for a rigorous statistical evaluation of the data. Accordingly, DTSC recommends that risks be estimated using maximum concentrations.

The primary objective of the indoor air sampling investigation is to determine if the contamination underneath the building is entering the indoor environment. Interpretation of indoor air sampling results should be done in conjunction of all available lines of evidence associated with a vapor intrusion evaluation. The following items should be considered when interpreting indoor air data:

1) Chemicals of Potential Concern. An important line of evidence is the identification of subsurface contaminants at the site. Vinyl chloride and other products from the breakdown of chlorinated solvents, such as 1,1-dichloroethene and cis-1,2-dichloroethene, which are uncommon in consumer products and not typically found in ambient air, can be indicative of vapor intrusion. Likewise, radon in indoor air is another indicator that soil gas is migrating into the building.

2) Ambient Measurements. If indoor air concentrations are generally greater than ambient concentrations, and there are no known indoor air sources according to the building survey, there is a great likelihood that the indoor air concentrations are due to vapor intrusion. Ambient air in California contains numerous volatile chemicals, and these volatile chemicals, such as benzene and tetrachloroethlyene (PCE), should be found in both outdoor and indoor air, regardless of the occurrence of vapor intrusion. If no contaminants are detected in outdoor or indoor samples, the data are suspect and the samples should be reanalyzed.

3) Subslab Measurements. Subslab samples provide a good indication of the volatile chemicals that could migrate into the building. If the concentration of a chemical in subslab soil gas is equal to or less than indoor air concentrations, it is reasonable to conclude that the indoor air concentration may be derived in part from sources other than from vapor intrusion. This conclusion assumes that soil gas naturally attenuates in the migration from the subslab into an overlying structure and that barometric pressure fluctuations are not causing reversible vapor flow.

4) Comparison of Attenuation Factors. Volatile chemicals beneath a building should move from the subsurface into indoor air at approximately the same rate. Thus, chemical-specific attenuation factors, derived from indoor air and subsurface sampling data, should be similar. If not, indoor sources of contamination may be present within the subject building.

5) Soil Gas Measurements. Typically, the greater the concentration of contaminants in soil gas, the more likely vapor intrusion will result in detectable concentrations in indoor air.

6) Constituent Ratios. Evaluating the ratio between concentrations of different chemicals in soil gas, subslab, and indoor air may help to identify potential vapor intrusion or screen out background sources (Feenstra, 2006). For many volatile chemicals, the background concentration ratios are distinct from subsurface-derived volatile chemical ratios. If the ratios of constituents in the indoor air sample are similar to the ratios observed in soil gas, one may conclude that the two are linked and that there is a contribution from the subsurface sources, especially if subsurface concentrations are significantly higher than indoor air concentrations. This is a reasonable assumption because volatile subsurface contaminants will move into indoor air at similar rates. Comparison of chemical ratios in groundwater to ratios in indoor air may also be considered. However, these ratios should be adjusted for different relative volatilities of the contaminant using their Henry's law constants.

7) Isotope Analysis. Compound-specific isotope analysis (CSIA), such as chlorine-36 and carbon-13, potentially can be used to distinguish between different chlorinated solvent

sources (Van Warmerdam et al., 1995). The use of stable isotopes is a developing technique for vapor intrusion that may merit consideration in some situations. Isotopic analysis might indicate whether the indoor contaminants have the same isotopic signature as subsurface contaminants, yielding an additional line of evidence for vapor intrusion (McHugh et al., 2011). While no specific regulatory guidance exists for isotopes for vapor intrusion, USEPA (2008c) is a resource concerning isotopes in groundwater characterization.

8) Indoor Air Contamination by Consumer Products. The identification of indoor sources of contamination is an important activity because chemicals present in the building attributed to consumer products that are risk drivers will not be reduced when mitigation controls and source remediation are implemented.

Risk Characterization

Unless the data are sufficiently robust for statistical approximation of the average concentration, the maximum measured indoor air concentration of each chemical should be used in the equations in Appendix C to estimate the risk and hazard posed by vapor intrusion. The risks from all volatile chemicals should be added to obtain the total potential risk for the indoor air exposure pathway. Any site-specific exposure evaluation that deviates from the assumption of residential land use should be performed only with the approval of the oversight agency. DTSC stresses that vapor intrusion is only one of many exposure pathways that are evaluated in a human health risk assessment. Hence, the risk or hazard from the vapor intrusion pathway is added to the risks and hazards posed by all other chemicals and all other potentially complete exposure pathways in the characterization of the cumulative risk at a site, as discussed in Appendix C and USEPA (1989).

As the final step in the risk assessment process, risk characterization integrates quantitative and qualitative information, and identifies the important strengths and uncertainties for each component of the assessment as part of the discussion of the confidence in the risk assessment. The characterization of risk associated with the vapor intrusion pathway is a key step in decision-making and, along with other factors, in determining appropriate response actions.

Response Actions for Risk Management

Indoor air sampling data should be used along with other site data in the determination of appropriate response actions. The need for specific responses will be determined on a case-by-case basis, depending on the data from the indoor air sampling events, other lines of evidence, and risk characterization. The response action for the site should follow the contingency plan as described in the approved indoor air sampling work plan. All response actions associated with indoor air sampling should be done in consultation with the oversight agency.

DTSC's Vapor Intrusion Mitigation Advisory provides information and guidance on risk-based decision-making for vapor intrusion sites. The risk management decision should take into account both site-specific and chemical-specific data. Multiple lines of evidence and collection of additional data as appropriate should be used to reduce the uncertainty in evaluating vapor intrusion at the site. Chemical-specific information to be evaluated would include: 1) toxicity endpoints and target-organs affected by the contaminants; 2) whether the chemical is a known human carcinogen or a suspected human carcinogen; and 3) the uncertainties associated with the derivation of the toxicity criteria.

The contingency plan outlined in the table below is an example of response actions based on certain quantitative risk assessment results. In the example below, if the results of the indoor air sampling events indicate subsurface contaminants migrating into indoor air pose a risk less than $1x10^{-6}$ and a hazard less than 1, and other lines of evidence indicate that subsurface contamination would not be expected to pose a greater risk in the future due to increasing concentration trends or transformation to more toxic contaminants, a no further action response is supported.

If the initial evaluation of vapor intrusion indicates a risk between $1x10^{-6}$ and $1x10^{-4}$ or hazard index greater than 1, pursuant to this example, more data collection, such as repetitive indoor air sampling, may be prudent to refine the risk estimates and further characterize temporal variability. In this example contingency plan, if the hazard posed by a single chemical exceeds one (hazard quotient > 1), an immediate response action may be warranted, particularly if an acute or subacute hazard may be indicated. The nature and toxicity of the contaminant must be considered. If multiple chemicals are present and the hazard index (HI) exceeds one but hazard quotients for individual chemicals are each less than one, a toxicological evaluation to segregate chemicals by target organ(s) and/or mechanisms of action may be conducted to further evaluate hazard. After evaluating any additional sampling data and considering the weight of all lines of evidence for risk characterization, a risk management decision would be made for the building. In some cases, it may be more prudent to mitigate vapor intrusion rather than collect additional indoor air data.

EXAMPLE CONTINGENCY PLAN

Vapor Intrusion Risk / Hazard[1]	Risk Management Decision	Activities
Risk $<1x10^{-6}$ Hazard Index ≤1.0	No Further Action	• None
$1x10^{-6}$ < Risk < $1x10^{-4}$ Hazard Index >1.0	Evaluate Need for Action	Possible Actions: • Additional Data Collection • Monitoring • Additional Risk Characterization • Mitigation • Source Remediation
Risk $>1x10^{-4}$	Response Action Needed	• Vapor Intrusion Mitigation • Source Remediation

[1] Estimated from multiple lines of evidence.

If the measured or predicted volatile chemical concentrations in indoor air, as contributed by subsurface vapor intrusion, are estimated to pose a potential long-term risk to human health above $1x10^{-4}$, both source remediation and vapor intrusion mitigation will be needed. The timing of this response action will depend on whether a building is existing or if future development will proceed before remedial goals are met. The decision to implement a mitigation action should be based on multiple lines of evidence to evaluate potential human health risks from vapor intrusion. The oversight agency must approve an appropriate response action decision document for any mitigation action.

Site-specific ambient air data should also be used to help guide risk management decisions to determine if a response action is warranted. DTSC does not anticipate a situation where vapor intrusion mitigation, such as a subslab depressurization system, would be warranted to reduce indoor air concentration below ambient (outdoor) levels. However, in many cases, subsurface contamination may warrant remediation to alleviate risk due to other exposure pathways and concerns about groundwater protection. Chemicals present in the building that are not known to be in the subsurface, but are risk drivers, will not be reduced when mitigation controls are implemented.

Indoor air sampling data in combination with other lines of evidence are used to characterize vapor intrusion risk and help guide risk management decisions regarding response actions. Public concerns and risks associated with other exposure pathways are also considered in determining response actions. The above table is provided as an example only and is not meant to circumvent or supersede any applicable regulatory processes or requirements. For example, the nine feasibility study criteria pursuant to Title 40, Federal Code of Regulations, Section 300.430 apply when selecting response actions for Superfund sites. All response actions associated with indoor air sampling should be done in consultation with the lead oversight agency.

Step 11: Mitigate Indoor Air Exposure, Monitoring, and Implementation of Engineering Controls

If the health risk evaluation indicates a significant risk or hazard, vapor intrusion must be mitigated if the site is occupied or will be used prior to completion of remediation. The goal of a vapor intrusion mitigation system is to reduce subsurface vapor contaminant entry into the building until the subsurface contamination source is remediated or no longer poses a significant risk to human health. Remediation and mitigation are complementary components of a response action for volatile contaminants, addressing cleanup of subsurface contamination and impacts to human receptors by the vapor intrusion pathway, respectively. DTSC does not consider a vapor intrusion mitigation system as a means of remediating the source of the subsurface contamination.

The most commonly accepted mitigation techniques are subslab venting and subslab depressurization. These and other techniques are discussed in detail in DTSC's Vapor Intrusion Mitigation Advisory. Alteration of the HVAC system to provide positive pressure within commercial buildings may be considered as an interim mitigation measure to reduce vapor intrusion exposure, but should not be considered a long-term solution. DTSC acknowledges that other potential mitigation approaches may be appropriate and that flexibility is needed to address site-specific conditions. Moreover, mitigation technologies may be developed in the future that will have equal or better performance than subslab venting or subslab depressurization systems.

At some sites, where the removal or reduction of contaminant source concentrations to an acceptable level of risk is not possible, engineering measures and institutional controls must be utilized to reduce or prevent potential vapor intrusion exposure. Land use covenants will be required in these cases, typically include the following:

- A description of the potential cause of the unacceptable risk
- A prohibition against construction unless contaminant concentrations are reduced to acceptable risk levels through the removal or treatment of contamination
- The implementation and monitoring of appropriate engineered remedies to prevent or reduce vapor intrusion until risk-based cleanup levels have been met
- A Site Management Plan containing
    - Notification requirements to utility workers or contractors that may have contact with contaminated soil, soil gas, and/or groundwater while installing utilities or undertaking construction activities
    - Site-specific worker health and safety plans

This documentation should be recorded at the local County Recorder's Office after approval by the oversight agency. More information about institutional controls can be found in DTSC's Vapor Intrusion Mitigation Advisory and USEPA (2010).

FIVE-YEAR REVIEWS

When a response action results in residual contamination remaining on site at concentrations that would preclude unrestricted land use, reviews must be conducted every five years to evaluate the functionality and effectiveness of the selected remedy. These reviews usually address the following questions:

- Are the response action and/or mitigation functioning as intended?
- Are the cleanup objectives, goals, and criteria used at the time of initial implementation still valid?
- Does new information question the protectiveness of the remedy?
- Have there been significant changes in the distribution or concentrations of contaminants at the site?
- Are modifications needed to make the operations and maintenance plan more effective?

Older sites where volatile chemicals were evaluated without consideration of vapor intrusion may be reopened during a five-year review to determine if the original response action remains protective of human health. See USEPA (2001) for more information about the five-year review process.

VOLATILE PETROLEUM HYDROCARBONS

For petroleum release sites, specific volatile indicator compounds within petroleum (such as benzene, toluene, ethyl benzene, xylenes [BTEX] and naphthalene) should be evaluated for vapor intrusion exposure. Analysis of just these indicator compounds may be sufficient for risk assessment purposes. If it is necessary to quantitatively assess risk associated with total petroleum hydrocarbon (TPH), a fractionated TPH analysis can be performed. A fractionated TPH analysis provides information regarding the class of compounds present, such as aliphatic and aromatic hydrocarbons. These analyses provide much more detailed information about the petroleum mixture, which is needed for fate-and-transport estimates and human health risk assessment for TPH. Having these more definitive data allows for the development of site-specific cleanup goals that eliminate reliance on conservative screening levels. Depending on the nature and extent of the contamination, TPH fraction and mixture, concentrations, and degree of weathering, representative samples for TPH fraction analysis may be collected from a subset of the locations sampled for TPH.

Aerobic biodegradation of petroleum hydrocarbon vapors will occur if proper conditions exist in the vadose zone. If sufficient oxygen is present along with appropriate soil moisture, nutrients, and pH conditions, volatile petroleum hydrocarbons can readily biodegrade in the vadose zone. To evaluate the vapor intrusion of petroleum hydrocarbons, the California State Water Resources Control Board's updated Leaking Underground Fuel Tank Guidance Manual should be followed in conjunction with the procedures with this Guidance.

CONFIRMATION SAMPLING FOR THE COMPLETION OF REMEDIATION

To verify that cleanup activities have reduced subsurface volatile chemical concentrations to levels protective of human health, including receptors subject to vapor intrusion, subsurface confirmation samples should be collected and analyzed for appropriate COPCs. DTSC (2010) concluded that excavation with off-site disposal and soil vapor extraction (SVE) were the most frequently selected cleanup alternatives for sites contaminated with chlorinated VOCs. The sampling strategy for each proven technology is discussed below.

Excavation with Offsite Disposal

Soil matrix samples should be collected from the floor and sidewalls of excavations to demonstrate achievement of remedial objectives. These samples should be collected in accordance with USEPA Method 5035 (DTSC, 2004). Post-excavation soil matrix sampling should occur as soon as possible after completion of excavation activities. Soil matrix samples should not be obtained from exposed excavation surfaces. Rather, soil matrix samples should be collected approximately six to eight inches interior to the exposed surface to alleviate potential sample bias due to the volatilization of contaminants.

Soil gas samples should be collected from the around the perimeter of the excavation, and within and/or below the excavation footprint, to evaluate the effectiveness of the remedy on eliminating the possibility of vapor intrusion. These samples should be collected at least five feet from exposed soil surfaces to minimize the effects of atmospheric influences on sample representativeness. Soil gas samples should be collected in accordance with Cal/EPA's Active Soil Gas Investigation Advisory which recommends the installation of semi-permanent soil vapor wells.

Non-excavated subsurface volatile chemical sources can potentially contaminate clean backfilled material through vapor transport. Hence, where excavations are above contaminated groundwater or adjacent to residual volatile chemical contamination, soil gas monitoring in the backfilled material may be necessary to determine if the remedial objectives have been achieved. The duration of the post-excavation monitoring within the backfilled material should be based upon the time needed to re-establish subsurface equilibrium. The time to reach steady-state conditions can be estimated using the methods described in Johnson and others (1999). Figure 4 contains an example of timeframes for approaching steady-state vapor concentrations for a hypothetical site. The timeframes can be lengthy for large excavations. If these monitoring timeframes are incompatible with schedules for property redevelopment, consideration should be given to expanding the size of the proposed excavation. Further characterization of adjacent soils to refine estimates of contaminant distribution should also be considered.

Soil Vapor Extraction

Soil gas samples should be collected from vapor monitoring wells during the operation and rebound testing of SVE systems. Upon completion of SVE, rebound testing should be conducted to determine if subsurface concentrations increase after a reasonable shutdown period. For rebound testing, data from soil vapor monitoring wells are preferred over data from extraction wells because of their shorter screen intervals. Significant concentration rebound during the first few sampling events after system shutdown indicates a need to optimize and restart a SVE system. If no significant rebound occurs, the next step typically is an assessment of whether the system is ready for site closure. The closure assessment for a SVE system should be based on concentration and trend data obtained from the system's inlet stream, extraction wells, and depth-specific vapor monitoring wells located in the original contaminant plume. Final confirmation sampling should be conducted only after the subsurface has reached equilibrium. These timeframes can be determined using Johnson and others (1999) and an example is shown in Figure 4.

DOCUMENTING VAPOR INTRUSION INVESTIGATIONS

DTSC anticipates that numerous documents will be submitted for agency review and approval during the process of evaluating a site for vapor intrusion. Work plans should be submitted for all phases of work, such as characterization of subsurface contamination, fate and transport modeling, community outreach, sampling of indoor air, health risk determination, and implementation of mitigation measures. Likewise, reports describing the completion of each of these activities, along with interpretations and conclusions derived from the data, should also be submitted to the oversight agency for approval.

The following components should be included in a vapor intrusion risk assessment report:

1) <u>Conceptual Site Model.</u> The CSM should describe site conditions and state the assumptions made to generate the CSM. The CSM should describe the potential for exposure to hazardous chemicals based on the sources of contamination, the release mechanisms, the transport media, the exposure pathways, and the potential receptors. The CSM should include a diagrammatic or schematic presentation that relates the source of contamination to human receptors and identifies all the potential sources of contamination, the potentially contaminated media, and exposure pathways.

2) <u>Laboratory Analytical Reports.</u> Laboratory reports are routinely submitted to the oversight agency to demonstrate the quality of the analytical data collected during all phases of site characterization. Thus, all laboratory reports associated with vapor intrusion, involving both chemical and geotechnical analyses, should be submitted for review. The laboratory reports should include all quality assurance and quality control information, such as analytical methods, laboratory control samples, calibration data, matrix spikes, matrix spike duplicates, field duplicates, trip blanks, and equipment blanks. Additionally, analytical detection limits should be annotated in the laboratory reports and detection limits should be sufficiently low so that risk assessment can be properly conducted.

3) <u>Contaminant Distribution.</u> Plume maps should be provided to show the spatial distribution of contaminants in the subsurface. The maps should display the contaminant distribution for soil gas, soil matrix, and groundwater, through the depiction of isoconcentration contour maps for the COPCs. All data used to construct the contour maps should be clearly annotated on the maps. Ideally, the base map for plume presentation should be provided

on an aerial photograph. Likewise, geological cross sections, which illustrate the distribution of contaminants, should be provided

4) Modeling and Input Parameters. The methods used to evaluate the fate and transport of contaminants should be described. All input parameters and the technical justification for their selection should be provided. All parameters should be summarized into a single table. Any models supporting the evaluation of vapor intrusion, such as groundwater transport models and calculations of equilibrium times, should be reported.

6) Vapor Intrusion Risk Assessment. Indoor air concentrations, exposure assumptions, cancer and noncancer toxicity criteria, and risk assessment equations used to estimate vapor intrusion risks should be provided, along with chemical-specific and multi-chemical cumulative cancer risk and hazard estimates. If risk-based screening concentrations are used to estimate risks, the screening concentrations, reference/source, and toxicity basis should be reported. If the USEPA Vapor Intrusion Model is used, copies of the EXCEL™ spreadsheets should be provided. The risk characterization should include the uncertainty analysis as described below.

7) Risk Isopleths. As appropriate, site maps demonstrating contour lines of equal risk (isopleths) should be generated to assist in the understanding of the spatial distribution of risk. For sites with multiple contaminants, the total risk must be calculated for each sampling location to construct the isopleth.

9) Uncertainty Analysis. An analysis of uncertainty associated with risk estimates should be performed in a semi-quantitative fashion. Uncertainty is a consequence of imperfect knowledge and can usually be reduced by addressing potential data gaps. Typically, uncertainty exists in characterization of the nature and extent of contamination, in environmental fate and transport modeling, and in the magnitude and duration of exposure of various receptors. Accordingly, all vapor intrusion evaluations should include a discussion of the likely bias and magnitude of errors associated with uncertainties in estimating the risk. A fair and balanced characterization of uncertainty is important because most risk estimates are not highly precise and many risk managers are tempted to over-interpret the resulting values. Risk characterization, including a well-performed uncertainty analysis, will place the risk estimates in the proper perspective for informed decision-making. The uncertainty analysis should include a tabular summary of the values used to estimate exposure as well as those used to estimate the transport of volatile chemicals in the subsurface. For each variable, the table should include the range of possible values. In addition, a brief description of the selection rationale should be included. In conjunction with the table, the uncertainty discussion summarizes the major assumptions of the exposure assessment, discusses the uncertainty associated with each, and describes how this uncertainty is expected to affect the estimate of exposure. See Appendix C for uncertainties associated with vapor intrusion risk assessment. DTSC recommends that the uncertainty analysis for vapor intrusion modeling be conducted in a similar manner to that described by Johnson (2002). USEPA (1989) should be consulted for analysis of uncertainties in other components and aspects of the risk characterization.

10) Professional Certification. To comply with the Geologist and Geophysicist Act, codified in Section 7835 of the Business and Professions Code, and the Professional Engineers Act, codified in Sections 6700-6799 of the Business and Professions Code, any report submitted that contains geologic or engineering conclusions, recommendations, or

technical interpretations must be signed or stamped by a qualified California professional geologist or professional civil engineer who takes responsibility for the report's technical.

PUBLIC OUTREACH

Community outreach is an essential component of the investigation and remediation of any contaminated site, but is particularly critical when dealing with potential or confirmed vapor intrusion. Vapor intrusion concerns are unique as compared to other exposure pathways. Simple avoidance techniques are not an option for impacts to the air people breathe in their homes, schools, or workplaces. Hence, the scope of public participation activities at potential or known vapor intrusion sites likely will require more extensive strategy and outreach than is applied at other types of contaminated sites. Thus, it is recommended that the public is engaged as early as possible and is kept informed about all field work and project decisions. Face-to-face meetings with those stakeholders who live, work, or otherwise occupy the buildings under investigation, and in which mitigation measures are needed, are essential. As with any contaminated site, DTSC's Public Participation Policy and Procedures Manual should be followed and a site-specific communication plan and strategy should be developed. Additionally, DTSC's Vapor Intrusion Public Participation Advisory provides guidance for public outreach efforts and includes sample documents and public information materials for use during all phases of work associated with vapor intrusion.

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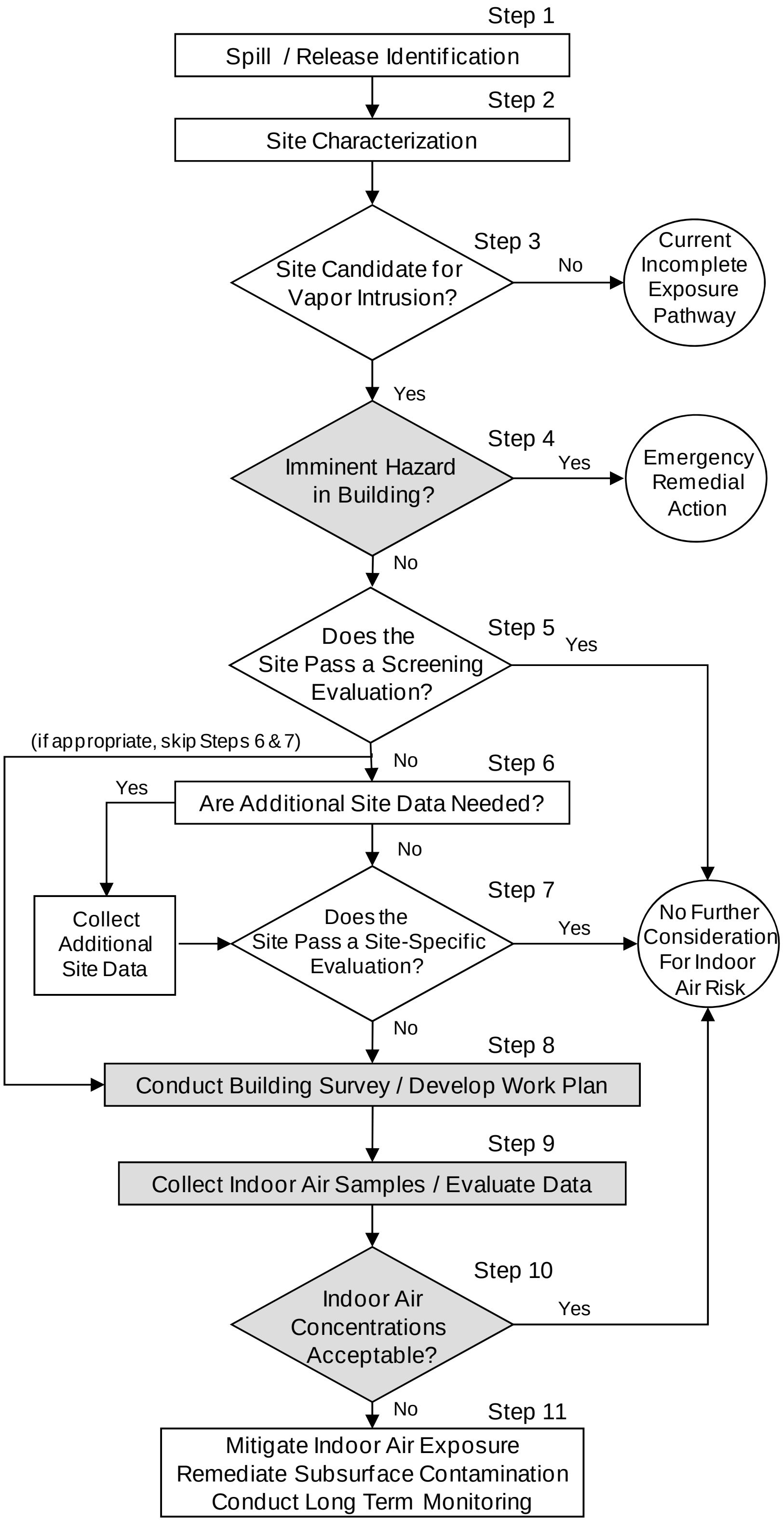
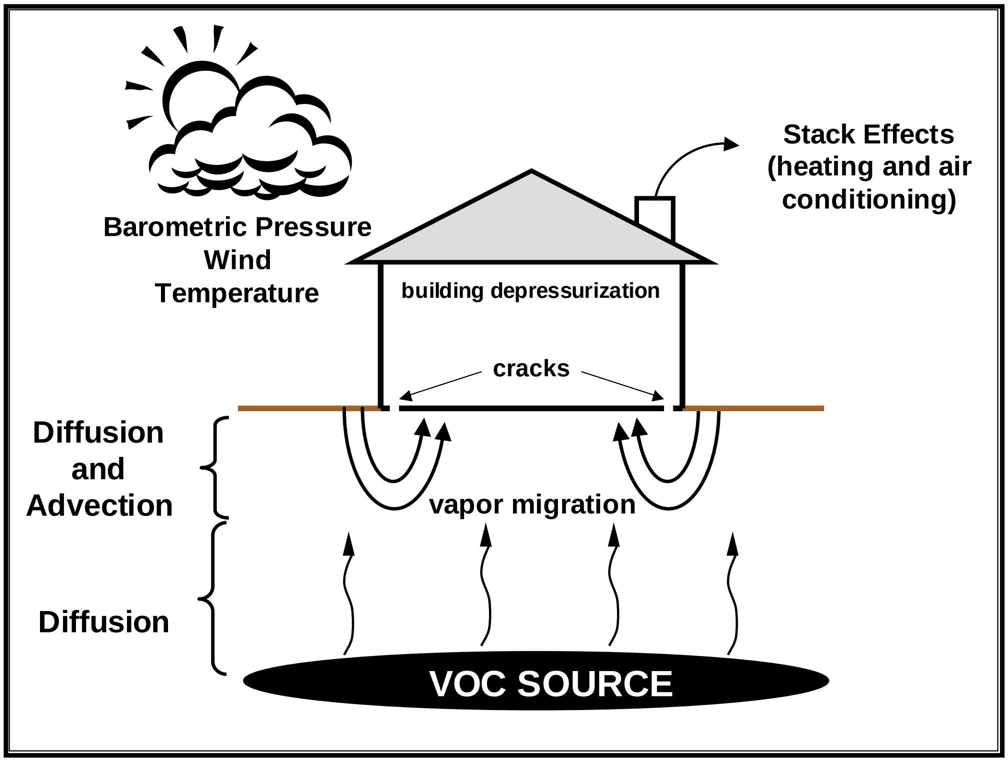
FIGURE 1 – VAPOR INTRUSION TO INDOOR AIR ASSESSMENT



Note: Shaded steps do not apply to future building scenarios

FIGURE 2 – CONCEPTUAL MODEL FOR VAPOR INTRUSION



Vapor intrusion is the migration of volatile chemicals from contaminated soil and groundwater through the subsurface and into the indoor air spaces of overlying or nearby buildings. Vapors enter the buildings through foundation openings, such as cracks, seams, and utility holes. The vapor concentrations attenuate, or decrease, as they migrate upwards. The attenuation occurs as a result of the processes that control vapor migration in soil, which are diffusion and advection, coupled with the dilution that occurs when the vapors enter a building and mix with indoor air.

Diffusion is the mechanism by which soil gas migrates from high concentration to low concentration due to a concentration gradient. Advection is the transport mechanism by which soil gas moves due to differences in pressure. As diffusion causes vapors to migrate through the soil, they tend to accumulate under buildings due to the capping effect of the foundation. The pressure beneath a building is typically higher than the pressure indoors due to a phenomenon called "building depressurization." Depressurization causes buildings to draw soil gas indoors. A number of factors can cause building depressurization, such as wind and barometric pressure changes, thermal differences between soil and indoor air, operation of fans, vents and furnaces, and stack effects due to chimneys and flues.

Once soil gases enter the "building zone of influence" in the subsurface, they are generally swept into the building through foundation openings by advection induced by the indoor-outdoor building pressure differential. The depth of the "building zone of influence" beneath the building is usually less than one meter. Soil gas not within the zone of influence of the building will continue to migrate within the subsurface or escape to the atmosphere.

FIGURE 3 – UTILITY CORRIDOR DECISION TREE

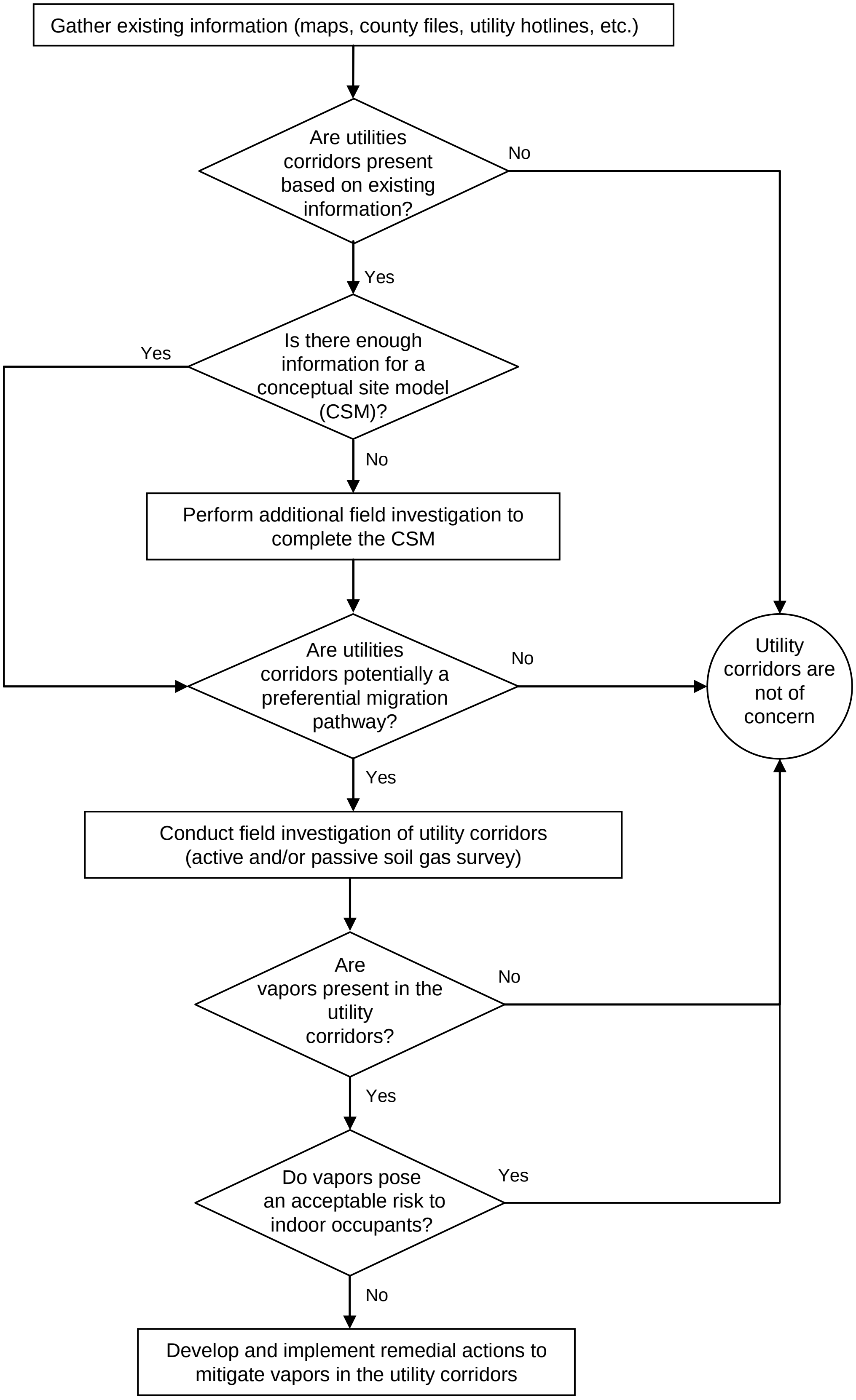
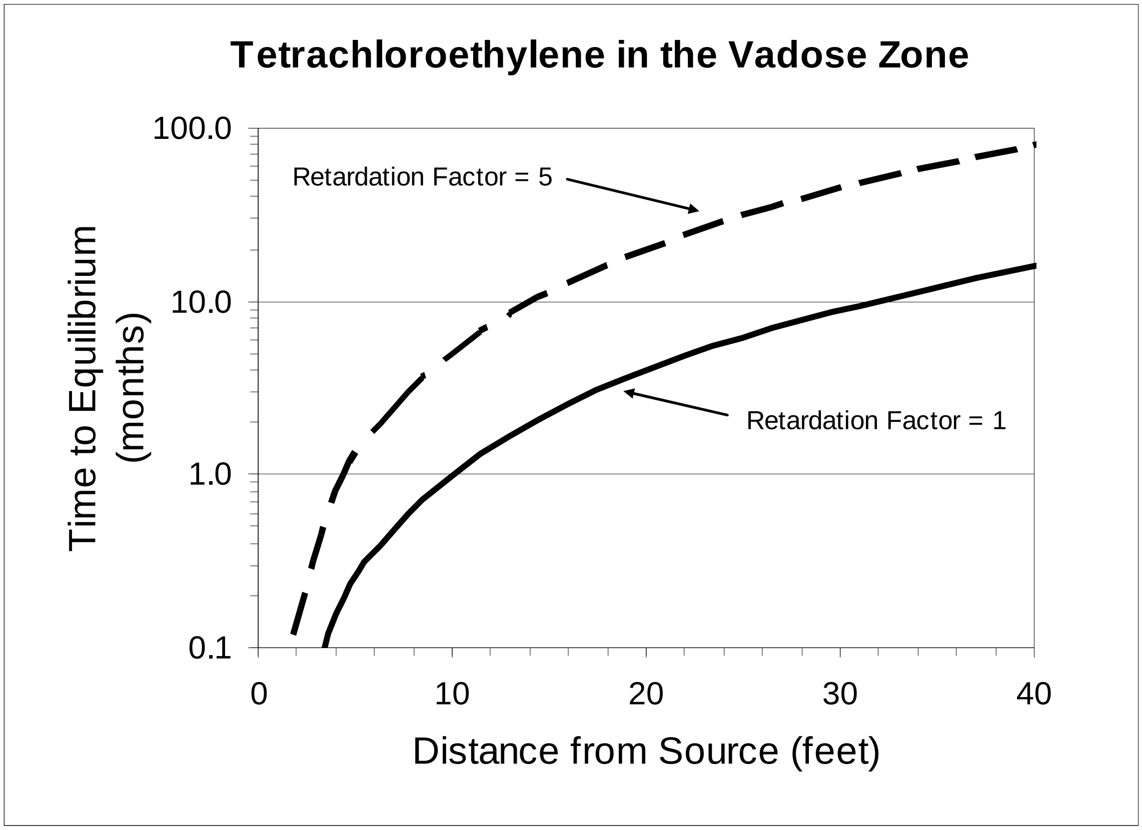


FIGURE 4 – TIME TO REACH STEADY-STATE CONDITIONS



The figure demonstrates the estimated time to reach near steady-state vapor concentration at some distance from a contaminant source (Johnson et al., 1999; Equation 4) for PCE in the vadose zone. The figure shows time to equilibrium for two retardation factors. Sandy conditions were assumed (effective diffusion coefficient = 0.012 centimeters squared per second) with PCE physical properties from USEPA (2002a).

TABLE 1 - List of Chemicals to be Considered for the Vapor Intrusion Pathway

CAS Number	Chemical	Chemical Sufficiently Volatile?[2]	Chemical Sufficiently Toxic?[3]	Recommended Laboratory Method
630-20-6	1,1,1,2-Tetrachloroethane	yes	yes	TO-15
71-55-6	1,1,1-Trichloroethane	yes	yes	TO-15
79-34-5	1,1,2,2-Tetrachloroethane	yes	yes	TO-15
76-13-1	1,1,2-Trichloro-1,2,2-trifluoroethane	yes	yes	TO-15
79-00-5	1,1,2-Trichloroethane	yes	yes	TO-15
75-34-3	1,1-Dichloroethane	yes	yes	TO-15
75-35-4	1,1-Dichloroethylene	yes	yes	TO-15
96-18-4	1,2,3-Trichloropropane	yes	yes	TO-15
120-82-1	1,2,4-Trichlorobenzene	yes	yes	TO-15
95-63-6	1,2,4-Trimethylbenzene	yes	yes	TO-15
96-12-8	1,2-Dibromo-3-chloropropane	yes	yes	TO-15
106-93-4	1,2-Dibromoethane	yes	yes	TO-15
95-50-1	1,2-Dichlorobenzene	yes	yes	TO-15
107-06-2	1,2-Dichloroethane	yes	yes	TO-15
78-87-5	1,2-Dichloropropane	yes	yes	TO-15
108-67-8	1,3,5-Trimethylbenzene	yes	yes	TO-15
106-99-0	1,3-Butadiene	yes	yes	TO-15
541-73-1	1,3-Dichlorobenzene	yes	yes	TO-15
542-75-6	1,3-Dichloropropene	yes	yes	TO-15
106-46-7	1,4-Dichlorobenzene	yes	yes	TO-15
123-91-1	1,4-Dioxane	yes	yes	TO-15
109-69-3	1-Chlorobutane	yes	yes	TO-15
126-99-8	2-Chloro-1,3-butadiene (chloroprene)	yes	yes	TO-15
95-57-8	2-Chlorophenol	yes	yes	TO-13A
75-29-6	2-Chloropropane	yes	yes	TO-15
91-57-6	2-Methylnaphthalene	yes	yes	TO-13A
79-46-9	2-Nitropropane	yes	yes	TO-15
83-32-9	Acenaphthene	yes	yes	TO-13A
75-07-0	Acetaldehyde	yes	yes	TO-11A, TO-15
67-64-1	Acetone	yes	yes	TO-11A, 15, 17
75-05-8	Acetonitrile	yes	yes	TO-15
98-86-2	Acetophenone	yes	yes	TO-15
107-02-8	Acrolein (propenal)	yes	yes	TO-15
107-13-1	Acrylonitrile	yes	yes	TO-15
309-00-2	Aldrin	yes	yes	TO-4A, 10A, 13A
319-84-6	alpha-HCH (alpha-BHC)	yes	yes	TO-4A, 10A, 13A
100-52-7	Benzaldehyde	yes	yes	TO-11A
71-43-2	Benzene	yes	yes	TO-15
205-99-2	Benzo(b)fluoranthene	yes	yes	TO-13A
100-44-7	Benzylchloride	yes	yes	TO-15
91-58-7	beta-Chloronaphthalene	yes	n/a	TO-13A
92-52-4	Biphenyl	yes	yes	TO-4A, 10A, 13A
111-44-4	Bis(2-chloroethyl)ether	yes	yes	TO-15
108-60-1	Bis(2-chloroisopropyl)ether	yes	yes	TO-15
542-88-1	Bis(chloromethyl)ether	yes	yes	TO-15
75-27-4	Bromodichloromethane	yes	yes	TO-15
75-25-2	Bromoform	yes	yes	TO-15
75-15-0	Carbon disulfide	yes	yes	TO-15
56-23-5	Carbon tetrachloride	yes	yes	TO-15
57-74-9	Chlordane	yes	yes	TO-10A, 13A

CAS Number	Chemical	Chemical Sufficiently Volatile?[2]	Chemical Sufficiently Toxic?[3]	Recommended Laboratory Method
108-90-7	Chlorobenzene	yes	yes	TO-15
124-48-1	Chlorodibromomethane	yes	yes	TO-15
75-45-6	Chlorodifluoromethane	yes	yes	TO-15
75-00-3	Chloroethane (ethyl chloride)	yes	yes	TO-15
67-66-3	Chloroform	yes	yes	TO-15
218-01-9	Chrysene	yes	yes	TO-13A
156-59-2	cis-1,2-Dichloroethylene	yes	yes	TO-15
123-73-9	Crotonaldehyde (2-butenal)	yes	yes	TO-11A
98-82-8	Cumene (isopropylbenzene)	yes	yes	TO-15
72-55-9	DDE	yes	yes	TO-4A, 10A, 13A
132-64-9	Dibenzofuran	yes	yes	TO-13A
25512-42-9	Dichlorobiphenyl (PCB)[4]	yes	yes	TO-4A, 10A, 13A
75-71-8	Dichlorodifluoromethane	yes	yes	TO-15
60-57-1	Dieldrin	yes	yes	TO-4A, 10A, 13A
108-20-3	Diisopropyl ether (DIPE)	yes	yes	TO-15
115-29-7	Endosulfan	yes	no	TO-10A, 13A
106-89-8	Epichlorohydrin	yes	yes	TO-15
60-29-7	Ethyl ether	yes	yes	TO-15
637-92-3	Ethyl tert-butyl ether (ETBE)	yes	n/a	TO-15
141-78-6	Ethylacetate	yes	yes	TO-15
100-41-4	Ethylbenzene	yes	yes	TO-15
75-21-8	Ethylene oxide	yes	yes	TO-15
97-63-2	Ethylmethacrylate	yes	yes	TO-15
86-73-7	Fluorene	yes	yes	TO-13A
110-00-9	Furan	yes	yes	TO-15
58-89-9	gamma-HCH (lindane)	yes	yes	TO-4A, 10A, 13A
76-44-8	Heptachlor	yes	yes	TO-4A, 10A, 13A
87-68-3	Hexachloro-1,3-butadiene	yes	yes	TO-15
118-74-1	Hexachlorobenzene	yes	yes	TO-4A, 10A, 13A
77-47-4	Hexachlorocyclopentadiene	yes	yes	TO-10A, 13A
67-72-1	Hexachloroethane	yes	yes	TO-15
110-54-3	Hexane	yes	yes	TO-15
74-90-8	Hydrogen cyanide	yes	yes	OSHA ID-120
78-83-1	Isobutanol	yes	yes	TO-15, 17
7439-97-6	Mercury (elemental)	yes	yes	OSHA ID-140
126-98-7	Methacrylonitrile	yes	yes	TO-15
72-43-5	Methoxychlor	yes	no	TO-4A, 10A, 13A
79-20-9	Methyl acetate	yes	yes	TO-17
96-33-3	Methyl acrylate	yes	yes	TO-17
74-83-9	Methyl bromide (bromomethane)	yes	yes	TO-15
74-87-3	Methyl chloride (chloromethane)	yes	yes	TO-15
1634-04-4	Methyl tert-butyl ether (MTBE)	yes	yes	TO-15
108-87-2	Methylcyclohexane	yes	yes	TO-15
74-95-3	Methylene bromide	yes	yes	TO-15
75-09-2	Methylene chloride	yes	yes	TO-15
78-93-3	Methylethylketone (2-butanone)	yes	yes	TO-15
108-10-1	Methylisobutylketone	yes	yes	TO-15
80-62-6	Methylmethacrylate	yes	yes	TO-15
27323-18-8	Monochlorobiphenyl (PCB)[4]	yes	yes	TO-4A, 10A, 13A
108-38-3	m-Xylene	yes	yes	TO-15
91-20-3	Naphthalene	yes	yes	TO-15, 17
104-51-8	n-Butylbenzene	yes	yes	TO-15

CAS Number	Chemical	Chemical Sufficiently Volatile?[2]	Chemical Sufficiently Toxic?[3]	Recommended Laboratory Method
98-95-3	Nitrobenzene	yes	yes	TO-13A, 15
924-16-3	N-Nitroso-di-n-butylamine	yes	yes	TO-13A
103-65-1	n-Propylbenzene	yes	yes	TO-15
88-72-2	o-Nitrotoluene	yes	yes	TO-13A, 17
95-47-6	o-Xylene	yes	yes	TO-15
106-42-3	p-Xylene	yes	yes	TO-15
129-00-0	Pyrene	yes	no	TO-13A
135-98-8	sec-Butylbenzene	yes	yes	TO-15
100-42-5	Styrene	yes	yes	TO-15
994-05-8	Tert-amyl methyl ether (TAME)	yes	n/a	TO-15
75-65-0	Tert-butyl alcohol (TBA)	yes	n/a	TO-15
98-06-6	tert-Butylbenzene	yes	yes	TO-15
127-18-4	Tetrachloroethylene	yes	yes	TO-15
108-88-3	Toluene	yes	yes	TO-15
156-60-5	trans-1,2-Dichloroethylene	yes	yes	TO-15
79-01-6	Trichloroethylene	yes	yes	TO-15
75-69-4	Trichlorofluoromethane	yes	yes	TO-15
108-05-4	Vinyl acetate	yes	yes	TO-15
75-01-4	Vinyl chloride (chloroethene)	yes	yes	TO-15

CAS = Chemical Abstracts Service
n/a = not available

Notes:

1. Table 1 was generated from the chemicals listed in USEPA (2002a) with the addition of fuel oxygenates and two polychlorinated biphenyl congeners due to the volatility and toxicity of monochlorobiphenyl and dichlorobiphenyl (Davis et al., 2002; Davis and Wade, 2003).

2. Sufficiently volatile is defined as having a Henry's law constant of greater than 10^{-5} atmospheres-meter cubed per mole (USEPA, 2002a).

3. Sufficiently toxic is defined as exposure to indoor air concentrations from subslab soil gas at saturated conditions where attenuation over the foundation slab is 0.05. Only endosulfan, methoxychlor, and pyrene are not sufficiently toxic to be considered for vapor intrusion evaluations.

4. The physical properties of Arochlor 1221 were used for monochlorobiphenyl and dichlorobiphenyl.

TABLE 2 - Attenuation Factors for Preliminary Screening Evaluations (Step 5)

Building Scenario	Building Type	Sample Location	Attenuation Factor
Existing	Residential	Contaminant Source	0.002
		Crawl Space	1.0
		Subslab	0.05
	Commercial	Contaminant Source	0.001
		Subslab	0.05
Future	Residential	Contaminant Source	0.001
	Commercial	Contaminant Source	0.0005

Note: The basis for the attenuation factors can be found in Appendix B.

TABLE 3 - Input Parameters for Site-Specific Screening Evaluations (Step 7)

Primary Input Parameters		Site-Specific Evaluation	Basis for Site-Specific Parameter
C_s	Subsurface concentrations[1]	Statistical approximation[1]	-
θ_t	Soil total porosity[2]	Site-specific	Use ASTM D854
θ_w	Soil volumetric water content[2]	Site-specific	Use ASTM D2216
θ_a	Soil volumetric air content[2]	Site-specific	Calculate from θ_w
ρ_s	Soil bulk density	Site-specific	Use ASTM 2937
θ_{tcap}	Capillary zone total porosity	Site-specific	Use ASTM D854
θ_{wcap}	Capillary zone volumetric water content	Site-specific	Calculate from USEPA, 2003
θ_{acap}	Capillary zone volumetric air content	Site-specific	Calculate from θ_{wcap}
L_{cap}	Thickness of the capillary fringe	Site-specific	Calculate from Fetter (2001)
k	Soil permeability[3]	Site-specific	In-situ measurement (Appendix J)
f_{oc}	Soil fraction organic carbon	Site-specific	Use Walkley-Black method
°T	Soil and groundwater temperature	Site-specific	Field measurement
ΔP	Indoor – outdoor pressure differential	40 g/cm-s^2	USEPA, 2002a
η	Crack-to-total area ratio	0.005	Johnson, 2002
E_b	Indoor air exchange rate – residential	0.5 / hour	USEPA, 1997b (California data)
E_b	Indoor air exchange rate - commercial	1.0 / hour	CEC, 2001
L_{crack}	Foundation slab thickness	Site-specific	-
L_b,W_b,H_b	Building dimensions[4]	Site-specific	-
L_f	Foundation depth below grade – building with no basement	15 cm	USEPA, 2002a
	Foundation depth below grade – building with basement	200 cm	USEPA, 2002a
L_t	Distance from foundation to source	Site-specific	-
L_{wt}	Distance from foundation to groundwater	Site-specific	-
Q_{soil}	Soil gas advective rate[5]	5 L/minute	USEPA 2002a

CEC = California Energy Commission
cm = centimeters
g/cm-s^2 = grams per centimeter – seconds squared
L = liters

Notes:

1. For existing buildings, maximum concentrations should be used unless a statistically robust dataset is available to approximate the contaminant source term. A robust dataset usually requires the collection of at least eight samples (USEPA, 1992b). Statistical approximations can be determined with ProUCL (USEPA, 2004b). For future buildings, the maximum subsurface concentrations should be used. Ideally, for the future building scenario, there should be at least one soil gas sample per residential building footprint.

2. In-situ measurement of effective diffusion coefficient is recommended over inferring the input parameter from the soil's water content, air content, and total porosity. See Appendix I.

3. A soil gas advection rate (Q_{soil}) of 5 liters per minute should be used with the default building size unless an in-situ measurement of air permeability of the shallow soil is available. Hence, the USEPA Vapor Intrusion Model should only calculate a site-specific Q_{soil} when site-specific permeability measurements are available.

4. The default building size is 10 meters by 10 meters (USEPA 2002a).

5. For structures larger than the default building size, the default value for Q_{soil} of 5 liters per minute should be proportionally increased in a linear fashion as a function of the spatial footprint of the building. For example, a building of 1,000 square meters will have, for modeling purposes, a soil gas advection rate of 50 liters per minute.

APPENDIX A - FLUX CHAMBERS

The development of the emission isolation flux chamber arose from the need to assess vapor emissions from contaminated soil and other environmental media at Superfund sites as part of remedial investigation efforts. An enclosure or chamber is used to isolate a soil surface and provide a direct measurement of the contaminant flux at the soil-air interface. The flux chamber results are then used to evaluate the impact of contaminated soil and other media on ambient air quality. The assessment of emissions of volatile chemicals with flux chambers is usually done in conjunction with either TO-14A (USEPA, 1999a) or TO-15 (USEPA, 1999b) analytical techniques.

There are two types of flux chambers, the static chamber method and the dynamic chamber method.

1) Dynamic Method. A sweep gas is continuously introduced into the chamber during the incubation period and an equivalent amount of chamber gas is allowed to escape. The chamber is assumed to reach a steady-state condition after it has been swept four or five times by the sweep gas. At steady-state conditions, the contaminant concentration in the outlet gas is equivalent to the concentration in the chamber. The outlet gas is then usually sampled with a passivated metal canister.

2) Static Method. Contaminants migrate into the static chamber and the contaminant concentration builds-up over the incubation period. Discrete samples for analysis are withdrawn either at the end of the incubation period or at regular intervals during the incubation period. The required equipment for static testing is very simple, consisting essentially of a collection container with sampling ports.

USEPA PUBLICATIONS ON THE USE OF FLUX CHAMBERS

USEPA developed procedures for the use of emission isolation flux chambers for evaluating the flux of chemicals from the soil-air interface (USEPA, 1986). While USEPA (1986) describes the construction of flux chambers and procedures for the collection of flux chamber data in the field, the USEPA document is a technical reference only. The document provides no information concerning the use of flux chambers to estimate human health risk associated with vapor emissions from the ground surface. Subsequent USEPA technical documents (USEPA 1990, 1992a, and 1992b) discuss the general application of flux chambers for evaluating the impact of contaminated soil and other media on ambient air quality.

USEPA (1992c) recommends that flux chambers should not be used to evaluate vapor intrusion. Rather, the guidance recommends that soil gas samples be collected as a mechanism to evaluate vapor intrusion. The USEPA document states that “flux chambers. . . may give significantly negatively biased results if building underpressurization is exerting an effect on soil gas flow rates” and that “low permeability zones near the surface, frozen ground, or wet surfaces may also result in low flux chamber results.”

USEPA’s 2002 guidance document on vapor intrusion recommends quantifying subsurface contaminant sources through soil gas and groundwater sampling and then using this data as a means to evaluate indoor air exposure. This USEPA guidance document provides screening values for both soil gas and groundwater that are protective of human exposure due to vapor intrusion. The USEPA guidance document does not provide information on using flux chambers to estimate the impact of subsurface contamination on indoor air receptors. Rather, USEPA implies that flux chamber measurements can be used as an additional line of evidence for evaluating vapor intrusion at sites where no buildings exist. Accordingly, in their guidance document, USEPA did not recommend flux chambers as a primary mechanism to evaluate the indoor air pathway.

INDOOR FLUX CHAMBER MEASUREMENTS FOR THE EVALUATION OF INDOOR AIR

Flux chambers cannot effectively evaluate soil gas entry points into a building due to design limitations of the chamber. Soil gas enters a building along cracks or voids at structural footings, along cracks or voids at the foundation-wall interface, along utility conduit entry points into the structure, and at cracks or voids within the foundation and basement walls. The design of the flux chamber precludes its use at all these locations except for foundation cracks or voids where the chambers can be placed directly on flat-lying surfaces. Therefore, given the likelihood of multiple entry points into a building, flux chamber testing of only the foundation cracks or voids will not yield representative entry rates of contaminants into a building.

Even if foundation cracks or voids are the sole entry point for soil gas into a building, difficulties still exist in using flux chambers to evaluate indoor air quality. When evaluating a foundation slab, selection of measurement locations is crucial to the success of the evaluation. Without access to the entire foundation, it becomes impossible to select appropriate areas for testing. Hence, for residential structures where the foundation slab is covered with carpet, tile, or linoleum, representative flux chamber sampling is not possible without removing all floor coverings (an unlikely event). Even if an entire foundation slab is available for flux chamber testing, the subset of cracks or voids responsible for the degradation of indoor air quality is unknown, necessitating the testing of all areas.

SOIL FLUX CHAMBER MEASUREMENTS FOR THE EVALUATION OF INDOOR AIR

Flux chamber measurements of open soil surfaces may not be representative of actual contaminant flux into a building. The measured flux could be biased high due to the lack of a building foundation impeding the movement of vapors. Conversely, the measured flux could be biased low because the flux chamber cannot duplicate the pressure-induced advective flow caused by a building's depressurization.

When using flux chamber measurements on open soil, one method to account for vapor flux attenuation over the foundation slab is to multiply the flux measurements by an infiltration ratio of 0.01 (Bjorklund et al., 2002; Schmidt et al., 2004; Copeland and Van de Water, 2004; Sager et al., 1997). While this approach has been used as a method to determine indoor air concentrations from outdoor flux chamber measurements, the approach has not been field validated. No scientific studies have been published that specifically provide documentation that this procedure is appropriate for evaluating risk to indoor receptors.

The intrinsic design of the flux chamber only allows for the measurement of vapors moving into the chamber by diffusion or by atmospheric driven advection due to ambient temperature and pressure changes. Hence, the flux chamber cannot estimate vapor movement into a building due to its heating and ventilation system. To address the issue of building-induced advective flow, Sheldon and Schmidt (2002) developed and tested a procedure that allows the flux chamber to depressurize to values observed in buildings; the intent of the depressurization procedure is to create a "mini-building" in which flux measurements could be made. However, the induced depressurization of the flux chamber to mimic building depressurization warrants field validation.

The need for field validation, and the limitation associated with quantification of infiltration ratios, seriously inhibits the flux chamber as a means to directly evaluate vapor intrusion.

SOIL FLUX CHAMBER MEASUREMENTS FOR THE EVALUATION OF OUTDOOR AIR

The testing of surface soil with flux chambers yields the amount of VOCs being released at the soil-air interface. VOC concentrations in ambient air can be estimated from the soil flux data. Using an appropriate transport model, along with the flux chamber measurements, the concentrations of VOCs within the breathing zone in outdoor air can be determined. Therefore, flux chamber measurements can be used to estimate human exposure to outdoor air contamination if representative samples can be obtained with the flux chamber.

REPRESENTATIVENESS OF FLUX CHAMBER MEASUREMENTS

Numerous factors influence the flux chamber's ability to obtain data representative of site conditions, as follows:

- Variability of vapor flux at soil surfaces
- Changing meteorological conditions
- Operational procedures of the flux chamber

Investigators should use flux chambers with an understanding of these factors and, when generating work plans, discuss the specific procedures that will be used to address these issues. The remainder of this appendix describes the scientific studies that demonstrate the complexities associated with obtaining representative data with flux chambers.

Variability of Vapor Flux at Soil Surfaces

Multiple studies indicate that vapor flux from the ground surface is not constant. Diurnal variability in surface flux presents challenges in obtaining flux data indicative of site conditions. Hence, flux chamber work plans should address temporal variation in surface flux.

1) Majewski and others (1995) used the aerodynamic gradient method to estimate methyl bromide flux from the ground surface. Fumigant flux was cyclic, varying by about a factor of three. The highest fluxes were observed during the day and the lowest fluxes were observed during the evening or early morning hours.

2) Wang and others (1997) used a dynamic flux chamber to estimate methyl bromide flux from the ground surface. Air samples were collected from a flux chamber every three hours. The study demonstrated that fumigant flux was cyclic, exhibiting diurnal variation with high fluxes occurring between noon to early afternoon and low fluxes between midnight and early morning. The magnitude of daily flux change was approximately a factor of four.

3) Ryden and others (1978) determined nitrous oxide emissions from soil at a celery farm in Santa Barbara County, California. The study utilized four flux chambers collecting concurrent measurements over a 76-hour period. During the study, the mean nitrous oxide flux ranged from 0.2 to 15.8 grams of nitrogen per hectare per hour, with the highest fluxes observed in the early afternoon. The authors observed a "pronounced diurnal variation" in nitrous oxide flux and concluded that diurnal variation in flux "poses the problem of establishing a representative sampling time".

4) Wyatt and others (1995) collected gas measurements under plastic tarps (groundsheets) placed on a hazardous waste landfill to evaluate leakage through the landfill soil cover. Gas samples were taken every four hours over a two-week period, for a total of 369 individual samples. For the groundsheets over known methane plumes, the gas concentrations under the groundsheets increased "dramatically" during periods of decreasing barometric pressure. Barometric pressure changes of 5 to 20 millibars increased the methane under the groundsheets by a factor of five to ten. The authors concluded that "barometric pumping is an important and fundamental process in the movement of volatile species in the near-surface environment".

Changing Meteorological Conditions

Because temperature and barometric pressure influence vapor flux from soil surfaces, flux chamber work plans should address these influences.

Temperature

Ambient temperature change has implications on the collection of representative data from flux chambers, as indicated by the following studies.

1) Carpi and Lindberg (1998) studied natural vapor-phase mercury flux with a dynamic flux chamber. Four test plots were evaluated near Oak Ridge National Laboratory by collecting approximately 80 flux measurements. Soil temperature and solar radiation measurements were collected concurrent with the flux chamber data. Soil temperature was measured at a depth of one to two centimeters. At all locations, solar radiation was found to play a significant role in the emission of mercury from surface soils, yielding a correlation coefficient of greater than 0.71 between flux and solar radiation. Also, at three of the four test plots, a 15°C temperature increase in soil temperature within a single day produced an order-of-magnitude increase in mercury flux from the soil surface.

2) Mercury flux at the soil surface was measured at the Idaho National Engineering and Environmental Laboratory using a dynamic flux chamber (Abbott, 2003). The flux of mercury from the subsurface was not constant, exhibiting a daily cyclic behavior over the six days of continual analysis. The highest flux occurred during the daytime with little or no flux at night. The daytime and nighttime fluxes differed by about a factor of four. The author correlated the cyclic behavior of flux to solar radiation, wind speed, and air temperature.

Barometric Pressure

Barometric pressure change influences flux, as demonstrated by the following studies.

1) Chen and others (1995) measured fumigant flux from soil using the aerodynamic vertical-profile flux method. Changes in fumigant flux from the soil surface correlated with changes in barometric pressure, indicating that flux from the soil surface is not constant. The magnitude of flux change from the soil in response to barometric pressure fluctuations of 3 millibars was approximately a factor of two.

2) Smith and others (1996) compared flux chamber measurements with predicted diffusive fluxes. The predictive flux was estimated by using Fick's law and measured trichloroethylene (TCE) concentration gradients in the vadose zone. In most cases, the chamber measurements were one to four orders of magnitude greater than the predicted

diffusive fluxes. The authors concluded that other mechanisms besides diffusive flux were contributing to the transport of organic vapors in the unsaturated zone. The authors suggested that these mechanisms may be changes in atmospheric pressure and temperature.

Operational Procedures of the Flux Chamber

The movement of air inside and outside of the dynamic flux chamber during sampling has implications on the collection of representative samples. The scientific literature indicates that the following procedures should be followed for the collection of representative flux measurements.

- Sweep air should be drawn-out of the flux chamber rather than blown-in during sampling.
- Sweep air rates should not exceed one liter per minute and tubing lengths of less than 20 centimeters and tubing diameters of greater than 1.2 centimeters should be used.
- A pressure difference of less than 0.2 to 0.8 Pascal (Pa) should be maintained between the inside and outside of the flux chamber during sampling.
- Sweep air should not have stagnant zones or vertical airflow directions.
- An exterior anemometer to measure wind speed should be used so that synchronization between the internal and exterior air velocity can be obtained during sampling.

The basis for each recommended operating procedure is presented below.

Sweep Air Direction

Kanemasu and others (1974) evaluated the effect of internal airflow in the dynamic chamber on flux measurements. The intent of the study was to explain the difference in flux measurements as a function of sweep air introduction into the chamber. To evaluate the effect, two chambers were placed on soil about 100 centimeters apart and eleven concurrent flux measurements were collected over a period of three months. Sweep air was blown into one chamber and the other chamber had the sweep air drawn out. The difference in observed carbon dioxide flux ranged from a factor of 4 to 20 with the chamber subject to blown air yielding the lower flux measurements.

Sweep Airflow Rates and Tubing Sizes

Fang and Moncrieff (1996) determined that the impact of pressure differences between the inside and outside of the chamber, as generated by airflow within the chamber, on carbon dioxide flux is significant even if the pressure differences are as small as 0.5 Pa. Fang and Moncrieff concluded that a pressure difference of less than 0.2 Pa must be maintained to achieve a reliable estimation of surface flux. They also concluded that low pressure differences are difficult to obtain. In their evaluation, Fang and Moncrieff also experimented with different inlet and outlet tubing diameters and different tubing lengths. They concluded that favorable flux measurements are collected when flow rates are no more than one liter per minute, tubing lengths are less than 20 centimeters, and tubing diameters are greater than 1.2 centimeters. Long tubing length and small diameter tubing produce unacceptable pressure differences within flux chambers, yielding flux measurements with large errors.

Experimental studies by Gao and Yates (1998) with the dynamic flux chamber indicate that measured flux is a function of chamber airflow rate. A dynamic chamber may overestimate the actual flux when the chamber is operating at a high airflow rate. High airflow rates cause chamber underpressurization relative to the soil, thus artificially drawing soil gas into the chamber. Likewise, the dynamic chamber may underestimate the actual flux when airflow rates are low. This underestimation is mainly due to the presence of a headspace concentration. As the concentration gradient across the enclosed soil surface becomes smaller, a smaller diffusive flux from the subsurface is produced. Pursuant to Gao and Yates (1998), one possible solution to this issue is to select an airflow rate so that the steady-state concentration in the chamber is close to that of ambient air. Ideally, so that representative measurements can be obtained, the pressure deficit inside the chamber should induce an advective flow to compensate for the depressed diffusive flux.

Chamber Pressure Differences

Lund and others (1999) evaluated carbon dioxide flux with a dynamic chamber, where air was blown rather than drawn into the chamber. Flux measurements were made at progressively higher chamber pressures over the course of several hours. Soil temperature measurements were collected concurrent with the pressure measurements. The surface flux of carbon dioxide decreased in a non-linear fashion with increasing chamber pressure. The decrease in flux was not correlated with changes in soil temperature, which varied by 3°C over the experiment, and the change in flux became more pronounced in drier soils. The results indicate that pressures of less than 1 Pa can substantially reduce carbon dioxide flux and that chamber pressures greater than 20 Pa entirely suppress flux in dry soils. The results of the experiment were consistent with results from Kanemasu and others (1974) and Nakayama and Kimball (1988), and the authors agreed with Fang and Moncrieff (1996) that accurate measurements of soil flux might only be obtainable at chamber pressures within a few tenths of a Pascal of ambient pressure.

Reichman and Rolston (2002) later confirmed these above studies. Their study concluded that the dynamic chamber yielded accurate flux measurements when the pressure differences ranged from 0.46 to 0.79 Pa. Pressure deficits larger than 1.2 Pa caused a twenty percent overestimation in measured flux when air was drawn, rather than blown, through the chamber. The study recommended that dynamic chambers be instrumented with sensitive pressure transducers to monitor and minimize pressure deficits.

Stagnant Zones and Airflow Patterns

Gao and others (1997) noted that a potential issue with the dynamic chamber is the airflow pattern within the chamber. If the chamber's inlet and outlet are not designed properly, the flowing air through the chamber may not sweep over the entire covered surface, leaving stagnant air zones inside the chamber. In addition, the airflow may have vertical components (downward or upward) that will exert a direct positive or negative pressure upon the covered soil surface. The authors concluded that both stagnant zones and vertical airflow components can cause spatially variable flux measurements and thus make analysis of chamber behavior very difficult, if not impossible.

Wind Speed and Anemometers

Pearson and others (1965) intuitively reasoned that a relationship existed between air speed across the soil surface in a flux chamber and radon emission rate as measured by the chamber. To verify this relationship, an anemometer was placed inside the chamber at 1.25 centimeters (cm) above the soil surface. A variety of flow rates were used while radon emissions were measured. The data indicated a linear relationship between flow rate and emission rate. When flow rates increased by a factor of four, radon emissions increased by a similar amount. The authors concluded that during sample collection the wind speeds in the chamber should be equal to the ambient wind speed in order to reduce potential sampling bias.

Gao and others (1997) indicate that a major challenge associated with dynamic chambers is that the sweep air flowing in the chamber may change the pressure gradient between the soil gas and the chamber interior. Such a change in the pressure gradient may create an advective flow of the soil gas, which may create a different pressure regime from that created by surface winds outside the chamber. Gao and others (1997) state that when the air in the chamber flows relatively fast and the wind outside the chamber is relatively slow, the flowing air in the chamber may create a pressure deficit, which produces an additional flow from the soil into the chamber. This pressure deficit may result in an overestimate of the emission from the uncovered soil. Gao and others (1997) recommends the use of an exterior anemometer to measure wind speed so that synchronization between the internal and exterior air velocity can be obtained to alleviate biased results.

Xu and others (2004) evaluated the effects of wind speed on carbon dioxide flux with a dynamic chamber. Flux data were obtained with and without a vent tube. With a vent tube, wind gusts always produced rapid negative pressure excursions, which were probably due to venturi effects at the vent as suggested by Conen and Smith (1998). However, elimination of the vent tube led to even larger pressure fluctuations (either positive or negative). Fluctuations in wind speed of five meters per second yielded as much as ±15 Pa pressure change in the non-vented chamber. During the field experiment, continuous wind speed measurements were made at an elevation of 0.5 meters. The field experiment lasted only ten minutes, which alleviated potential temperature and barometric pressure influences on the study.

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APPENDIX B – PRELIMINARY SCREENING ATTENUATION FACTORS

This appendix describes the basis for the selection of attenuation factors (α) for preliminary vapor intrusion screening evaluations.

Existing or Future Residential Structures: Soil Gas Samples Near the Contaminant Source

Pursuant to Senate Bill 32, the California Land Environmental Restoration and Reuse Act, the Office of Environmental Health Hazard Assessment (OEHHA) published a list of risk-based screening numbers, known as the CHHSLs (Cal/EPA, 2005). Numerous exposure pathways were evaluated in calculating the CHHSLs, one of which included vapor intrusion to indoor air. To evaluate vapor intrusion for existing or future residential buildings, OEHHA used the J&E model (1991) as programmed into Microsoft EXCEL™ by USEPA (2003). The conceptual site model and the rationale for selection of J&E model input parameters can be found in the OEHHA document, along with the California-specific toxicity factors. For the default attenuation factors for residential structures, DTSC averaged the OEHHA attenuation factors for 16 volatile organic compounds, including ethyl benzene (Cal/EPA, 2010) but excluding mercury and tetraethyl lead. The average attenuation factors for existing and future residential buildings are 0.002 and 0.001, respectively.

Existing Residential Structures: Crawl Space Air Samples

No vapor attenuation should be assumed between a building's crawl space and indoor air. This implies that the attenuation for crawl space air is 1.0 and this approach is consistent with USEPA (2002). Likewise, the national empirical vapor attenuation database indicates that attenuation of crawl space vapors to indoor air is minimal (USEPA, 2008).

Existing Residential or Commercial Structures: Subslab Soil Gas Samples

The national empirical vapor intrusion database (USEPA, 2008) was used to select a default subslab attenuation factor. The paired subslab soil vapor and indoor air measurements from the database were filtered to exclude data where one or both of the paired results were equal to or less than the reporting limit. The paired measurements were also filtered to exclude data for which measured indoor air concentrations at vapor intrusion sites were less than the 95th percentile of background indoor air concentrations for the respective analyte. Indoor air concentrations greater than background were considered more likely to be the result of vapor intrusion rather than fugitive indoor sources. For determination of background, USEPA used a comprehensive compilation of indoor air quality studies for North American residences. The statistics for indoor air background were based on studies for which samples were collected after 1990. Before 1990, background concentrations for many VOCs in indoor air were typically higher.

The resulting data set consisted of 311 paired subslab-indoor air samples representing 13 sites. An attenuation factor of 0.05, representing approximately the 90th percentile of the data, was selected as an appropriate subslab attenuation factor for screening purposes for residential structures. The national database lacks sufficient information concerning commercial buildings to conclusively infer a subslab attenuation factor for this building scenario. Hence, the residential subslab attenuation factor of 0.05 should also be used for commercial buildings. This attenuation factor also applies to subslab samples for buildings with basements.

Existing or Future Commercial Structures: Soil Gas Samples Near the Contaminant Source

The attenuation factors for existing and future commercial buildings were derived by OEHHA in a similar fashion as the residential attenuation factors. DTSC averaged the OEHHA commercial attenuation factors for 16 volatile organic compounds, including ethyl benzene (Cal/EPA, 2010) but excluding mercury and tetraethyl lead. The average attenuation factors for existing and future commercial buildings are 0.001 and 0.0005, respectively. The commercial building attenuation factors are less than those for residential buildings as a result of the higher indoor air exchange rate for commercial buildings.

Existing or Future Schools

OEHHA's 2004 guidance should be followed when conducting vapor intrusion assessments at existing or proposed school sites.

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APPENDIX C – HUMAN RISK ASSESSMENT

When a site or facility first comes to the attention of regulatory agencies, the question to be answered is, has there been a release of hazardous chemicals that could pose a risk to human health or the environment? During the initial investigation, as described in DTSC's Preliminary Endangerment Assessment Guidance Manual, a health risk screening evaluation, by applying conservative default assumptions to an initial, and sometimes limited data set, may be performed to answer this question. If this screening evaluation shows that risk is insignificant, then further action may not be necessary. An insignificant risk resulting from long-term exposure is one in which the theoretical excess risk of getting cancer is less than one-in-a-million (10^{-6}) or the hazard index is less than one (unity) for noncarcinogenic effects. However, if the screening evaluation shows that the theoretical excess cancer risk is greater than 10^{-6} or the hazard index is greater than one, further investigative studies are conducted to fully characterize the site and then the risk and hazard posed by the contaminants are reevaluated.

If volatile organic compounds (VOCs) are present, the health risk assessment would usually include the evaluation of the following exposure pathways:

- Inhalation of vapors that have intruded to indoor air from the subsurface
- Inhalation of vapors outdoors emitted from the subsurface
- Inhalation of vapors from groundwater being used as tap water for showering and general household use
- Ingestion of groundwater used as tap water
- Leaching of vadose zone contamination to groundwater (soil leaching to groundwater pathway) and subsequent exposures via tap water

The following exposure pathways are not usually relevant for volatile chemicals, but should not be dismissed without a demonstration that the exposures and associated risks are insignificant.

- Incidental ingestion of VOC contaminated soil
- Dermal contact with VOC contaminated soil
- Ingestion of food products grown in VOC contaminated soil and groundwater
- Dermal contact with groundwater contaminated with VOCs used for bathing and showering; USEPA (2004) provides a method for evaluating the significance of this exposure pathway

Regulatory agency experience indicates that vapor intrusion into indoor air is often the most significant exposure pathway for VOCs in the subsurface. That is, with the exception of household use of VOC-contaminated groundwater, vapor intrusion is the exposure pathway that usually poses the greatest risk from long-term (chronic) exposure for this class of chemicals. Therefore, it is the pathway that has the greatest effect on the calculations performed to estimate concentrations of VOCs that may be safely left behind after remediation or corrective action.

The discussion below focuses on the evaluation of the vapor intrusion pathway only. The approach for evaluating all other exposure pathways associated with VOCs is described in other USEPA and DTSC guidance documents, including:

- USEPA Risk Assessment Guidance for Superfund (RAGS), Volume 1 Human Health Evaluation Manual, Part A (USEPA, 1989)
- USEPA RAGS, Volume 1 Human Health Evaluation Manual, Part E (USEPA, 2004)

- DTSC Supplemental Guidance for Human Health Multimedia Risk Assessments of Hazardous Waste Sites and Permitted Facilities (DTSC, 1992)
- DTSC Preliminary Endangerment Assessment Guidance Manual (DTSC, 1994)
- USEPA Soil Screening Guidance (USEPA, 1996)

OVERVIEW OF THE HUMAN HEALTH RISK ASSESSMENT PROCESS

The human health risk assessment process for a site has four parts: 1) data collection and evaluation, 2) exposure assessment, 3) toxicity assessment, and 4) risk characterization. In data collection and evaluation, site conditions are characterized, chemicals of potential concern (COPCs) are identified, and the nature and extent of contamination are delineated in all appropriate environmental media.

The exposure assessment builds on the results of the site investigation. The concentrations of the COPCs in environmental media (soil, soil gas, air, and groundwater) are evaluated in the framework of the possible land uses and receptor scenarios (residential, commercial, industrial, recreational, etc.). Exposure pathways that would be associated with each land use are identified, and the exposure to each COPC is estimated. In addition to environmental sampling, exposure assessment often involves environmental fate and transport modeling of contaminants to estimate exposure, including chemical and physical transformation, compartmental partitioning, and contaminant migration from the point of release to the point of exposure. With respect to the indoor air exposure pathway, fate and transport modeling may be used to simulate: (1) the upward diffusion of a chemical as it migrates as a vapor through soil pores toward the surface; and (2) the pressure-driven flow of a vapor from soil through a building foundation into indoor air.

Toxicity assessment refers to the identification of a chemical as one that may cause an adverse health effect under certain exposure conditions and the dose of that chemical necessary to cause that effect. For chemicals commonly found at release sites, numeric criteria that define the toxicity of the chemical have been developed by regulatory agencies. A reference dose (RfD) or reference concentration in air (RfC) for a chemical is a daily exposure level for a human that will not result in an adverse noncancer health effect. A cancer slope factor (CSF) or unit risk factor (URF) for a chemical is an expression of the potency of that chemical to cause cancer. The CSF or URF represents the probability (risk) of the chemical to cause cancer after a lifetime of exposure. For inhaled contaminants, the unit risk factor is expressed as the inhalation unit risk (IUR).

In risk characterization, the exposure and toxicity assessment are summarized and integrated into quantitative and qualitative expressions of risk (USEPA, 1989). The estimated exposure and toxicity criteria are brought together to develop an estimate of hazard (noncarcinogenic effects) and risk (probability of an individual developing cancer over a lifetime as a result of exposure to the chemical). The risk equations are described below. The quantitative expressions of risk must be accompanied by a discussion of the interpretation and qualification of the results, including a description of uncertainties.

RISK EQUATIONS FOR INDOOR AIR INHALATION EXPOSURE

Equations for estimating excess cancer risks and hazard quotients (HQs) from inhaled contaminants are given below and are consistent with USEPA methodology for inhalation exposure assessment and for development of inhalation toxicity values (USEPA RAGS, Part F, 2009). The equation used to calculate the theoretical excess cancer risk from inhalation exposure to a volatile chemical may be expressed as:

$$\text{Risk} = \text{EC}_{\text{c}} \text{ x IUR}$$

The equation used to calculate the HQ for noncancer toxic effects from inhalation exposure to a volatile chemical may be expressed as:

$$\text{HQ} = \text{EC}_{\text{nc}} \text{ / RfC}$$

where:

EC_{c} = exposure concentration for assessing cancer risk (μg/m^3)
EC_{nc} = exposure concentration for assessing hazard (μg/m^3)
IUR = inhalation unit risk, representing the increase in lifetime cancer risk per microgram of chemical inhaled per cubic meter ((μg/m^3)$^{-1}$)
RfC = reference concentration, the concentration to which humans may be exposed without risk of adverse health effects (μg/m^3)

The equations for estimating the exposure concentration for inhalation exposure to volatile chemicals in indoor air for cancer risk and for hazard, respectively, are:

$$\text{EC}_{\text{c}} = \frac{\text{C}_{\text{indoor air}} \text{ x ET x EF x ED}}{\text{AT}_{\text{c}} \text{ x 365 days/year x 24 hours/day}}$$

$$\text{EC}_{\text{nc}} = \frac{\text{C}_{\text{indoor air}} \text{ x ET x EF x ED}}{\text{AT}_{\text{nc}} \text{ x 365 days/year x 24 hours/day}}$$

where:

$\text{C}_{\text{indoor air}}$ = contaminant concentration in indoor air (μg/m^3)
ET = exposure time (hours per day)
EF = exposure frequency (days per year)
ED = exposure duration (years)
AT = period of time over which exposure is averaged (years)
AT_{c} = averaging time for carcinogens (years)
AT_{nc} = average time for noncancer toxic effects, equal to the exposure duration (years)

Combining the above equations yields the following:

$$\text{Risk} = \frac{\text{C}_{\text{indoor air}} \text{ x ET x EF x ED x IUR}}{\text{AT}_{\text{nc}} \text{ x 365 days/year x 24 hours/day}}$$

$$\text{Hazard Quotient} = \frac{\text{C}_{\text{indoor air}} \text{ x ET x EF x ED}}{\text{AT}_{\text{nc}} \text{ x 365 days/year x 24 hours/day x RfC}}$$

These equations may be rearranged to calculate the indoor concentration for the target risk (usually one-in-a-million, 10^{-6}) and target HQ (usually one or less). A fate and transport model, or appropriate attenuation factor, may then be used to estimate the concentration in soil gas or groundwater that would result in the target concentration for indoor air.

EXPOSURE ASSESSMENT

The indoor air concentration of a volatile contaminant that has migrated or is predicted to migrate from the subsurface into indoor air can be estimated by fate and transport modeling or by use of an appropriate default vapor attenuation factor, such as those described in Appendix B. As appropriate for some sites, the volatile contaminant concentration may be measured directly by indoor air sampling that has been carefully planned and conducted, as described in this document.

Using the USEPA Vapor Intrusion Model

In the USEPA Vapor Intrusion Model (USEPA, 2003), as modified by DTSC, concentrations in soil gas or groundwater are input into the spreadsheet along with default or site-specific input parameters describing the characteristics of the subsurface. The overall objective of the model is to calculate the attenuation factor “alpha” (α), which is the ratio of contaminant concentration in indoor air to the vapor phase concentration in soil gas. The model uses subsurface concentration data and simulates the migration of the contaminant vapor upward through the soil and building foundation into indoor air. The predicted indoor air concentration, "$C_{\text{indoor air}}$", represents the concentration in the exposure medium in the above equations. The USEPA Vapor Intrusion Model also performs the risk calculations to provide the quantitative estimates of risk and hazard posed by the chemical. A discussion of the fate and transport part of this model is found in Appendix D.

Exposure Parameters and Land Use Assumptions

The default exposure scenario when evaluating vapor intrusion is the residential home dweller. The resident is assumed to remain at home 24 hours per day and live in the same home for 30 years. The DTSC version of the USEPA Vapor Intrusion Model assumes a residential building of relatively small size with a conservative air exchange rate for California residences (see Appendix D). The indoor worker is the most common alternative site-specific exposure scenario. In this scenario, it is assumed that the work day is eight hours and the worker remains at the same job location or facility for 25 years. Office buildings and other indoor work spaces are generally assumed to have higher air exchange rates than residential buildings.

The exposure parameter values recommended by DTSC for the evaluation of vapor intrusion are the same as those recommended by USEPA in various guidance documents (USEPA, 1989, 1996, 1997, and 2009), and those used by OEHHA in development of human health risk-based soil gas screening numbers (Cal/EPA, 2005). The relevant default exposure parameter values assumed for residential land use in the USEPA Vapor Intrusion Model are:

ET = exposure time, 24 hours per day
EF = exposure frequency, 350 days per year
ED = exposure duration, 30 years
AT_c = averaging time for carcinogens, 70 years
AT_{nc} = averaging time for non-carcinogens, 30 years

Two other exposure parameter values, body weight (70 kg) and contact or intake rate (breathing rate of 20 cubic meters per day) are intrinsic to the URF and RfC.

Site-Specific Exposure Parameters

In some circumstances, site-specific inputs for human exposure parameters may be used to estimate chemical intake with appropriate documentation. For example, in an occupational setting where it is expected that current operations will continue into the foreseeable future, employment records for the facility may be used to estimate a reasonable, representative exposure duration based on duration of employment.

TOXICITY ASSESSMENT

OEHHA and USEPA have conducted toxicity assessments for numerous chemicals and developed numeric toxicity criteria values for specific chemicals.

Toxicity Criteria

An inhalation unit risk (IUR, risk per $\mu g/m^3$ or $(\mu g/m^3)^{-1}$) is the toxicity criterion defining the potency of a carcinogenic chemical when inhaled. A chronic RfC ($\mu g/m^3$) for a chemical is derived from the threshold concentration at which no adverse noncarcinogenic health effects are expected to occur from long-term exposure to that chemical. The DTSC version of the USEPA Vapor Intrusion Model uses the toxicity criteria values acceptable to DTSC for the risk calculation component of the model. Generally, the OEHHA inhalation unit risk values should be used for evaluating cancer risk. For noncarcinogenic effects, the USEPA Integrated Risk Information System (IRIS) RfC values should be used. When an RfC (IRIS or USEPA Peer-Reviewed Provisional Toxicity Value, PPRTV) is not available for a chemical, the OEHHA chronic inhalation Reference Exposure Level (REL) should be used. These criteria are automatically selected by the model when the chemical is identified, and may also be used to estimate risks when a default attenuation factor is used instead of the model to estimate indoor air concentration or when indoor air sampling data are available. A DTSC toxicologist should be consulted regarding exceptions to the values in the updated DTSC version of the model.

Occupational Standards versus Risk-Based Standards

OSHA Permissible Exposure Limits (PELs) are not appropriate criteria for evaluating risks associated with vapor intrusion. OSHA sets PELs to regulate worker exposures to hazardous vapors and gases present in workplace air from chemical handling or use, not exposure to air contaminants originating from the subsurface. OSHA PELs are not indices of toxicity and are not intended to protect against “continuous, uninterrupted exposures or other extended work periods” (American Conference of Governmental Industrial Hygienists, 1994). OSHA PELs are based on an assumption that the potentially exposed worker is healthy, has been trained in workplace regulations and procedures regarding chemical exposures, and is subjected to routine biomedical monitoring, as necessary. This means that PELs may not be sufficiently protective for office workers or other workers at the site. The California Health and Safety Code dictates that chemical releases in California should be characterized and mitigated based upon risk to human and ecological receptors. Accordingly, the health risk assessment approach as described in this guidance should be utilized for all vapor intrusion exposure scenarios, including the indoor worker scenario. See Appendix F for more information about OSHA PELs.

RISK CHARACTERIZATION

Chemical-specific toxicity criteria and the estimated exposure are used to quantify risk and hazard. Risk is estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to the potential carcinogen. The hazard potential posed by a chemical for noncarcinogenic effects is evaluated by comparing the exposure level over time with a reference dose or concentration for a similar exposure period to produce a hazard quotient.

Risk characterization includes assessment of the overall potential for cancer and noncancer effects posed by contaminants at a site. Therefore, a human health risk assessment for a site must include the risks and hazards posed by all COPCs and all complete exposure pathways. For assessing risks for possible future site conditions or exposure scenarios, potentially complete exposure pathways also should be evaluated.

As the final step in the risk assessment process, risk characterization integrates quantitative and qualitative information, and identifies the important strengths and uncertainties for each component of the assessment as part of the discussion of the confidence in the risk assessment (USEPA, 1989 and 1995). USEPA (1989) states: "A risk characterization cannot be considered complete unless the numerical expressions of risk are accompanied by explanatory text interpreting and qualifying the results."

Risk Calculations

The equations described above for estimating the chemical-specific excess cancer risk and HQ from an inhaled contaminant provide quantitative expressions of the vapor intrusion risk. The USEPA Vapor Intrusion Model includes the risk equations and calculates the risk or hazard posed by inhalation exposure to a single, specific chemical intruding into and contaminating indoor air.

Screening assessments may estimate the risk or hazard posed by a chemical by directly comparing the measured or predicted volatile chemical concentration with a human health risk-based screening concentration (RBC) for the environmental medium of concern. For risk calculations, it is critical to distinguish RBCs based on reference concentrations for chronic toxic effects other than cancer from those based on the unit risk for carcinogenic effects. To evaluate the hazard for carcinogens, a RBC for noncarcinogenic effects should be used. If unavailable, the RBC for noncarcinogenic toxic effects may be derived using the appropriate exposure assumptions and toxicity criteria as described above (and consistent with the assumptions used to develop the particular set of RBCs).

The cancer risk for inhalation exposure to a carcinogenic contaminant may be estimated as the ratio of the site contaminant concentration, C, in a specific medium and the cancer risk-based concentration for that medium, RBC_c, multiplied by the target risk, 10^{-6}, as shown in the generic equation:

$$\text{Risk} = [C/RBC_c] \times 10^{-6}$$

The HQ is estimated as the ratio of the site contaminant concentration, C, in a specific medium and the medium-specific RBC for noncarcinogenic chronic toxic effects, RBC_{nc}:

$$HQ = C/RBC_{nc}$$

In OEHHA's Human-Exposure-Based Screening Numbers Developed to Aid Estimation of Cleanup Costs for Contaminated Soil (Cal/EPA, 2005), human health risk-based screening concentrations for chemicals in soil gas have been developed for many of the toxic volatile chemicals found at release sites. These concentrations, known as California Human Health Screening Levels (CHHSLs), may be used in the initial evaluation of vapor intrusion risks at a site by comparing the soil gas concentration of a volatile contaminant with the corresponding CHHSL for soil gas, replacing "RBC" in the equations above with the CHHSL for carcinogenic and noncarcinogenic toxic effects, as appropriate. Similarly, the contaminant concentrations estimated from indoor air sampling may be compared with the OEHHA target indoor air concentrations used to develop the soil gas CHHSLs (Cal/EPA, 2005).

Cumulative Risk Calculations

For sites with multiple contaminants, risks and hazards posed by all chemicals for each separate, complete, or potentially complete, exposure pathway are summed to provide pathway-specific risk. Then, the risks and hazards from all exposure pathways are summed to provide an estimate of total risk and hazard, respectively, posed by site contamination.

For the vapor intrusion pathway, the cumulative incremental cancer risk from multiple volatile contaminants is the sum of all of the chemical-specific cancer risks for the pathway. For carcinogenic chemical species S_1, S_2, . . . , S_n with chemical-specific risks of $Risk_1S_1$, $Risk_2S_2$, . . . , $Risk_nS_n$, the cumulative incremental cancer risk is:

$$\text{Risk} = \text{Risk}_1S_1 + \text{Risk}_2S_2 + \ldots + \text{Risk}_nS_n$$

The hazard index (HI) for the vapor intrusion pathway is the sum of the chemical-specific HQs, including the HQs for noncarcinogenic effects posed by carcinogenic contaminants. For chemical species S_1, S_2, . . . , S_n with chemical-specific hazard quotients of HQ_1S_1, HQ_2S_2, . . . , HQ_nS_n, the hazard index is:

$$\text{HI} = \text{HQ}_1S_1 + \text{HQ}_2S_2 + \ldots + \text{HQ}_nS_n$$

Screening assessments using risk-based concentrations, such as CHHSLs, must also present cumulative incremental cancer risk and HI. As noted above, the basis for the risk-based screening concentrations should be identified, and those based on chronic effects other than cancer should be segregated from those based on cancer risk for calculation of the HI and cumulative incremental cancer risk, respectively. For carcinogens, RBCs for noncarcinogenic effects should be used for the HI.

For example, the cumulative cancer risk for vapor intrusion is the sum of the ratios of the soil gas concentration and the RBC, multiplied by 10^{-6}. For carcinogenic chemical species S_1, S_2, . . . , S_n with soil vapor concentrations C_1, C_2, . . . , C_n and cancer-risk-based concentrations for soil gas RBC_cS_1, RBC_cS_2, . . . , RBC_cS_n, the cumulative cancer risk is calculated using the expression:

$$\text{Risk} = [C_1/\text{RBC}_cS_1 + C_2/\text{RBC}_cS_2 + \ldots + C_n/\text{RBC}_cS_n] \times 10^{-6}$$

The screening concentrations used in this risk calculation must be based on cancer risk.

The HI is the sum of HQs for chemical species S_1, S_2, . . . , S_n with soil gas concentrations C_1, C_2, . . . , C_n and noncancer RBCs for soil gas $RBC_{nc}S_1$, $RBC_{nc}S_2$, . . . , $RBC_{nc}S_n$:

$$\text{Hazard Index} = C_1/\text{RBC}_{nc}S_1 + C_2/\text{RBC}_{nc}\,S_2 + \ldots + C_n/\text{RBC}_{nc}S_n$$

The RBC used in this hazard calculation must be based on a reference concentration for chronic toxic effects other than cancer.

When using indoor air concentrations, predicted or measured, the HI and cumulative risk posed by all volatile chemicals for the vapor intrusion assessment may be calculated using the equations above and the OEHHA target (risk-based) indoor air concentrations (Appendix B in Cal/EPA [2005]). RBCs for volatile contaminants in indoor air may also be derived by rearranging the exposure equations provided above.

Uncertainties

Discussion of major assumptions and uncertainties is an essential component of risk characterization and interpretation of the quantitative risk assessment. Assumptions are inherent in the risk assessment process because complete information is never available about the physical aspects of a site and there is no method to accurately predict future exposures and consequent risks from those exposures. Therefore, risk assessment assumptions must be reasonably conservative to be protective of human health but not so conservative as to be outside of the range of probability. See USEPA (1989 and 1995) for additional information on risk characterization.

The multiple lines of evidence in a vapor intrusion investigation are used to develop conclusions about potential exposures and to identify some of the major uncertainties affecting the risk estimates. The following are some of the uncertainties that should be discussed for the vapor intrusion into indoor air exposure pathway. Uncertainties that could result in a risk or hazard greater than that calculated are:

- The presence of volatile contaminants that were not detected or for which concentrations were underestimated.
- The existence of unidentified preferential pathways in the subsurface that would facilitate the movement of soil vapors into indoor air spaces, such as utility corridors and geological discontinuities (fault zones, sand channels, etc.).
- Reduction of soil moisture content by the capping effect of future buildings.
- A decrease in ventilation rates in current and future buildings that could lead to increased concentrations of toxic contaminants in indoor air.
- The biotransformation of a chemical to a more toxic compound, such as the transformation of numerous precursors to vinyl chloride.
- Any exposure scenario that involves extended vigorous indoor activities resulting in greater inhalation of volatile chemicals intruding indoors than is assumed by the default parameters used for home dwellers or commercial workers. See USEPA (2009) for additional information.

Uncertainties that could result in a risk or hazard lower than that calculated are:

- A decrease over time in the subsurface contaminant mass or concentration due to natural attenuation.
- Lower receptor exposure (exposure time, frequency, and/or duration).

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APPENDIX D – OVERVIEW OF THE JOHNSON AND ETTINGER MODEL

Fate and transport models can assist in evaluating the degradation of indoor air quality due to the intrusion of subsurface volatile chemicals. When used in combination with site-specific information, the results of modeling will add to the overall weight of evidence used to evaluate the exposure pathway. The J&E model (1991) is one of the more commonly used models for evaluating indoor air exposure. DTSC has selected the J&E model as the recommended approach to evaluate vapor intrusion in California. For the USEPA Vapor Intrusion Model, USEPA programmed the J&E model into Microsoft EXCEL™ and added a health risk component that calculates the risk from inhaling a specific chemical at the concentration estimated in indoor air. Examples of the USEPA Vapor Intrusion Model, as modified by DTSC for use in California, can be found on DTSC's webpage. However, other vapor intrusion models are available and this Guidance does not preclude the use of different models to evaluate indoor air quality. The use of any model other than the USEPA Vapor Intrusion Model at a site should be approved by the oversight agency during the work plan stage prior to use of the model to evaluate human health risk.

The J&E model is a simple, deterministic model, having single-point inputs and outputs. The J&E model is based on the basic principles of contaminant fate and transport, the physical and chemical properties of the contaminant, properties of the environmental media, and contaminant partitioning among media. The model incorporates both diffusion and advection as mechanisms of transport of subsurface vapors into the indoor air environment. Diffusion is the mechanism by which vapor moves under a concentration gradient (from high to low concentration). Advection is the transport mechanism by which vapor moves due to differences in pressure. For the J&E model, diffusion is the dominant mechanism for vapor transport within the vadose zone. Once the vapor enters into the "building zone of influence", the vapor is swept into the building through foundation cracks by advection due to the indoor–outdoor building pressure differential. The depth of the "building zone of influence" is usually less than a meter. The J&E model uses the conservation of mass principle and is based on the following assumptions:

- Steady-state conditions exist for contaminants in the subsurface.
- Contaminants are homogeneously distributed.
- Biodegradation of contaminants does not occur.
- Subsurface preferential migration pathways do not exist.
- Buildings are constructed on slabs or with basements with floors.
- Contaminant vapors enter a building primarily through cracks in the foundation and walls.
- Ventilation rates and pressure differences are assumed to remain constant.
- Air mixing in the building is uniform.

The J&E model cannot evaluate preferential migration pathways and fractured bedrock conditions. Each of these conditions has the potential to significantly increase the rate of vapor intrusion beyond what the model would predict.

With an understanding of the above-mentioned limitations, the J&E model can allow users to quickly screen sites for vapor intrusion risk. The output of the J&E model is the dimensionless attenuation factor "alpha" (α) that represents the ratio of the indoor air concentration to the subsurface concentration. Indoor air concentrations can be estimated from subsurface data (soil gas or groundwater) and the attenuation factor. Using the attenuation factor and the appropriate target indoor air concentrations, contaminant concentrations in soil gas and groundwater that are protective of human health can be calculated. These calculated values can be used as site cleanup objectives.

The J&E model is most robust under homogeneous site conditions with uniform building construction features. Conversely, the model is weakest under variable conditions. Using a range of potential input parameters, the model can predict a wide range of indoor air impacts spanning over several orders of magnitude. Thus, when using the J&E model for California sites, the input parameters for a given site must be appropriately conservative and match site-specific conditions. This is especially true for sites with nonbiodegradable chemicals, shallow to moderate depths of contamination, and high advective potential (Hers et al., 2003). Even under optimal conditions, the J&E model is generally considered to have a precision no greater than an order of magnitude (Weaver and Tillman, 2005). Hence, it is important to understand the sensitivity of the model to various input parameters and DTSC recommends that all vapor intrusion evaluations include a sensitivity analysis.

EVALUATION OF VAPOR RISK

DTSC recommends the use of a two-phased approach when evaluating vapor intrusion at a site. A phased approach ensures that simple cases can be evaluated relatively quickly with minimal resources. The first phase of the evaluation utilizes default attenuation factors to estimate the risk for vapor intrusion (Step 5). Conservative assumptions, appropriate for California, were used to generate the default attenuation factors (see Appendix B). If the preliminary screening demonstrates that the risk associated with vapor intrusion is acceptable, further evaluation of the exposure pathway may not be necessary.

After preliminary screening for vapor intrusion, the responsible party has numerous options if the site risk is unacceptable. One option is further evaluation of the vapor intrusion risk through a site-specific evaluation (Step 7) that builds on the preliminary evaluation and utilizes conditions specific to the site concerning input parameters, land use, and exposure scenarios. The site-specific approach calls for increasingly sophisticated levels of data collection and analysis. Another option is to remediate the subsurface of the site to reduce exposures and risks to an acceptable level determined in a preliminary evaluation. Accordingly, responsible parties may opt to pursue remediation without further site-specific modeling if the cleanup is time critical or if the volume of subsurface contamination is limited and can be remediated in a straightforward manner. Appropriate mitigation measures may be needed while the subsurface contamination is remediated (see Step 11).

DISCUSSION OF MODELING INPUT PARAMETERS

This portion of the appendix discusses the following input parameters for site-specific J&E modeling in California:

- Total porosity (n)
- Soil water-filled porosity (θ_w)
- Soil air-filled porosity (θ_a)
- Dry bulk density (ρ_s)
- Air permeability (k_v)
- Soil gas advection rate (Q_{soil})
- Building ventilation rate ($Q_{building}$)
- Indoor-outdoor pressure differential (ΔP)
- Crack-to-total area ratio (η)
- Residential indoor air exchange rate (E_b)
- Commercial indoor air exchange rate (E_b)
- Soil and groundwater temperature (T_s)

The basis for the selection of these input parameters is provided below. DTSC will consider the use of other modeling input parameters if an appropriate technical justification is provided.

Soil Input Parameters for the USEPA Vapor Intrusion Model (n, θ_w, and θ_a)

When conducting site-specific screening evaluations with the USEPA Vapor Intrusion Model, the geotechnical parameters in the model must be adequately determined to reduce uncertainty concerning human health exposure. Investigators have numerous options for the determination of these parameters, three of which are given in this appendix. This appendix is not intended to be prescriptive in the methods of determining or estimating these soil properties, but acknowledges that standard geotechnical and geophysical methods exist for measuring or estimating these values.

1) Grain Size Distribution. Physical properties of soil associated with the United States Soil Conservation Service (USSCS) classification are available for use within the USEPA Vapor Intrusion Model. Laboratory testing should be conducted to determine the grain size distribution in each layer used in the model so that an appropriate USSCS soil can be selected from the spreadsheet's pull-down menus. DTSC recommends no less than three sieve analyses (grain size distribution determination) to classify each soil layer that is used for modeling purposes. The sieve analysis yielding the most conservative results (greatest contaminant migration potential) should be used in the USEPA Vapor Intrusion Model. Otherwise, a statistically robust number of tests per layer should be conducted and the tests should be averaged using an appropriate statistical technique. Typically, a robust dataset implies the collection of at least eight samples (USEPA, 1992). Also, Atterberg limit determinations may be used to assist in the soil-type selection. Estimating geotechnical properties from a visual description of subsurface soil, as annotated onto a boring log, is not an appropriate approach for the selection of model input parameters. Appendix H identifies the recommended method for the grain size distribution test.

2) Geotechnical Laboratory Analysis. The physical properties of each soil layer can be determined by a geotechnical laboratory. Parameters used in the USEPA Vapor Intrusion Model are air-filled porosity, water-filled porosity, total porosity, and bulk density. Most geotechnical laboratories report soil moisture in units of weight percent, but the USEPA Model requires moisture in terms of volume percent; hence, unit conversion may be necessary. DTSC recommends no less than three geotechnical measurements to classify each soil layer. The measurements yielding the most conservative results should be used in the USEPA Vapor Intrusion Model. Otherwise, a statistically robust number of tests per layer should be conducted and the tests should be averaged using an appropriate statistical technique. Again, estimating geotechnical properties from a visual description of subsurface soil, as annotated onto a boring log, is not an appropriate approach for the selection of model input parameters. Appendix H describes the recommended methods for determining these parameters.

3) In-Situ Measurements. Direct field measurements can determine the soil's effective diffusion coefficient and air permeability, which can be used directly within the USEPA Vapor Intrusion Model. In-situ measurements of air permeability should be conducted in the shallow vadose zone, in the area subject to advection by building-driven depressurization. The reach of the "building zone of influence" on soil gas flow is usually less than one meter. It should be noted that since default values for the flow rate of soil gas into the building (Q_{soil}) may be used instead of calculations based on near surface soil permeability, in-situ air permeability measurements may not be necessary. Guidance on

effective diffusion coefficient and air permeability determination can be found in Appendices I and J, respectively.

Air Permeability (k_v)

The approach of using soil air permeability in the USEPA Vapor Intrusion Model is a function of whether the building is existing or proposed, as follows:

1) Existing Building. A soil gas advection rate (Q_{soil}) of 5 liters per minute should be used with the default building size in the USEPA Vapor Intrusion Model unless site-specific measurements of air permeability of the shallow soil are available. Accordingly, if site-specific permeability measurements are available, the model can calculate a site-specific Q_{soil} from the permeability measurements. If air permeability measurements are not available and existing buildings are larger than the default size, the Q_{soil} of 5 liters per minute should be proportionally increased in a linear fashion as a function of the spatial footprint of the building. For example, a building of 1000 square meters will have, for modeling purposes, a soil gas advection rate of 50 liters per minute because a building of this square footage is ten times larger than the default building size.

2) Future Building. Making a reasonable prediction for vapor intrusion into future buildings is difficult. Construction activity may alter subsurface vapor concentrations and the physical character of the subsurface. Accordingly, rather than inputting a site-specific air permeability value into the USEPA spreadsheet, DTSC recommends that a default value of 5 liters per minute for the soil gas advection rate (Q_{soil}) should be used as proportionally corrected for building size.

Ratio of Q_{soil} to $Q_{building}$

Pursuant to Johnson (2002), an important parameter in evaluating the reasonableness of modeling outputs for residential buildings is to ensure that the ratio of $Q_{soil}/Q_{building}$ is between 0.01 and 0.0001, where Q_{soil} is the soil gas advection rate from the subsurface into the enclosed space and $Q_{building}$ is the enclosed space volumetric airflow rate of fresh air entering the building. For vapor intrusion modeling with the USEPA spreadsheet, these parameters are calculated from user inputs and can be found in the INTERCALC sheet of the model. The range in values for the ratio of $Q_{soil}/Q_{building}$ comes from the radon and contaminant transport literature where both subslab and indoor air concentrations were reported. Therefore, vapor intrusion model results having a $Q_{soil}/Q_{building}$ ratio of less than 0.0001 should be considered suspect.

Indoor-Outdoor Pressure Differential (ΔP)

Advective transport of soil vapors into buildings occurs as the result of the depressurization of buildings relative to the pressure in the surrounding soil. This pressure differential (ΔP), referred to as negative pressure, drives the flow of vapors into the building. The soil vapor flows into the building through cracks, gaps, and openings within the foundation. The pressure differential is caused by meteorological, mechanical, and occupant behavioral factors. The meteorological factors include indoor-outdoor temperature differences (i.e., 'stack effect'), wind loading on the building superstructure, and barometric pressure changes. Examples of mechanical and occupant behavioral factors that lead to building depressurization include the operation of exhaust fans, ceiling fans, fireplaces, and furnaces.

The potential range of values for indoor-outdoor pressure differential is 0 to 20 Pascals (1 Pa = 10 g/cm-s^2) (Loureiro et al., 1990; Eaton and Scott, 1984). Individual values for indoor-outdoor pressure differential have been published as follows:

Author	Building Effect	ΔP values (Pascals)
Nazaroff and others (1985) Put and Meijer (1989)	Wind and stack effects	2
Loureiro and others (1990) Grimsrud and others (1983)	Wind and heating effects	4 -5
Fischer and others (1996)	Wind effects	3
Lindmark and Rosen (1985)	n/a	0 – 2*

* Buildings with mechanical ventilation and good insulation may have pressure differentials three times these values.

The above information indicates that some degree of building depressurization should be incorporated into any vapor intrusion evaluation. Quantifying the degree of building depressurization is a highly uncertain process because of the difficulty in obtaining accurate long-term measurements and in estimating the simultaneous interactions of all the depressurization factors. Therefore, a value for building depressurization of 4 Pa (40 g/cm-s^2) was chosen as a conservative default for California.

Crack-to-Total Area Ratio (η)

The crack-to-total area ratio (η) is the ratio of the total area of cracks and openings in a foundation to the total area of the foundation. The parameter is also referred to as the “crack factor”. With respect to model sensitivity to crack factor, Johnson (2002) states that the J&E model is not sensitive to the selection of a crack factor for scenarios where advection dominates the movement of soil vapor. However, in scenarios where the intrinsic permeability of the soil is below 1.0 x 10^{-9} square centimeters (cm^2), the movement of vapor will be dominated by diffusion and the selection of a crack factor becomes important. Johnson (2002) suggests a crack factor range of 0.0005 to 0.005. The American Society of Testing and Materials (1995) suggested a default value of 0.01 for the crack-to-total area ratio in their standard for risk-based corrective action. USEPA (2002) used a crack factor of 0.0002 for houses with basements and 0.0038 for slab-on-grade houses. A crack factor of 0.005 was selected as a conservative default value for California. Hence, a value of 0.005 should be indicated on the INTERCALC sheet for the crack-to-total area ratio when submitting modeling evaluations to oversight agencies.

Indoor Air Exchange Rate (E_b)

Indoor air exchange is the principal mechanism for diluting indoor air contamination. The air exchange rate is defined as the number of times that the total volume of air within a building is replaced by external air, and the rate is usually expressed in terms of air exchanges per hour (i.e., hour^{-1}). Air within a building is exchanged through three processes: a) mechanical or forced ventilation, b) natural ventilation, and 3) infiltration. Mechanical or forced ventilation systems include the operation of exhaust fans, ceiling fans, fireplaces, and furnaces. Natural ventilation relates to occupant behaviors and activities like the opening and closing of doors and windows. Infiltration is defined as the uncontrolled airflow through foundation cracks, gaps, and openings. The infiltration of air is caused by indoor-outdoor temperature differences, wind loading on the building superstructure, and barometric pressure changes.

The scientific literature indicates that residential air exchange rates can range from 0.2 to 2.0 air exchanges per hour. Rates vary as a function of calendar season, building construction, building energy efficiency, and climatic conditions. Two nationwide studies of residential air exchange rates included data from California. Versar (1990) compiled about 100 separate field research projects by various organizations, which involved both random sampling and judgmental sampling. Most of the studies involved the use of perfluorocarbon tracer (PFT) gas to measure time-averaged air exchange rates. The PFT technique utilizes miniature permeation tubes as tracer emitters and passive samplers to collect the tracers, which were analyzed by gas chromatography. Murray and Burmaster (1995) also analyzed the PFT database and summarized distributions of exchange rates in subsets defined by climate and season. In this data evaluation, Murray and Burmaster lumped California data with other climatically appropriate states. A comprehensive review of residential indoor air exchange rates can be found in the Exposure Factors Handbook by USEPA (1997).

Air exchange rates for California are summarized below and were taken from USEPA (1997). For residential buildings in California, a value of 0.50 air exchanges per hour should be used as a conservative default value. This value is approximately the 25th percentile of houses in California.

Summary of Air Exchange Rates for California

Project Code	Month(s)	Percentiles				Number of Measurements
		10th	25th	50th	90th	
ADM	May - Jul	0.29	0.36	0.48	1.75	29
BSG	Jan, Aug - Dec	0.21	0.30	0.40	0.90	40
RT11	Feb	0.38	0.48	0.78	1.52	45
RT12	Jul	0.79	1.18	2.31	5.89	41
SOCAL1	Mar	0.29	0.44	0.66	1.43	551
SOCAL2	Jul	0.35	0.59	1.08	3.11	408
SOCAL3	Jan	0.26	0.37	0.48	1.11	330
weighted average		0.31	0.48	0.78	1.95	

Note: 1) Units are air exchange rates per hour.
2) Data taken from USEPA (1997).

For commercial buildings, a default rate of 1.0 air exchange per hour should be used. This number is based upon the minimal ventilation requirements pursuant to the 2001 Energy Efficiency Standards for Nonresidential Buildings (California Energy Commission, 2001). The minimum ventilation requirement is 0.15 cubic feet per minute per square foot of building space. For a single story commercial building, this equates to approximately 1.0 air exchange per hour.

Average Soil and Groundwater Temperature (T_s)

For vapor migration, the average soil and groundwater temperature is used to correct Henry's law constant for the chemical of concern. When possible, the site-specific subsurface temperatures should be used when making the correction to Henry's law constant. During the routine sampling of groundwater monitoring wells, temperature is collected as a stabilization parameter during well purging. If available, this temperature value should be used to make the Henry's law constant correction. If no monitoring wells exist at the site, groundwater temperatures as collected at nearby sites can be used when the wells are screened within the water table. In cases where no subsurface temperature data are available, the subsurface temperature can be determined from the mean air temperature using the procedures from Toy and others (1978). A temperature of 24°C should be used as a default for the USEPA Vapor Intrusion Model.

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APPENDIX E - SOIL GAS CONCENTRATIONS FROM SOIL MATRIX ANALYTICAL RESULTS

Soil matrix sampling, in some instances, can be used as an additional line of evidence for evaluating vapor intrusion. Samples should be collected pursuant to USEPA Method 5035A (DTSC, 2004). The associated soil gas concentration from the soil matrix data should be determined using the following partitioning calculation (Feenstra et al., 1991) and associated default parameters.

$$C_{gas} = \frac{H_c \, C_{soil} \, \rho_s}{(\theta_w + k_{oc} f_{oc} \rho_s + H \theta_a)}$$

where,

Input Parameter		Units	Default Value	Basis for Default Value
C_{gas}	Soil gas concentration	g/cm^3	Calculated	-
C_{soil}	Soil matrix concentration	g/g	Measured at site	-
θ_w	Soil volumetric water content	cm^3/cm^3	0.054	Cal/EPA (2005)
θ_a	Soil volumetric air content	cm^3/cm^3	0.321	
ρ_s	Soil bulk density	g/cm^3	1.66	
f_{oc}	Soil fraction organic carbon	g/g	0.002	
H_c	Henry's law constant	unitless	Chemical specific	-
k_{oc}	Carbon-water sorption coefficient	cm^3/g	Chemical specific	-

g = grams
cm^3 = cubic centimeters

The above equation assumes equilibrium conditions exist in the subsurface that allow for complete partitioning of contaminants into their respective phases. Hence, the above equation should only be used with a full understanding of these potential limitations.

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APPENDIX F – USE OF PERMISSIBLE EXPOSURE LIMITS

The Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PELs) are not appropriate criteria for evaluating the risk associated with vapor intrusion to indoor air in California. Pursuant to the California Health and Safety Code, Sections 25150, 25187, 25200.10, and 25356, chemical releases in California should be characterized and mitigated based upon the risk to human and ecological receptors. Hence, for vapor intrusion sites, potential adverse effects to humans should be evaluated in terms of acceptable exposure based upon risk rather than upon comparison to OSHA PEL endpoints. For sites in California, regardless of whether the exposure scenario is residential, commercial, or industrial, OSHA PELs should not be used as indoor air screening levels for vapor intrusion. DTSC regulates chemicals in the subsurface and any human exposure derived from the associated contaminant migration, whereas OSHA regulates workspaces and any associated exposure derived from workplace air contaminants.

OSHA regulates exposure to chemicals in an industrial setting. OSHA regulations prescribe controls and monitoring of the workplace environment to limit employee exposure to vapors and gases. For employees working in an environment where they may be exposed to vapors and gases that exceed the PELs, the employer must make available training, medical surveillance, personnel monitoring, exposure information, and respiratory protection. Those workplaces that handle volatile materials must control exposure to employees, which is typically done with ventilation systems, process enclosures, work practices, and personal protection equipment. OSHA requires that employees have access to Material Safety Data Sheets (MSDSs) and that employees are trained to recognize hazardous conditions. Hence, workers subject to potential exposure to gases and vapors by the nature of their working environment are regulated under OSHA. These workplaces are usually commercial and industrial settings where hazardous chemicals are handled inside a building as part of a commercial or industrial process. Employees working with a commercial or industrial process that involves hazardous gases or vapors usually work in these conditions voluntarily, are aware of the potential risk of exposure, and have implicitly accepted exposure as an occupational hazard. For gases and vapors, the PEL is the maximum concentration of a chemical in the air that a worker may be exposed to without respiratory protection (Cal. Code of Regs., tit. 8, §5155). PELs are based on the assumption that only healthy, appropriately trained and monitored workers may be exposed to chemical concentrations as great as or exceeding the PELs. OSHA did not envision that children, the elderly, or unhealthy adults would be exposed to PEL concentrations.

PELs are based on the assumption that only healthy, appropriately trained and monitored workers may be exposed to chemical concentrations as great as or exceeding the PELs.

When Congress enacted OSHA, it gave States the option to preempt federal OSHA standards pursuant to an approved State plan (29 U.S.C. §667(b)). However, it did not state that workers covered under the Act may not be subject to any supplemental State requirements. Courts have held that State laws whose primary purpose addressed a concern other than occupational health and safety were not preempted by OSHA (Manufacturers Association of Tri-County v. Knepper [1986] 801 F.2d 130, 138). In fact, the Secretary of Labor endorsed the view that an OSHA standard "should not preempt State laws addressing ‘general environmental problems originating in the work place, but whose effects are outside it . . .’" (New Jersey State Chamber of Commerce v. Hughey [1985] 774 F.2d 587, 593). There is a presumption that the historic police powers of the State to regulate matters of health and safety are not to be superseded by federal regulation unless it is a clear and manifest purpose of Congress.

After issuing their 2002 vapor intrusion guidance, USEPA has asked OSHA to research the issue of whether USEPA has the authority to address workplace vapor intrusion. The Administration responded that under Section 5(a)(1) of OSHA, known as the General Duty Clause, its authority only extended to contaminants originating in the workplace (Inside EPA, 2004). The clause covers areas of occupational safety and health that are not addressed by a specific standard and requires that each employer "shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm." OSHA concluded that it lacks statutory authority to prevent USEPA from addressing contamination when it does not originate from inside the facility.

At sites subject to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), cleanup levels are generally determined either by Applicable or Relevant and Appropriate Requirements (ARARs) or the risk assessment process. OSHA standards are not ARARs under CERCLA statute and regulations. Therefore, OSHA standards should not be applied to CERCLA cleanups.

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APPENDIX G - SOIL GAS SAMPLING DIRECTLY UNDER BUILDING FOUNDATIONS (SUBSLAB SAMPLING)

Subslab soil gas data will determine if vapors are collecting directly under a building's foundation and will demonstrate which contaminants potentially represent a threat to human health. If a building is determined to have a moisture barrier and/or a tension slab, special care should be given when hand-drilling through the concrete slab. In particular, for tension foundation slabs, the tension cables within the slab should be located prior to drilling either through visual observation or through remote-sensing with either a metal detector or ground penetrating radar. The cutting of a tension cable within a slab during drilling could disrupt the integrity of the slab and potentially cause injury to the field crew.

When evaluating subslab soil gas for a building, DTSC recommends that permanent sampling points be installed so that repeated sampling can be conducted, as necessary, to evaluate seasonal or temporal variations.

The following procedures should be considered when collecting subslab data.

1) After removal of the floor covering, a small-diameter hole should be drilled through the concrete of the foundation slab. Typically, holes are 1.0 to 1.25 inches in diameter. Either an electric hand drill or concrete corer is used to drill the holes. All subslab utilities, such as water, sewer, and electrical, should be located and clearly marked on the slab prior to drilling. Subslab holes should be advanced three to four inches into the engineering fill below the slab. All drill cuttings should be removed from the borehole. The sampling probe should be constructed with the following specifications:

   - Vapor probes are typically constructed of 1/8 inch or 1/4 inch diameter tubing, with a permeable probe tip. A Teflon™ sealing disk should be placed, as needed, between the probe tip and the blank pipe to prevent the downward migration of wet bentonite into the sand pack.

   - Dry granular bentonite should be used to fill the borehole annular space to above the base of the concrete foundation. Hydrated bentonite should then be placed above the dry granular bentonite. The bentonite for this portion of probe construction should be hydrated at the surface to ensure proper sealing. Care should be used in placement of the bentonite to prevent post-emplacement expansion which might compromise both the probe and cement seal. The remainder of the hole should be filled with bentonite grout if the probe is permanent or with hydrated bentonite if the probe is semi-permanent. Prior to the introduction of this material, the concrete surfaces in the borehole should be cleaned with a damp towel to increase the potential of a good seal. The vapor probe tip should be covered with sand to ensure proper airflow to the probe tip.

   - All water used in the construction of the probe should be deionized, the cement should be contaminant-free and quick drying, and all metal probe components should be thoroughly cleaned to remove manufacturer-applied cutting oils.

   - Each probe should be constructed with a gas-tight fitting and flush-mounted well box so that the probe completion is not a tripping hazard.

   - Prior to sampling, at least two hours of time should elapse following installation of a probe to allow the construction materials to cure and allow for the subsurface to equilibrate (USEPA, 2006).

- An example of a subslab sampling probe is shown in the attached schematic diagram.

2) The collection of subslab samples should follow the procedures in Cal/EPA's Active Soil Gas Investigation Advisory, which recommends purge volume testing, leak testing, and shut-in testing. Purging and sampling rates should not exceed 200 milliliters per minute. To avoid air breakthrough from nearby foundation cracks within the slab, DTSC recommends using sampling containers with volumes of less than or equal to one liter. If using passivated metal canisters, the canisters should be returned to the laboratory slightly depressurized.

3) Subslab soil gas sampling should be performed using analytical methods in Cal/EPA's Active Soil Gas Investigation Advisory. These methods include USEPA Methods 8260B, 8021B, 8015B, TO-14A, TO-15, and TO-17. All methods should meet the site-specific data quality objectives (DQOs) and the analytical method reporting limits should be low enough for risk determination.

4) A sufficient number of subslab sampling events should be conducted to account for seasonal and spatial variability. At a minimum, two subslab sampling events are warranted before a final risk determination is made.

5) Upon completion of all sampling, the foundation probes should be properly decommissioned. The probe tip, probe tubing, bentonite, and grout should be removed by over-drilling. The borehole should be filled with grout and concrete patch material. Surface restoration should include a follow-up visit for final sanding and finish work to restore the floor slab, and associated coverings, to their original condition.

At least two subslab probes should be installed at each residential structure, with one probe installed in the center of the building's foundation. The probes should be installed in inconspicuous areas, such as utility closets or beneath stairs. Subslab probes should not be installed near the edges of the foundation due to the effects of wind on the representativeness of contaminant concentrations (Luo et al., 2009).

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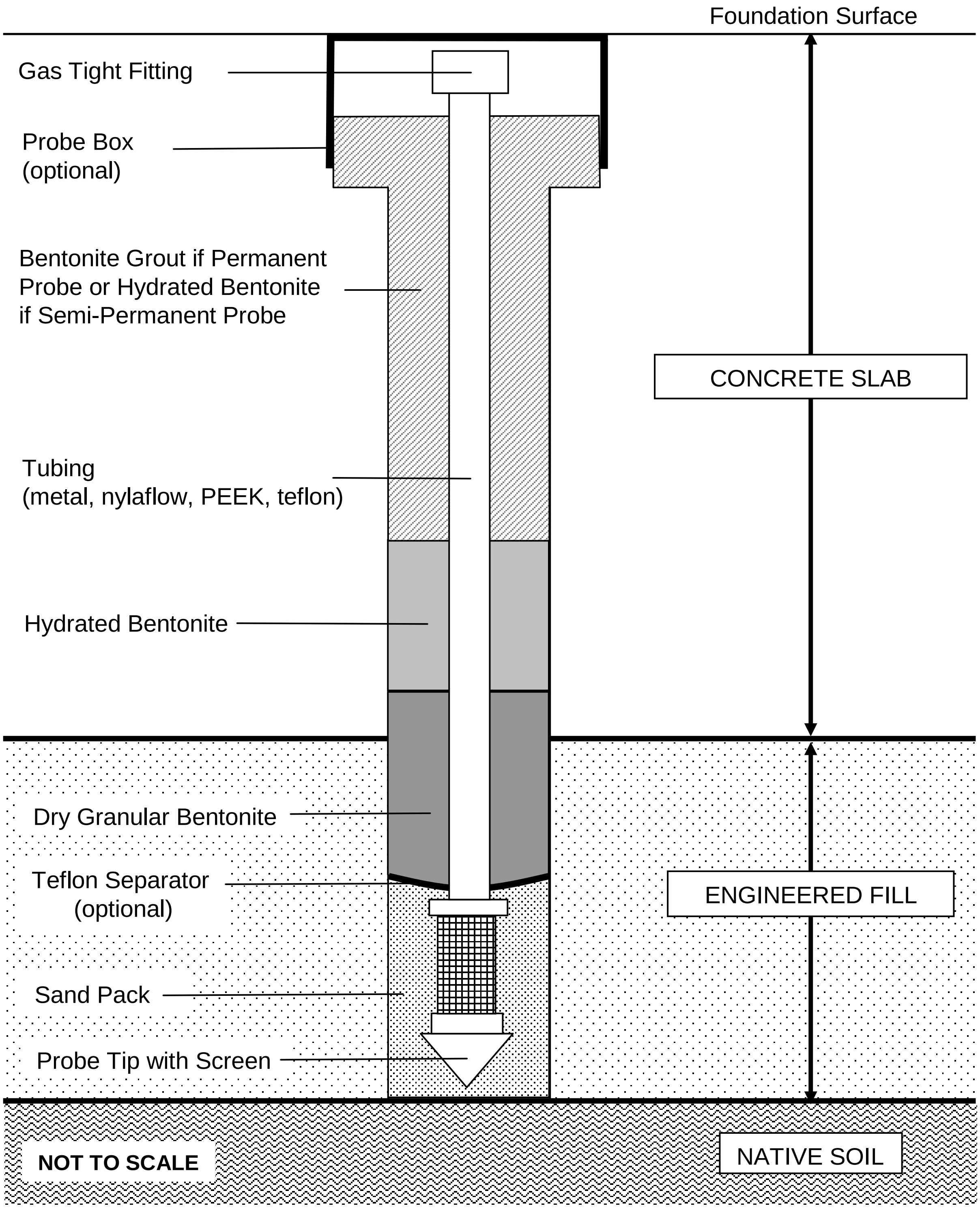
SCHEMATIC DIAGRAM OF A SUBSLAB SAMPLING PROBE



APPENDIX H – SOIL LABORATORY MEASUREMENTS

For site-specific evaluations of vapor intrusion, determination of the physical properties of the vadose zone may be needed. See Appendix D for a discussion of the recommended number of samples and how the physical property data are used. Soil can be submitted to laboratories for the measurement of bulk density, grain density, total porosity, moisture content, fraction of organic carbon, and grain size. The recommended geotechnical laboratory methods are:

Soil Bulk Density: ASTM D2937

Grain Density: ASTM D854

Total Porosity: Calculate from soil bulk density and grain density

Soil Moisture Content: ASTM D2216

Fraction Organic Carbon: Walkley-Black method (Nelson and Sommers, 1996) with modification to include heating to 150ºC for 30 minutes during the sample digestion process (USEPA, 2002)

Grain Size: ASTM D422

Most geotechnical laboratories report soil moisture in units of weight percent but the USEPA Vapor Intrusion Model requires soil moisture in terms of volume percent; hence, unit conversion may be necessary. Ideally, effective diffusion coefficient and air permeability of the subsurface should be determined with in-situ testing procedures (see Appendices I and J, respectively).

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APPENDIX I – IN-SITU SOIL EFFECTIVE DIFFUSION COEFFICIENT MEASUREMENTS

For site-specific evaluations of vapor intrusion, determination of the soil's effective diffusion coefficient by in-situ methods may be warranted. In these cases, measurement of soil effective diffusion coefficient can be conducted using the same equipment that is used to collect soil gas samples. The effective diffusion coefficient is determined by injection of a known volume of a tracer gas at a known concentration into the subsurface. The tracer gas is later extracted and the mass difference is attributed to diffusional loss in the subsurface. The effective diffusion coefficient of the soil can then be determined from this diffusional loss.

The approach described in this appendix for the quantification of soil effective diffusion coefficient (D_v^{eff}) is derived from Johnson and others (1998). Field investigators should read and understand the Johnson paper before applying this method at a particular site. In this approach, a small volume of a tracer gas (V_o) is injected at a known concentration (C_o) at a point in the subsurface. With time, the chemical diffuses away from the injection point. At some time (t_s), a finite volume of gas (V_s) is withdrawn, and the vapor concentration (C_s) is measured in the sampling container after equilibration. These parameters, along with the initial mass injected (m_o) and the recovered mass (m_s), can be used to quantify the soil effective diffusion coefficient with the aid of a nomogram.

The method is based upon the following conditions:

- The tracer is inert and nonsorbing, with a high Henry's law constant.
- The subsurface media is relatively homogeneous and isotropic over the scale studied.
- The test well has small diameter tubing ($\leq$ 0.25 inches).
- The screen on the test well is small ($\leq$ 4.0 inches).
- Sand pack around the screen is small ($V_o \geq 10$ times the void space of the sand pack).

The measurement of soil effective diffusion coefficient should be obtained in subsurface areas between contaminant sources and building foundations. These in-situ tests should only be conducted after soil gas sample collection due to potential disruption of subsurface contaminants by the movement of air.

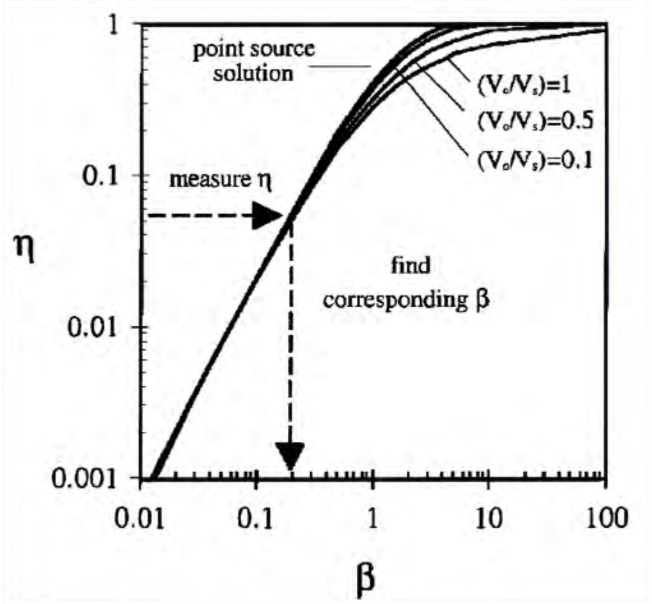
Soil effective diffusion coefficient for the tracer gas is calculated with the following equation:

$$D_v^{eff} = \left[\frac{\theta_v^{1/3}}{\beta}\right]\left[\frac{1}{4t_s}\right]\left[\frac{3V_s}{4\pi}\right]^{2/3}$$

where,

D_v^{eff} = soil effective diffusion coefficient (cm^2/second)
θ_v = volumetric air content of soil (cm^3/cm^3)
β = nomogram parameter (dimensionless)
t_s = sampling time (seconds)
V_s = volume of tracer gas removed (cm^3)
π = pi (3.1416)

The nomogram parameter β is determined from the following chart where $\eta = m_s/m_o$ (recovered mass divided by initial mass injected) at time t_s.



(Taken from Johnson et al., 1998)

The following field procedures are provided for the determination of the soil effective diffusion coefficient:

1) A mixture of the tracer gas is prepared in a tedlar bag. Note the tracer concentration (C_o).

2) Inject a known volume (V_o) of the tracer gas mixture into the subsurface.

3) Follow this injection with sufficient tracer-free air to ensure that the tracer gas is flushed into the vadose zone. The tracer-free volume should be approximately equal to the tubing dead space and sand pack volume.

4) After 5 minutes, extract a known volume of air from the subsurface, at least ten times the amount of the air injected. Note the tracer concentration (C_s) after the gas has equilibrated, the volume of air extracted (V_s), and the time (t_s).

5) Inject 10 – 15 liters of clean air into the subsurface to clear remnants of the tracer gas from near the borehole.

6) Repeat the process for longer periods of time (t_s = 15 and 60 minutes) as needed.

The use of a single small diameter well may systematically underestimate the in-situ soil effective diffusion coefficient due to the measurement length scale. Thus, when possible, numerous in-situ measurements should be conducted as a means to evaluate the underprediction.

Knowing D_v^{eff} for the tracer gas allows D_v^{eff} to be calculated for the subsurface contaminants by simply correcting for differences in the molecular diffusion coefficients of the chemicals in air, as follows:

$$D_{v-cont}{}^{eff} = \left(\frac{D_{a-cont}}{D_{a-tracer}}\right) D_{v-tracer}{}^{eff}$$

where,

$D_{v\text{-}cont}{}^{eff}$ = soil effective diffusion coefficient for contaminant (cm^2/second)
$D_{a\text{-}cont}$ = air diffusion coefficient for contaminant (cm^2/second)
$D_{a\text{-}tracer}$ = air diffusion coefficient for tracer (cm^2/second)
$D_{v\text{-}tracer}{}^{eff}$ = soil effective diffusion coefficient for tracer (cm^2/second)

The method requires that the air-filled porosity (θ_v) of the subsurface be known. However, in many cases, it is not necessary to measure θ_v to determine soil effective diffusion coefficient with reasonable precision. For cases where the total porosity ranges from 0.25 to 0.45 with moisture saturations ranging from 5 to 50 percent, the associated air-filled porosity is between 0.13 and 0.43. Calculating soil effective diffusion coefficient under this range of conditions would only change the result by approximately 23 percent. Accordingly, when quantifying $D_v{}^{eff}$ without information concerning air-filled porosity, the value should be assumed to be between 0.13 and 0.43, with ultimate selection of the parameter based upon professional judgment.

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APPENDIX J – IN-SITU SOIL AIR PERMEABILITY MEASUREMENTS

For site-specific evaluations of vapor intrusion, determination of the air permeability of the shallow soil may be needed. In these cases, air permeability measurements can be conducted using the same equipment that is used to collect soil gas samples. Air permeabilities are determined by measuring the gas pressure in a vapor well as a metered flow of air is passed through the well. The method is valid for both the injection and extraction of air.

The measurement of in-situ air permeability should be conducted in the shallow vadose zone in the areas subject to advection by building-driven depressurization. Typically, the depth of building-driven depressurization is no more than three feet below a building's foundation. These in-situ tests should only be conducted after soil gas sample collection due to potential disruption of subsurface concentrations by the movement of air.

The following equation can be used to determine in-situ air permeability. The equation has been adapted from an analytical expression by Hvorslev (1951) and Hsieh and others (1983) for the spatial distribution of steady-state water pressure around an injection interval. Derivation of the equation can be found in Bassett and others (1994) and field application of the equation can be found in Guzman and others (1995). The validity of the method is further discussed in Illman and Neuman (2000) and Vesselinov and Neuman (2001). The equation assumes that, during each relatively stable period of air injection, air is the only mobile phase within the soil near the test interval and is controlled by a steady-state pressure field with prolate spheroidal symmetry. Such symmetry implies that the soil forms a uniform, isotropic porous continuum. The equation is:

$$k = Q_{sc} \frac{\mu \ln \left(L / r_w \right)}{\pi L \left(p^2 - p_o^2 \right)} \frac{T p_{sc} Z}{T_{sc}}$$

where,

k = air permeability (m^2)
Q_{sc} = volumetric airflow rate at standard conditions (m^3/s)
μ = dynamic viscosity of air at standard conditions (1.81×10^{-5} Pascal-s)
ln = natural logarithm operator
L = length of the well screen (m)
r_w = borehole radius (m)
T = air temperature in the test interval (° Kelvin)
p_{sc} = air pressure at standard conditions (1.013×10^5 Pascals)
Z = air compressibility factor (assume 1.0 [dimensionless])
π = pi (3.1416)
p = air pressure in the injection interval (Pascals)
p_o = ambient air pressure during injection (Pascals)
T_{sc} = temperature at standard conditions (273° Kelvin)

After obtaining a soil gas sample from a borehole, air is extracted or injected into the soil vapor well and the air pressure and flow rate are measured at the surface. To conduct the permeability measurements, a cylinder of compressed air can be used as an injection source or a purge pump can be used as an extraction source, along with a flow meter with a range of 5 to 500 cubic centimeters per minute (cm^3/min), and a differential pressure gauge with a range of 0 to 1000 Pascals (Pa). To obtain differential pressure measurements over the required range, multiple pressure gauges may be needed, because a single gauge may not yield the required measurement range. The following procedures should be considered when collecting and evaluating in-situ air permeability data.

- The in-situ test should continue until steady-state pressure occurs. The occurrence of steady-state pressure is defined as less than a 130 Pa pressure change within 30 minutes. The test should be terminated after 2 hours if pressure stabilization is not obtained.

- During the first hour of the test, air pressure (p), flow rate (Q_{sc}), air temperature (T_{sc} and T), and barometric pressure (p_o) should be measured at five minute intervals, or as appropriate. After the first hour, data can be collected less frequently but at a minimum interval of 30 minutes.

- The air permeability should be calculated using the data obtained during steady-state conditions.

- If the test well is constructed with a drive-tip where no filter pack is used, the diameter on the tip used for the test should be measured to within ± 0.1 centimeters before insertion into the soil and then remeasured upon retrieval from the subsurface to verify no tip diameter distortion occurred during installation.

- The above equation is based on the assumption that the flow of air is predominantly radial, which is assumed to occur when L/r_w is greater than 5 (Bassett et al., 1994). Hence, this ratio of greater than 5 must occur during all air permeability testing. Otherwise, the above equation cannot be used to calculate air permeability and the alternate method within Bassett and others (1994) should be followed.

- The air compressibility factor (Z) in the above equation indicates the extent to which the test air behaves as an ideal gas. The assumption that the air compressibility factor is 1.0 assumes the test air behaves as an ideal gas. If site conditions indicate non-ideal gas behavior, the air compressibility factor warrants quantification in order to accurately determine the in-situ air permeability. Most textbooks on thermodynamics contain a gas compressibility chart.

The use of a single small diameter well may systematically underestimate the in-situ air permeability due to the measurement length scale (Garbesi et al., 1996; Garbesi et al., 1999). Thus, when possible, numerous air permeability measurements should be conducted as a means to evaluate the underprediction.

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APPENDIX K – PASSIVE INDOOR AIR SAMPLING

Canister sampling is currently the predominant method for indoor air testing in the United States because the approach produces quantitative data and can achieve the low detection limits needed to support risk assessment. However, the high costs and complexities of canister deployment are causing investigators to look toward alternative air sampling methods, such as passive (diffusive) methods, to support indoor air investigations.

Passive samplers offer several advantages over canisters, including: lower cost (Groenevelt et al., 2008); simplicity and versatility of use; small size; unobtrusive appearance; and potential to collect samples over time periods longer than 24 hours (e.g., 3 to 30 days). Passive samplers may also be used to sample compounds not evaluated in canisters, such as aldehydes and hydrogen sulfide. Passive samplers have a long history of use in industrial hygiene applications. Since the mid-1990s, European scientists have worked to develop passive samplers capable of evaluating low concentrations of volatile chemicals in air and, for approximately the last ten years, have evaluated passive samplers for indoor air applications.

USEPA Region 9 is currently evaluating the use of passive air sampling for indoor air investigations by conducting comparison studies with canisters at several sites in California (Lee et al., 2010). Other researchers have also conducted comparison studies among canisters, passive samplers, and sorbent tubes for indoor air applications (Coyne et al., 2009; Bruno et al., 2008; Odencrantz et al., 2009; McAlary et al., 2010; Lutes et al., 2010). At present, passive samplers appear to have potential to supplement canister sampling, such as for screening to identify structures for further indoor air evaluation (Bruno et al., 2008; Coyne et al., 2009).

PASSIVE SAMPLER OVERVIEW

Passive samplers come in multiple forms but all function according to Fick's first law where contaminant molecules move under a concentration gradient into the sampler (i.e., via diffusion) and then are captured onto sorbent material within the sampler. Numerous types of passive samplers are commercially available. Sampler manufacturers place the sorbent material within some type of housing. Typically, either the contaminants diffuse through the wall of the housing into the sorbent material or there is an opening in the housing where contaminants may enter and the sorbent is held in-place by a screen or membrane.

The concentration of a contaminant of interest in sampled air, C, can be calculated by:

$$C = \frac{m}{t\,Q}$$

where m is the adsorbed mass, t is the sampling time, and Q is the contaminant-specific sampling rate (also known as the uptake rate). The sampling rate is a function of the sampler geometry as well as the air diffusion coefficient for the contaminant of interest.[1] The sampler manufacturers calculate parameter-specific sampling rates for their samplers under controlled laboratory conditions and typically at a temperature of 25°C. The sampling rates can be

---

[1] The diffusion coefficient, and hence the sampling rate, is a function of temperature and pressure. Studies have found that the sampling rate is relatively insensitive to pressure variations in the ranges typically encountered in environmental investigations.

adjusted to the temperature representative of sampling conditions by using the following equation:

$$Q_T = Q_{298} \left(\frac{T}{298} \right)^{1.5}$$

where T is the temperature in Kelvin (298°K is equals 25°C).

CONSIDERATIONS FOR APPLICATION TO INDOOR AIR INVESTIGATIONS

The most important consideration for use of passive samplers in an indoor air investigation is ensuring that use of the selected sampler supports the site's data quality objectives (DQOs). The following factors should be considered when contemplating use of passive samplers in an indoor air investigation:

- Consistency with the sampling objectives.
- Ability to achieve reporting limits lower than risk-based screening levels.
- Availability of sorbent materials appropriate for the contaminants of interest.
- Sensitivity of the sampling device to non-diffusive air movement.
- Potential for the sorbent to be "overloaded" by non-target volatile chemicals or water vapor.
- Time interval required to collect a representative sample and the potential for contaminants to diffuse off the sorbent over the desired sampling interval.
- When high indoor air concentrations are expected, charcoal-based sorbents or shorter sampling durations should be considered.
- Representativeness of exposure conditions for buildings with variable ventilation settings and that are not continuously occupied.
- The need to deploy multiple samplers at each location for sorbent types that only supports a single analytical "run" (i.e., thermally desorbed tubes).
- Use of the manufacturer's sampling rates will result in acceptable accuracy.

A laboratory experienced in passive sorbent sampler methods should be consulted to determine whether a sampler is suitable for a given application. If quantitative data are required, it should be ensured that the sampler, sorbent type, and compounds of interest have been independently validated, or are validated as part of the sampling effort.

Sampling Objectives

The site-specific sampling objectives will determine whether passive samplers are appropriate for all or part of the investigation. Examples of site-specific objectives for which passive samplers might be particularly viable include:

- Cost-effectively screen a broad area or identify areas for further investigation (semi-quantitative data)
- Collect longer-duration samples to account for temporal variability or provide more accurate time-weighted average concentrations (quantitative data)

Some sampling objectives may preclude use of passive samplers. For example, the level of uncertainty associated with passive sampler results may not support the site's DQOs (see sampling rate discussion below). Also, sorbents might not be available for all of the contaminants of interest or the target reporting limits may not be achievable.

Contaminants of Interest and Analysis

The contaminants of interest need to be matched with appropriate sorbent sampler and type. It may not be possible to identify a single sorbent sampler and type appropriate for all contaminants of interest. For example, vinyl chloride is not effectively captured by sorbent media commonly used to evaluate TCE and PCE. Reverse diffusion (loss of adsorbed analyte) can be a concern where the sorbent is not best suited for the contaminant or if the sampling duration is too long. Some sorbents analyzed by thermal desorption may be more prone to reverse diffusion (Coyne et al., 2010). Method TO-17 (USEPA, 1999) and ASTM Procedure D6196-03 provide guidelines for sorbent type selection. Some sampler manufacturers and analytical laboratories also have guidance on, and offer assistance with, matching sorbent materials with contaminants of interest. It is important to work with the manufacturer or analytical laboratory to ensure that the sampler is capable of analyzing the contaminants of interest.

The analytical method will depend on the contaminants of interest and the sampler manufacturer. For example, for VOC analysis, one badge sampler manufacturer uses thermal desorption and gas chromatographic techniques described in Method TO-17. In contrast, a radial sampler manufacturer has developed its own procedures for sorbent desorption and analysis for BTEX and VOCs. Another manufacturer uses ASTM Method 6196-03 for VOC analysis. Additionally, the International Organization of Standards (2004) has developed methodologies that apply to multiple charcoal-based samplers.

Reporting Limits

Reporting limits that can be achieved for a passive diffusive sampler are related to the sampler-specific sampling rates and are specific to each compound. Detection limits in the low parts-per-billion range can be achieved, and parts-per-trillion levels may be achievable for some samplers. It may be necessary to work with the analytical laboratory to ensure that target reporting limits can be achieved. A longer sampling duration may be able to achieve lower reporting limits provided that reverse diffusion is not a concern. The type of sorbent used also affects the achievable analytical reporting limits. For example, a sorbent that requires contaminant removal via thermal desorption may be able to achieve lower reporting limits than a sorbent that requires solvent extraction.

Environmental Conditions

The manufacturer specifications should identify the environmental conditions under which the sampler is recommended for use. For example, a passive sampler may be sensitive to high humidity or wind speed. Humidity may affect the adsorptive capacity of the sorbent material and result in underestimation of the contaminant mass. Introduction of excessive moisture may also cause analytical interference. Wind velocity across the opening of the sampler may affect the diffusion path length for the contaminant, increasing the path length at low wind speeds (less sorption) and decreasing the path length at high wind speeds (more sorption). Hence, placement of the sampler relative to doorways or ventilation grates may be a consideration for a given application.

Sampling Rates

Sampling rates are determined under laboratory controlled conditions, potentially at higher contaminant concentrations and velocities (10 to 200 cm/s) than encountered by indoor air applications (<5 cm/s). Also, the sampler manufacturer may not have determined sampling rates for all contaminants of interest so it is important to check the list of compounds identified in the sampler specifications. Furthermore, the sorbent uptake rate may vary if the VOC concentrations fluctuate widely during the sampling event and thus may bias the reported concentration for the sample (Lutes et al., 2010).

Passive samplers are currently considered to be semi-quantitative and quantitative (Lutes et al., 2010). Comparison studies of canister and passive samples have found that the sampling rates for indoor air samples collected using passive samplers are about 50 to 60 percent of sampling rates determined under controlled laboratory conditions (Odencrantz et al., 2009; Coyne et al., 2009). These findings have led some sampler manufacturers to provide laboratory determined "zero velocity" sampling rates (e.g., <5 cm/s) for use in indoor air applications. Odencrantz and others (2009) concluded that further evaluation is needed to fully understand sampling rates under real-world conditions. Even with the sampling rate issues noted for some indoor air applications, the strong correlation of passive and canister sampling results in multiple comparison studies (Coyne et al., 2009; Odencrantz et al., 2009) suggests that diffusive samplers could be used to quantify indoor air concentrations inside structures.

SAMPLING AND ANALYSIS

The manufacturer's instructions for passive sampler use should be consulted and used to develop project-specific sampling procedures. The methods discussed in Method TO-17 (USEPA, 1999) should also be considered in the development of the sampling procedure. Additional procedures should be included, consistent with other applicable guidance. Key items to address in the sampling procedures are outlined below.

<u>Planning</u>

- Sampler and sorbent selection appropriate for the compounds of interest, DQOs, target reporting limits, expected indoor air concentration, and sampling environment
- Identification and coordination with analytical laboratories capable of analyzing sorbent-based samples, or a given type of passive sampler
- Sorbent handling considerations (e.g., conditioning, storage, shelf life)[2]
- Assessment of expected building conditions (e.g., contaminant sources, building type, layout, ventilation system)
- Sampling design:
  - Number of samples
  - Sampling locations (e.g., within building, sampling height)
  - Sampling duration
  - Sample handling (e.g., preservation requirements, holding times)

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[2] Sorbents and/or entire samplers are stored in a sealed container prior to sampler deployment. The sorbents and/or samplers are resealed immediately after sampling. Sample handling by the analytical laboratory should minimize the potential for contaminant loss from the sorbent (e.g., by direct transfer of the sample to a sealed thermal desorption tube). Prior to and after sample collection, sorbents and samples are typically recommended for storage at a cool temperature and in an environment that will not cause cross-contamination (e.g., storage in an organic solvent-free environment).

  - Quality assurance / quality control (e.g., sorbent blanks, field duplicates)
  - Supplemental field measurements (e.g., temperature, humidity)

Sampling Activities

- Sampler deployment procedures pursuant to the sampler type used
- Procedures for sealing the sorbent after sampling is complete
- Procedures for supplemental field measurements
- Sample handling, preservation, shipping, and chain-of-custody procedures
- Field documentation (written notes, photographs)

Analysis

- Identification of analytical method(s) (see discussion above)
- Laboratory quality assurance / quality control requirements
- Method reporting limits and laboratory detection limits

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APPENDIX L - BUILDING SURVEY FORM

Preparer's Name: ______________________________ Date/Time Prepared: __________
Affiliation: ______________________________ Phone Number: __________

Occupant Information

Occupant Name: ______________________________ Interviewed: ☐ Yes ☐ No
Mailing Address: ______________________________
City: __________________ State: ______________ Zip Code: __________
Phone: __________________ Email: ______________________

Owner/Landlord Information (Check if same as occupant ☐)

Occupant Name: ______________________________ Interviewed: ☐ Yes ☐ No
Mailing Address: ______________________________
City: __________________ State: ______________ Zip Code: __________
Phone: __________________ Email: ______________________

Building Type (Check appropriate boxes)

☐ Residential ☐ Residential Duplex ☐ Apartment Building ☐ Mobile Home ☐ Commercial (office)
☐ Commercial (warehouse) ☐ Industrial ☐ Strip Mall ☐ Split Level ☐ Church ☐ School

Building Characteristics

Approximate Building Age (years): ______________ Number of Stories: ______________
Approximate Building Area (square feet): ______________ Number of Elevators: ______________

Foundation Type (Check appropriate boxes)

☐ Slab-on-Grade ☐ Crawl Space ☐ Basement

Basement Characteristics (Check appropriate boxes)

☐ Dirt Floor ☐ Sealed ☐ Wet Surfaces ☐ Sump Pump ☐ Concrete Cracks ☐ Floor Drains

Factors Influencing Indoor Air Quality

Is there an attached garage?	☐ Yes	☐ No	
Is there smoking in the building?	☐ Yes	☐ No	
Is there new carpet or furniture?	☐ Yes	☐ No	Describe: __________
Have clothes or drapes been recently dry cleaned?	☐ Yes	☐ No	Describe: __________
Has painting or staining been done with the last six months?	☐ Yes	☐ No	Describe: __________
Has the building been recently remodeled?	☐ Yes	☐ No	Describe: __________
Has the building ever had a fire?	☐ Yes	☐ No	
Is there a hobby or craft area in the building?	☐ Yes	☐ No	Describe: __________
Is gun cleaner stored in the building?	☐ Yes	☐ No	
Is there a fuel oil tank on the property?	☐ Yes	☐ No	
Is there a septic tank on the property?	☐ Yes	☐ No	
Has the building been fumigated or sprayed for pests recently?	☐ Yes	☐ No	Describe: __________
Do any building occupants use solvents at work?	☐ Yes	☐ No	Describe: __________

Sampling Locations

Draw the general floor plan of the building and denote locations of sample collection. Indicate locations of doors, windows, indoor air contaminant sources and field instrument readings.

Primary Type of Energy Used (Check appropriate boxes)

☐ Natural Gas ☐ Fuel Oil ☐ Propane ☐ Electricity ☐ Wood ☐ Kerosene

Meteorological Conditions

Describe the general weather conditions during the indoor air sampling event.

____

General Comments

Provide any other information that may be of importance in understanding the indoor air quality of this building.

____
____
____
____
____

APPENDIX M – BUILDING SCREENING FORM

Occupant of Building ____

Address ____

City ____

Field Investigator ______________________ Date ______________

Field Instrument Reading	**Measurement Location (Ambient Air, Foundation Opening, or Consumer Product)**	**If Consumer Product, Potential Volatile Ingredients**

Comments:

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____