TABLE OF CONTENTS

SECTION IV: VAPOR INTRUSION

A. Introduction

Releases of volatile and some semi-volatile regulated substances to soil or groundwater can result in vapor-phase intrusion of these regulated substances into indoor air. The resulting impacts to indoor air may pose a threat to human health in inhabited buildings. For this exposure pathway to exist there must be a source of volatile substances in the unsaturated zone soil or groundwater at the water table, current or future inhabited buildings, and a transport pathway along which vapors may migrate from the source into the inhabited building(s). Inhabited buildings are buildings with enclosed air space that are used or planned to be used for human occupancy. In order to properly address this pathway, the remediator first develops a Conceptual Site Model (CSM) based on the site characterization to guide further assessment and, if necessary, mitigation or remediation.

This section provides guidance for addressing potential vapor intrusion (VI) of volatile organic compounds (VOCs) and certain semi-volatile organic compounds (SVOCs) from soil and/or groundwater sources, including those impacted by separate phase liquid (SPL), into inhabited buildings at sites using the Statewide health standard (SHS) and the site-specific standard (SSS). As such, this guidance establishes screening values and assessment options that can be used under the SHS to address VI for existing or potential future inhabited buildings. The potential VI impacts from volatile inorganic substances (e.g., mercury and cyanide) can only be addressed using the SSS or mitigation. **The VI screening value tables in this guidance are not meant to evaluate VI under the SSS except under certain circumstances.** Guidance on VI evaluations under the SSS, including the use of a human health inhalation risk assessment, is provided in Section IV.K.

25 Pa. Code § 250.312 requires an assessment of the VI exposure pathway in an SHS final report (FR). An exposure pathway assessment that includes VI is required by 25 Pa. Code § 250.404, and a risk assessment is required by 25 Pa. Code § 250.405 under the SSS. VI must be addressed for existing inhabited buildings and undeveloped areas of the property where inhabited buildings are planned to be constructed in the future. The VI pathway must be addressed for Special Industrial Area (SIA) sites and for storage tank corrective action sites because cleanups at these sites ultimately achieve either the SHS or the SSS. A VI evaluation is generally not required for the background standard.

It is important to note that mitigation measures may be used for existing inhabited buildings to eliminate unacceptable risks associated with VI under the SHS and SSS at any time in the evaluation process. Mitigation can be used in lieu of a complete evaluation of the VI pathway. When choosing preemptive mitigation, the remediator needs to implement postremediation care to ensure: (1) that potential risks associated with VI will be evaluated and addressed when an inhabited building is constructed in the future or (2) that appropriate mitigation measures will be taken in lieu of a complete evaluation in buildings that exist or are constructed on the property. Mitigation, even if preemptive, requires a cleanup plan or remedial action plan (RAP). It is also important to note that any unplanned change to a property's use that results in a change in the VI exposure pathway will require additional VI evaluation to account for that change in exposure. In order to demonstrate attainment of an Act 2 standard for soil and/or groundwater, current or future planned inhabited buildings need to be evaluated for VI in the FR. If there are no

plans for future construction of inhabited buildings at the site, the remediator may choose, but is not required, to use an activity and use limitation (AUL) to address possible future VI issues.

If there is a petroleum release to surface or subsurface soil and a full site characterization has not been performed, a remediator may attain the SHS by following the requirements in 25 Pa. Code § 250.707(b)(1)(iii). Further VI analysis is not needed in these situations for soil if the following conditions are also satisfied: (1) all requirements of 25 Pa. Code § 250.707(b)(1)(iii) have been met; (2) at least one soil sample is collected on the sidewall nearest the inhabited building unless there are substantially higher field instrument readings elsewhere; and (3) contamination has not contacted or penetrated the building foundation based on observations of obvious contamination and the use of appropriate field screening instruments. Evaluation of groundwater for VI potential may still be necessary if groundwater contamination is identified as a potential VI concern.

The Department will not require remediators to amend or resubmit reports that have been approved under previous versions of this guidance.

This guidance provides multiple options for addressing VI including soil and groundwater screening values, alternative assessment options, mitigation with an environmental covenant, and remediation. The alternative assessment options consist of screening values for indoor air, sub-slab soil gas, and near-source soil gas in addition to VI modeling. Use of the screening values and other options as well as important terms is described below.

B. Definition and Use of Important Terms

Several of the terms used in this guidance may have multiple meanings within the context of the Land Recycling Program (LRP) or other DEP programs. Therefore, it is important that their intended use in this guidance be well-defined. The following definitions and uses are provided only for application under this VI guidance. They are presented in the order that allows the reader to make the best sense of each definition as opposed to alphabetical order.

- **<u>Hydrogeologic Zones:</u>**

    - ***Definition*** - When used in this guidance, the following hydrogeologic terms are related to one another as shown in Figure IV-1. In the *saturated zone*, all interconnected voids are filled with water. In practice, the top of the saturated zone is identified as the *water table,* which is the water surface at atmospheric pressure in appropriately constructed monitoring wells. *Groundwater* refers to water in the saturated zone, below the water table. The *capillary fringe* is the zone of tension saturation directly above the water table and its thickness is dependent on the soil type in which it occurs. The base of the capillary fringe is saturated, and soil pore space becomes progressively less filled with water upward from the water table. In the *vadose zone* above the capillary fringe the pores are not filled with water. The capillary fringe and the vadose zone are not readily distinguished in the field. The *unsaturated zone* is defined here as the zone above the water table, including both the capillary fringe and the vadose zone.

    - ***Use*** - These terms are used to define points of application for various screening values as shown in Figure IV-1 and applicable sampling intervals for soil, groundwater and near-source soil gas. They also pertain to the sources, fate, and transport of vapors in the subsurface.

- **<u>Point of Application (POA):</u>**

    - ***Definition*** - The locations in an inhabited building, the unsaturated zone, and the saturated zone where screening values are applied to evaluate VI.

    - ***Use*** - POAs guide the selection of indoor air, sub-slab soil gas, near-source soil gas, soil, and groundwater sampling locations. See Section IV.C.2. The relationship of the POAs to the building, the hydrogeologic zones, and the contamination are displayed in Figure IV-1. Sampling guidance for each POA is provided in Table IV-6 and Appendix IV-C.

- **<u>Acceptable Soil or Soil-like Material:</u>**

    - ***Definition*** - Any unconsolidated material containing some amount of organic material that occurs in the vadose zone above a potential VI source (soil and/or groundwater) that does not exceed the saturated hydraulic conductivity of sand or the net air-filled porosity of silt at residual water content, both as derived from Table 13 in U.S. EPA (2017). Natural soils and fill (including gravel) coarser than sand or with air-filled porosity greater than silt may not constitute acceptable soil. Conversely, fill material that is otherwise soil-like and does not exceed the characteristics described above may constitute acceptable soil-like material (e.g., mixtures of granular material comprised predominantly of sand, silt and clay with brick, block and concrete fragments where the granular material occupies virtually all of the interstitial space between the fragments).

- ***Use*** - A minimum of five feet of acceptable soil or soil-like material needs to be present between a potential VI source and foundation level to permit the use of the calculated groundwater screening values. The presence of acceptable soil or soil-like material is also a condition for using vertical proximity distances and applying separation distances for preferential pathways. Acceptable soil or soil-like material should NOT exhibit any of the following characteristics:

  - obvious contamination by a regulated substance of VI concern (e.g., staining or odors);
  - readings from an appropriate field screening instrument in the headspace above soil samples that are greater than 100 ppmv;
  - evidence of SPL; and
  - exceedances of soil screening values.

  Material that is suspected to be contaminated (via observation or from field equipment readings) may be sampled to determine if the soil screening values are exceeded. If screening values are not exceeded, then that soil can be regarded as an acceptable soil or soil-like material. Soil does not need to be sampled in areas beyond where soil has been directly impacted by a release of regulated substances to demonstrate an acceptable soil or soil-like material. For the purposes of the petroleum substance vertical proximity distances described below, the Department further defines acceptable soil or soil-like material as exhibiting greater than 2% oxygen in soil gas near the building slab.

- **Preferential Pathway:**

  - ***Definition*** - A natural or man-made feature that enhances vapor migration from a potential VI source to or into an inhabited building. An *external preferential pathway* is a channel or conduit that allows for a greater vapor flux than ordinary diffusion through vadose zone soil. A *significant foundation opening* is a breach in a building foundation or basement wall that may amplify the entry of subsurface vapors.

  - ***Use*** - A feature must be proximal to both the contamination and a building and have sufficient volume to be a preferential pathway. A significant opening in a building foundation, such as a dirt basement floor, can also act as a preferential pathway. A suspected preferential pathway should be investigated to determine if it results in an excess VI risk. The presence of a preferential pathway may preclude the use of proximity distances or certain screening values. Significant foundation openings may be sealed to inhibit vapor entry. Additional information regarding how to identify and evaluate preferential pathways is provided in Section IV.D and an example is shown in Figure IV-3.

- **Proximity Distance:**

  - ***Definition*** - The minimum distance, in the absence of a preferential pathway, which a potential VI source (see definition below) must be from a building or where a future inhabited building is planned to be constructed, to not pose a potential unacceptable VI risk.

  - ***Use*** - The presence of SPL or exceedances of soil or groundwater VI screening values within a proximity distance constitute a potential VI source. For petroleum substances, the horizontal proximity distance is 30 feet. The vertical proximity distance for petroleum hydrocarbons is five feet for adsorbed- or dissolved-phase contamination and 15 feet for SPL. The use of the vertical proximity distances requires the presence of acceptable soil or soil-like material. The horizontal proximity distance for non-petroleum contamination is 100 feet. There is no vertical proximity distance for non-petroleum contamination. Refer to Section IV.E for further guidance on proximity distances, and see Figure IV-4 for an example.

- **Separate Phase Liquid:**

  - ***Definition*** - That component of a regulated substance present in some portion of the void space in a contaminated environmental medium (i.e., soil or bedrock) that is comprised of non-aqueous phase liquid (NAPL). As such, SPL is distinct from the mass of a regulated substance in the contaminated environmental medium that is adsorbed onto or diffused into the soil or rock matrix, or dissolved in water or diffused into air that may also occupy a portion of that void space.

  - ***Use*** - SPL may be a potential VI source if it contains substances of VI concern. SPL may be analyzed to make this determination (Appendix IV-C, Section IV-C.7). The presence of SPL containing substances of VI concern provides one basis for limiting the applicability of screening values and the modeling assessment option. As shown in Figure IV-5, the presence of an SPL layer on the water table or SPL within a smear zone associated with such a layer precludes the use of the groundwater screening values or the modeling assessment option to evaluate groundwater contamination. This is the case whether the water table occurs in the soil or bedrock beneath a site. These options are available, however, beyond the limits of the SPL. In the unsaturated zone, soil contamination that includes interstitial residual SPL precludes the use of soil screening values and the modeling assessment option to evaluate soil contamination since the model assumes partitioning from adsorbed mass on the soil to pore water and then to soil gas, as opposed to direct evaporation from SPL to soil gas. The same is true for screening values based on the generic soil-to-groundwater numeric values since they also rely on this partitioning equation. However, near-source soil gas screening values may be used provided the sampling is performed above the SPL-impacted soil or groundwater (Figure IV-5). The soil gas version of the Johnson and Ettinger (J&E) model (Appendix IV-B) may also be used to evaluate near-source soil gas sampling results under the modeling assessment option.

- **<u>Potential VI Source:</u>**

  - ***Definition*** **-** Contamination by a regulated substance of VI concern under any one of the following conditions constitutes a potential VI source:

    - in the unsaturated zone, soil exceeding SHS screening values within proximity distances;

    - in the saturated zone, groundwater exceeding SHS screening values within proximity distances;

    - as SPL within proximity distances; and

    - associated with a preferential pathway.

  - ***Use*** **-** Identifies areas of a site where VI must be addressed through alternative assessment options, remediation, mitigation, or restrictions established in an environmental covenant. See Section IV.D and Figure IV-3 for preferential pathways and Section IV.E and Figure IV-4 for proximity distances. When utilizing the SSS VI evaluation process, a potential VI source is determined by exceedances of SHS soil and groundwater screening values (Section IV.K.4.).

C. Overview of the VI Evaluation Process

This guidance offers a flexible VI evaluation process for the SHS and SSS that provides multiple alternatives to the remediator. Figures IV-6 and IV-7 present flowcharts outlining the process for each standard, which is described in detail in the following sections. It is important to note that the purpose of Figures IV-6 and IV-7 is to illustrate how all of the steps in the VI evaluation process fit together. Figures IV-6 and IV-7 should not be used as your sole guide for performing a VI evaluation; rather, they should be used in conjunction with the text of this guidance.

The principal steps of a VI evaluation under the SHS (Figure IV-6) are:

- Develop the CSM and assess the presence of preferential pathways;
- Identify potential VI sources from exceedances of soil and groundwater screening values within proximity distances and/or the occurrence of SPL;
- Utilize alternative assessment options including screening near-source soil gas, sub-slab soil gas, or indoor air data, or conducting VI modeling;
- Mitigate buildings using activity and use limitations;
- Remediate the soil and/or groundwater contamination and reassess the pathway;
- Address the 25 Pa. Code Chapter 250 SHS requirements.

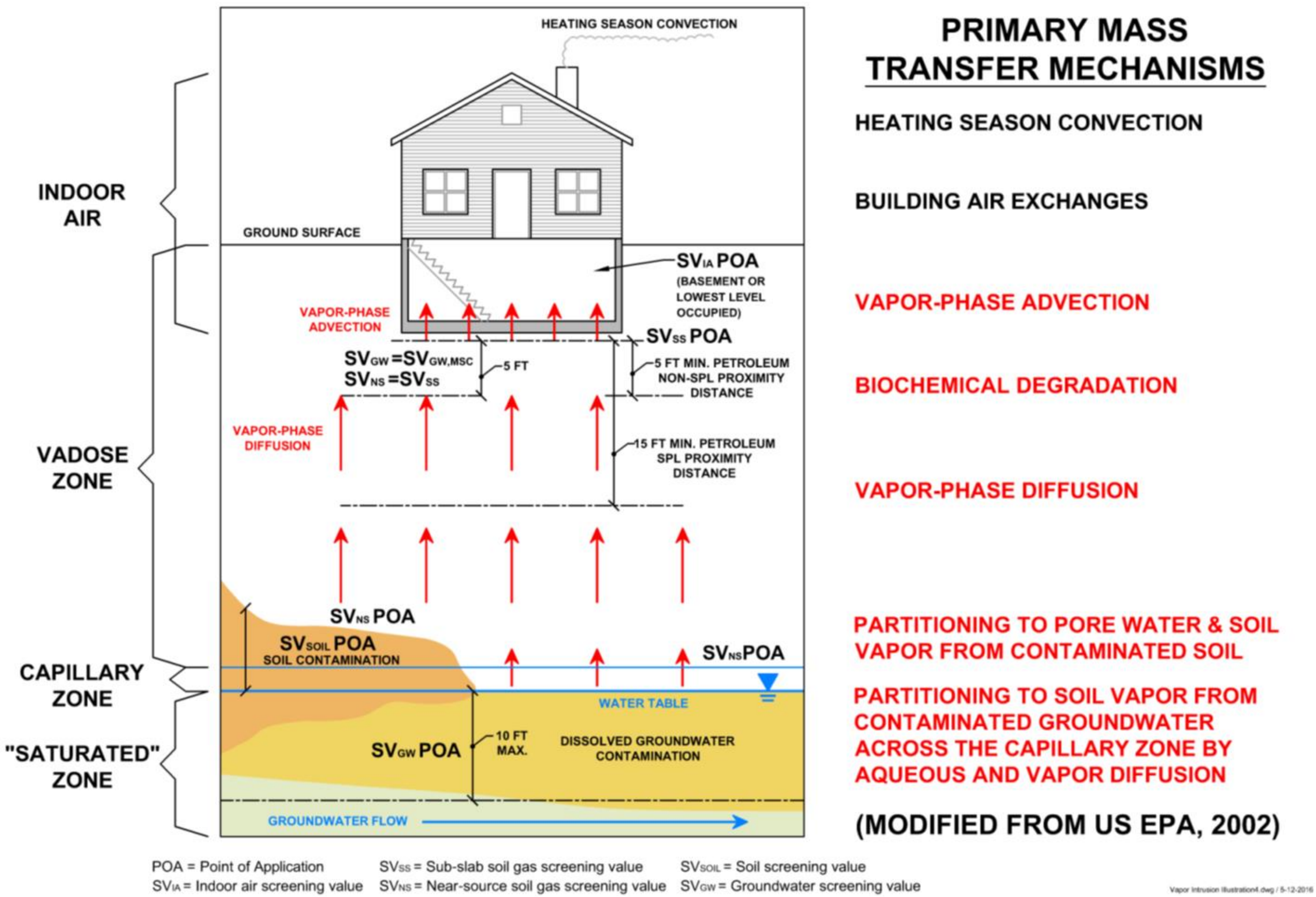
In most cases, all of the above steps will not be necessary and the remediator is not required to follow the process sequentially. For instance, buildings with a potentially complete VI pathway may be mitigated without the collection of soil gas or indoor air data. (See Section IV.K.1. for an overview of the SSS process.)

If conditions are identified that pose an immediate threat to human health or safety at any time in the VI evaluation process, prompt interim actions should be taken to protect human health. Such conditions include, but are not limited to, those that may result in injury or death resulting from inaction, such as acute toxicity to sensitive receptors (e.g., fetal cardiac malformations from TCE exposure (U.S. EPA, 2011a)), a fire or explosion hazard, or atmospheres that cause marked discomfort or sickness.

1. VI Conceptual Site Model

The VI CSM is central to the VI evaluation. The CSM is a representation of contaminant sources, migration pathways, exposure mechanisms, and potential receptors. The CSM drives the design of a sampling plan (Appendix IV-C), and as the CSM is revised, data gaps may be identified that will guide further sampling. The CSM is also a prerequisite for VI modeling (Appendix IV-B). The source description and contaminants of concern are components of the CSM supported by soil, groundwater, and possibly near-source soil gas data. The CSM development may also rely on sampling the vapor migration pathway (sub-slab soil gas) or receptor exposures (indoor air).

Figure IV-1: VI Screening Value POAs and Vertical Petroleum Proximity Distances



The goal of the VI CSM is to describe how site characteristics, such as subsurface and building conditions, might influence both the distribution of substances of VI concern in soil gas and the potential indoor air quality of structures in the vicinity of a soil or groundwater source of substances of VI concern. Concentrations of substances of VI concern in soil gas attenuate, or decrease, as the substances of VI concern move away from the source, through the soil, through the foundation, and into indoor air. The extent of attenuation is related to site conditions, building characteristics, and chemical properties. The soil vapor attenuation is quantified in terms of an attenuation factor defined as the ratio of indoor air concentration to source vapor concentration (Appendix IV-A).

The level of detail of the CSM should be tailored to the complexity of the site, the available data and the selected Act 2 remedial standard. For the VI pathway, complex relationships exist among the many factors that influence VI. Hence, multiple lines of evidence are often used to evaluate risks associated with the vapor pathway. Finally, it should be remembered that the CSM is a dynamic tool to be updated as new information becomes available during site characterization.

Some important elements of the VI CSM are included in the list below (California EPA, 2011a; Massachusetts DEP, 2011; U.S. EPA, 2012a, 2015a; Hawaii DoH, 2014). Some elements may not be known or pertinent to the case, and this does not imply a deficient CSM.

- Sources of contamination—origins, locations, substances, and concentrations; presence of SPL

- Transport mechanisms—route from source to indoor air, potential preferential pathways

- Subsurface and surface characteristics—soil type, depth to bedrock, heterogeneities; ground cover

- Groundwater and soil moisture—depth to water, water level changes, capillary fringe thickness, perennial clean water lens

- Fate and transport—biodegradation of petroleum hydrocarbons, transformation of substances into regulated daughter products

- Weather—precipitation, barometric pressure changes, wind, frozen ground

- Building construction—basement, slab on grade, or crawl space; a garage that is open to the atmosphere in between the ground surface and the occupied areas

- Foundation openings—cracks, gaps, sumps, French drains, floor drains

- Building heating and ventilation

- Background sources—indoor air contaminants, ambient air pollution

- Receptor types—residential, nonresidential, sensitive receptors; potential future development

2. Screening Values and Points of Application (POA)

SHS screening values for regulated substances of VI concern are published in Tables IV-1 through IV-5 for soil, groundwater, near-source soil gas, sub-slab soil gas and indoor air. These tables can be accessed on the VI page of the LRP website. Separate screening values are provided in these tables for residential and nonresidential uses of potentially affected inhabited buildings. In addition, there are two distinct nonresidential building categories: “nonresidential” and “converted residential.” The first category refers to buildings constructed for nonresidential use, and the second category refers to buildings that presently have a purely nonresidential use although they were originally constructed for residential use. An example is a dentist’s office in a converted home. The converted residential screening values are based on attenuation factors representative of residential structures but exposure factors for nonresidential settings. When a building has both residential and nonresidential uses (e.g., apartments over a retail store), the remediator may need to evaluate VI with both residential and nonresidential screening values.

The remediator should determine which structures at a site are inhabited and intended for human occupancy. Structures that are not routinely occupied, such as storage sheds or confined spaces, are not considered inhabited buildings. Structures that are not fully enclosed (e.g., carports, shelters) are also not inhabited buildings. Basements are generally regarded as an occupied space in a building; crawl spaces are not regarded as occupied space.

The POA for each of the screening values is shown on Figure IV-1. Groundwater screening values (SVGW) apply within the zone of groundwater saturation that will exhibit concentrations of regulated substances representative of concentrations at the water table. This is an interval within ten feet or less of the water table. Soil screening values (SVSOIL) apply throughout the volume of contaminated soil in the unsaturated zone. Near-source soil gas screening values (SVNS) apply just above an unsaturated zone soil VI source and just above the capillary fringe for a groundwater VI source. Near-source soil gas screening is also applicable to a preferential pathway, except in some cases if it penetrates the building foundation (Section IV.D). Sub-slab soil gas screening values (SVSS) apply immediately below the slab of a building potentially impacted by VI, whether the building has a basement or is slab-on-grade construction. Finally, indoor air screening values (SVIA) apply in the lowest occupied space of a potentially impacted building.

Screening values cannot be calculated for substances that have no inhalation toxicity data (Appendix A). Therefore, SHS and SSS VI evaluations are not required for substances without screening values. However, the remediator could choose to address the VI pathway by demonstrating that the concentrations for such substances are below practical quantitation limits (PQLs) or by installing a mitigation system. If soil concentrations are less than generic soil-to-groundwater numeric values and groundwater concentrations are less than used aquifer medium-specific concentrations (MSCs), then there is no potential VI source. In addition, proximity distances are applicable to substances that do not have screening values (see Section IV.E). The remediator could also evaluate VI using the SSS by developing toxicity values or utilizing published information (§ 250.605).

Table IV-6 summarizes data collection conditions for VI screening and how to apply the POAs. Methods for VI screening are described in Sections IV.F and IV.G and in Table IV-7. Appendix IV-A describes the methodology for developing the screening values. SSS screening is explained in Section IV.K.

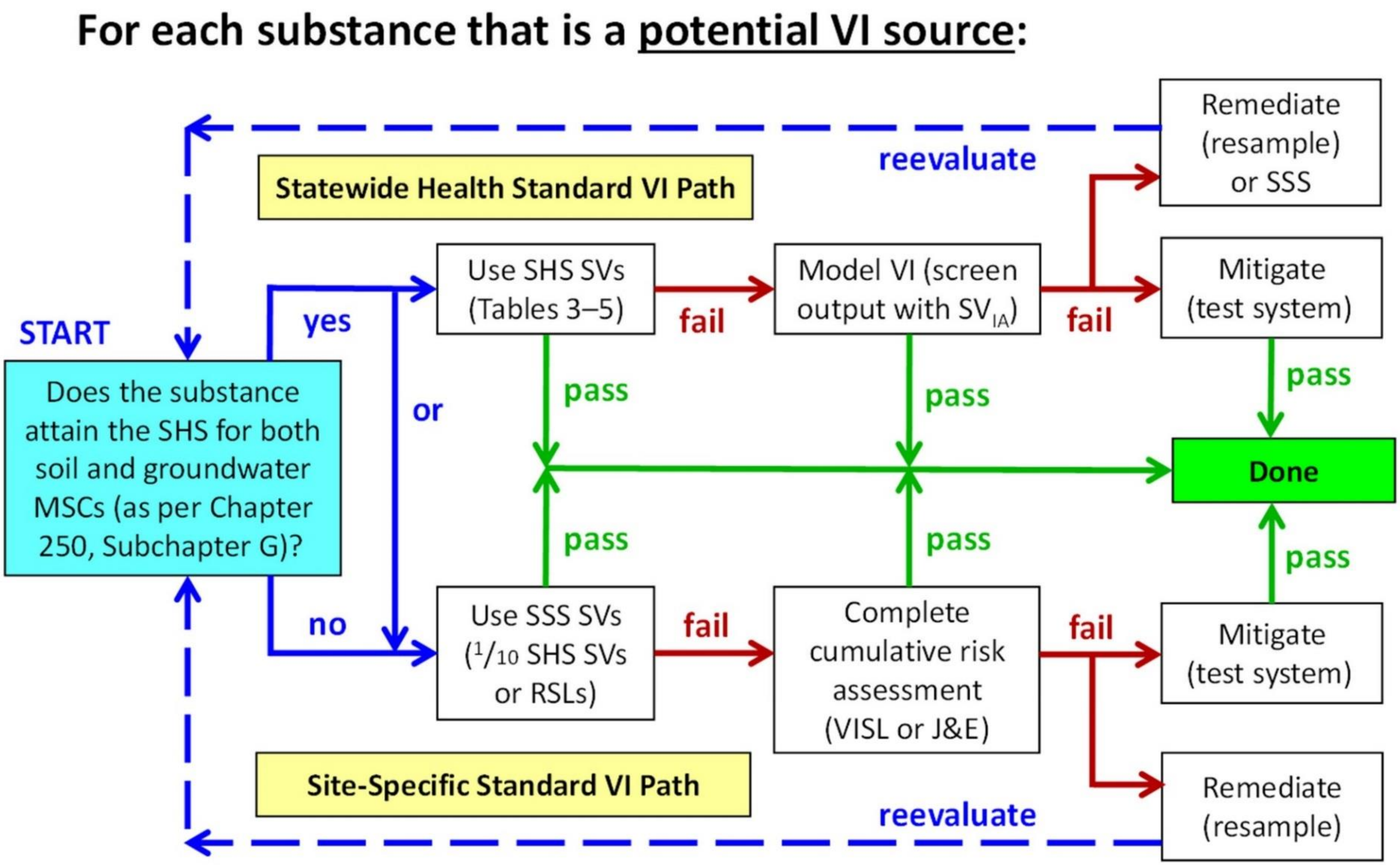
3. Guidelines for Evaluating VI Using a Combination of Standards

The VI pathway can be evaluated under the SHS, the SSS or a combination of both standards. When using a combination of standards, the VI pathway must be evaluated along with all of the other requirements of each standard being used. The screening values presented in Tables IV-1 through IV-5 were designed to be used only when attaining the SHS. However, under specific circumstances, adjusted SHS VI screening values can be used when evaluating VI under the site-specific standard. See Section IV.K.4 for additional detail on using screening values under the SSS.

The VI pathway must be assessed to satisfactorily attain the SHS for soil and groundwater (see 25 Pa. Code § 250.312(a)). Under the SHS, a remediator cannot evaluate the VI pathway without also evaluating soil and/or groundwater because Act 2 does not define indoor air or soil gas as environmental media. However, when using a combination of standards, a remediator can, for instance, evaluate soil under the SHS and groundwater under the SSS then separately evaluate VI entirely under the SSS. This is permissible because the SSS evaluates individual exposure pathways and Act 2 considers VI to be an exposure pathway, not an environmental medium. Under the SSS, a risk assessment is needed to evaluate the VI pathway if pathway elimination is not being used. The SHS does not evaluate individual exposure pathways separately so remediators cannot evaluate the VI pathway under the SHS if soil and groundwater are being evaluated under the SSS. The remediator may also choose to evaluate VI for each substance and medium using the process for the corresponding standard. Figure IV-2 shows how to treat substances independently with a combination of standards.

When using VI modeling under the SHS, the desired output is a predicted indoor air concentration (Appendix IV-B). This modeled concentration should be used in the evaluation of VI by comparing it to the associated indoor air screening value. The J&E model (U.S. EPA, 2017) also calculates risk values which should not be used for SHS evaluations. Use of risk calculations to evaluate VI is considered to be a risk assessment, which is a tool to be used under the SSS and is subject to additional reporting requirements and fees. If calculated risk values are used in the VI analysis, it will be assumed that the site is being remediated under a combination of standards and all associated fees and requirements of both standards will apply.

Figure IV-2: Representative Process to Evaluate VI with a Combination of Standards



Note: Figure must be used in conjunction with the text. Reference Section IV.C.3.

If the remediator uses the site-specific standard to evaluate the VI pathway, either solely or under a combination of standards, the SSS VI process described in Section IV.K should be used.

The following matrix illustrates the assessment needs for addressing the VI pathway using a combination of standards.

VI Assessment Needs When Using a Combination of Standards

Act 2 Standard Used to Address Soil and Groundwater	VI Evaluation Tools					
	Use Screening Values in Tables IV-1–5	Use 1/10 Screening Values in Tables IV-1–5*	Modeling	Risk Assessment	Mitigation with EC (i.e., pathway elimination)	Remediation
Statewide Health Standard (SHS)	✓		✓		✓	✓
Site-Specific Standard (SSS)		✓	✓	✓	✓	✓
Combination of Standards**	✓	✓	✓	✓	✓	✓

* When defining a potential VI source, a one-tenth adjustment to soil and groundwater screening values is not required for the SSS.

** Some media and/or substances may attain the SHS while others may attain the SSS.

D. Preferential Pathway Evaluation

A preferential pathway is a feature that increases the rate of vapor migration between a source and an inhabited building (see definition in Section IV.B). DEP defines two classes of preferential pathways. **An external preferential pathway** is a channel or conduit that allows for a greater vapor flux than ordinary diffusion through vadose zone soil (Figure IV-3). **Significant foundation openings** are breaches in the building foundation and basement walls that may enhance the entry of subsurface vapors. (Typical cracks, gaps, and utility line penetrations are not generally significant foundation openings; see Section IV.D.2.) The presence and significance of these features should be identified whenever possible during CSM development (Section IV.C.1.). When building access is not possible, other preferential pathway assessment and investigation techniques should be used, when available, to complete the CSM. Guidance for assessing and investigating external preferential pathways and significant foundation openings is provided in Sections IV.D.1. and IV.D.2., respectively. Guidance for using screening values when external preferential pathways and significant foundation openings are present is provided in Sections IV.F and IV.G.

Some recognized instances of preferential pathways include the following.

- **An external preferential pathway that does not penetrate the building foundation.** External preferential pathways can impact buildings through VI even if they do not penetrate the building foundation. If the external preferential pathway is not fully enclosed, vapors can migrate into a building via typical cracks and gaps in building foundations. An example is permeable backfill material (e.g., gravel or sand) around a utility line close to a building slab or a basement wall. The vapors can travel through the backfill material and then migrate through soil into the building via typical cracks and gaps in the building foundation. If a utility trench is backfilled with native soil, then it is unlikely to act as a preferential pathway. Another example is a drain line or cracked sewer pipe (Guo *et al.*, 2015). Water will travel through the line, but vapors can escape through cracks in the pipe and can migrate through soil into a building. Natural features such as open bedrock fractures could also transport vapors near a building.

- **A conduit (external preferential pathway) that enters the building.** This is when a utility line itself, not the backfill material, acts as a conduit for vapors. For example, liquid- and vapor-phase contamination can enter breaks in sewer and drain lines, permitting vapors to pass into buildings through failed plumbing components (Jarvela *et al.*, 2003; Pennell *et al.*, 2013).

- **A significant foundation opening without an external preferential pathway.** In this case, vapors migrate by diffusion through soil from the source to the building. All building foundations have minor cracks and gaps, but if there is a large opening—such as a dirt basement floor—then that opening will amplify the flux of vapors into indoor air. Sealing the opening(s) (e.g., pouring a concrete slab over the dirt floor) can eliminate the preferential pathway.

- **A combination of an external preferential pathway with a significant opening.** For example, vapors may migrate through gravel backfill around a utility line and then flow through a gap where the line penetrates the foundation. Sealing the gap would resolve VI through the significant opening but not the role of the external preferential pathway.

Reasonable effort should be made to determine whether external preferential pathways or significant foundation openings are present. It is recommended that remediators discuss how they plan to evaluate external preferential pathways and significant foundation openings with their Department Project Officer to ensure that all parties agree on the proposed approach.

As described later in this guidance, a preferential pathway may be eliminated by appropriate site remediation or mitigation actions.

1. External Preferential Pathways

Utility corridors and pipes are potential external preferential pathways common to most sites (U.S. EPA, 2015a, Sections 5.4, 6.3.2). When a preferential pathway is external to a building, the proximity distances to a source area (as described in Section IV.E) are insufficient to eliminate the source from consideration because proximity distances are based on the movement of vapors, and associated attenuation, through soil. Therefore, an area of contamination that exceeds screening values beyond a proximity distance from a building may be a potential VI source when an external preferential pathway is present (Figure IV-3). Heightened attention should be paid to external preferential pathways which may contain SPL.

For a subsurface feature that is external to a building, the following conditions allow it to be excluded as an external preferential pathway:

- Soil and groundwater contamination exceeding VI screening values is at least 30 horizontal or five vertical feet from the feature, and any SPL is at least 30 horizontal or 15 vertical feet from the feature; OR

- The feature is at least five feet away from the building foundation.

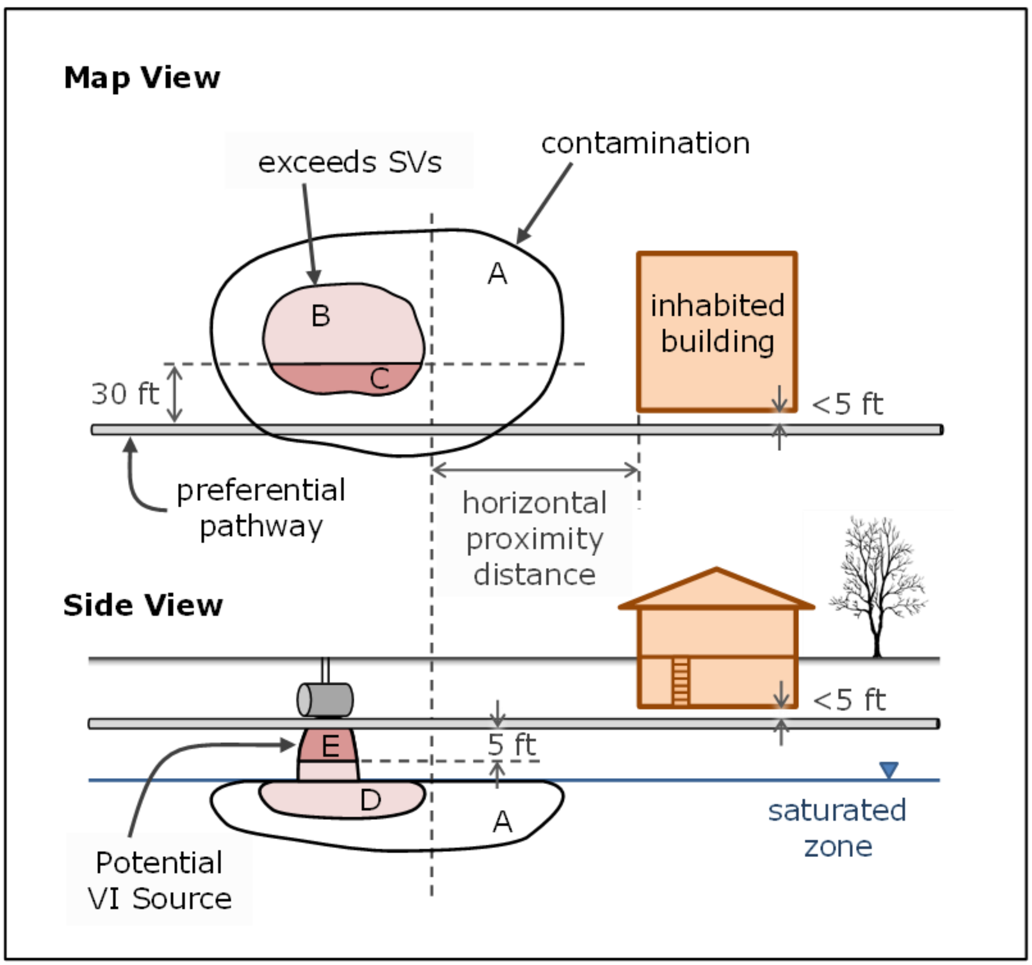
To exclude a feature as a preferential pathway, soil between the subsurface feature and the building foundation within the separation distances specified above should consist of acceptable soil or soil-like material. (For SPL, a minimum of five vertical feet of acceptable soil or soil-like material should be present within the overall 15-foot minimum separation.) As an example, consider an area of contaminated soil exceeding screening values which is beyond the horizontal proximity distance from a building. If a high-permeability backfilled trench passes through the soil contamination and near the building, but six feet of acceptable soil or soil-like material is present between the trench and the building foundation, then no further VI analysis would be necessary.

Figure IV-3 illustrates the evaluation of a potential external preferential pathway associated with a release from an underground storage tank (UST). (The assessment described here is not limited to USTs or petroleum hydrocarbons.) As shown in the separate map and side views, the distribution of contamination relative to the preferential pathway is important both horizontally and with depth. Zone A, shown in both views, is the volume of contaminated media identified in the site characterization. In the map view, the contamination in Zones B and C exceeds the soil and/or groundwater screening values, but these areas are beyond the horizontal proximity distance from the building.

However, Zone C represents the portion of contamination that exceeds screening values that is within 30 feet horizontally of the potential preferential pathway.

The side view of Figure IV-3 shows that some of the contamination is above the water table and some is below it. Zone D represents the contamination that exceeds soil and groundwater screening values but is greater than five feet below the potential preferential pathway, so the groundwater and soil contamination in Zone D is not of concern for vapor migration into the feature. Zone E, which is a portion of Zone C in unsaturated soil, is within five feet vertically of the feature, which means vapors from Zone E could enter the potential preferential pathway. Since the feature is separated by less than five feet from the building foundation, the feature is considered to be a preferential pathway with Zone E as a potential VI source. In this case, further VI assessment is required.

Figure IV-3: The Role of an External Preferential Pathway in the VI Evaluation



If a utility line trench is backfilled with native, low-permeability soil and the feature is intact (i.e., there is no evidence of the ability of groundwater or soil vapors to enter the pipe) then the feature is not considered to be an external preferential pathway. The Department does not expect remediators to prove that underground features do not have high-permeability backfill or are intact. However, if there is an indication that these conditions exist, then remediators should evaluate the feature further. For example, if the underground feature is the trench for a large diameter water line which is likely to be backfilled with gravel, it should be considered to be a potential external preferential pathway. If the underground feature is a small diameter fiber optic line, it is likely to have native soil backfill and the remediator could work under the assumption that it is not an external preferential pathway.

The Department recommends a progressive approach to evaluating external preferential pathways. The investigation can include sampling at the source (soil, groundwater, SPL, near-source soil gas), within the preferential pathway (soil gas or vapor), under the building (sub-slab soil gas), and within the building (indoor air). If a series of buildings is associated with one underground feature (e.g., a sewer line servicing multiple buildings along a street), then the buildings closest to the vapor source should be evaluated first. If it is determined that there are no VI concerns with the first building along the potential preferential pathway, then it is generally not necessary to evaluate the rest of the buildings along the line since they are increasingly farther away from the source.

Access to buildings is not always necessary for the evaluation of external preferential pathways because much of the pertinent information relates to their condition outside of the building. Examples of non-intrusive investigation techniques include a visual inspection of the exterior of the property for utility line entry points, an inspection of nearby streets and sidewalks for signs of underground utility lines and vaults, a Pennsylvania One Call notification, or a review of building plans.

The following recommendations pertain to assessing and screening external preferential pathways. (See Appendix IV-C, Figure IV-C-2 for an illustration.) The evaluation is described in terms of VI screening, but the remediator may also use the data with appropriate attenuation factors (Appendix IV-A) to carry out an SSS risk assessment (Section IV.K.5.). This is not a checklist of required evaluations; rather, if any of the following items is satisfied such that screening values or risk thresholds are not exceeded, then other items do not need to be examined.

- **Use of soil and groundwater screening values** – Contamination in the source area may be screened using soil and groundwater screening values unless SPL is present or contaminated groundwater enters the preferential pathway. Groundwater that is within a preferential pathway may be screened with used aquifer MSCs.

- **Use of indoor air modeling** – The default model for predicting indoor air concentrations (see Appendix IV-B) using soil, groundwater, or soil gas data may be used in the absence of an external preferential pathway. The default model should not be used if an external preferential pathway is present because this model is based on the diffusion of vapors through soil.

- **Use of near-source soil gas screening values** – If contaminated groundwater or SPL does not enter the preferential pathway, then near-source soil gas samples may be collected in the source area and the data screened with near-source soil gas screening values. Near-source soil gas data can also be screened against sub-slab soil gas screening values if an external preferential pathway or significant foundation opening is present or if a potential VI source is less than five feet below foundation level (see Section IV.G). This option is not available if the source is less than five feet below grade.

- **Soil gas sampling within a preferential pathway** – Soil gas samples may be collected in the preferential pathway (e.g., within trench backfill) between the source area and the building. These are not near-source soil gas samples (Section IV.G). They should be collected at a depth of at least 5 feet if the area is not paved and satisfy the other soil gas sampling criteria in this guidance (Table IV-6, Appendix IV-C). The data may be screened with sub-slab screening values.

- **Sampling within a sewer line** – If the preferential pathway is a sewer line or similar enclosed conduit that contains contamination, then the remediator may consider analysis of SPL, water, and vapor in the line. Flows and concentrations are likely to be highly variable, and there can be other sources of contamination in sewer lines. For these reasons, such sampling can be used as an informational line of evidence but not for screening.

- **Sub-slab sampling** – If the preferential pathway does not penetrate the foundation (e.g., trench backfill without a significant opening or a conduit that does not enter the building), then sub-slab samples through the foundation may be obtained (Section IV.G). This data may be screened with sub-slab screening values.

- **Sealed utility penetrations** – If the preferential pathway does penetrate the building, then the remediator should examine potential entry routes to indoor air. The basement or slab should be inspected for significant openings; foundation openings can be sealed (see Section IV.D.2.). If vapors travel within a sewer or drain line, then plumbing components could be inspected for integrity and repaired if necessary. Sampling should be performed to demonstrate that the pathway is incomplete, and this may require indoor air sampling.

- **Indoor air sampling** – Indoor air may be sampled at any time when there is an external preferential pathway, and the data may be screened with indoor air screening values (Section IV.G).

2. Significant Foundation Openings

Significant openings internal to a building's structure, such as a dirt basement floor, may enhance vapor entry (U.S. EPA, 2015a, Sections 2.3, 6.5.2). Typical cracks, gaps, and utility line penetrations on their own are generally not considered to be significant openings. In fact, all foundations, even new ones, will have these minor openings which will permit the ingress of some vapors if a potential VI source or an external preferential pathway comes close to a building foundation. Common foundation openings such as sealed sumps, French drains, and floor drains are not necessarily significant openings.

Significant foundation openings will have any one of the following characteristics.

- The combined area of openings in the foundation surface is more than five percent of the total foundation surface area (Appendix IV-A).

- There are direct indications of contaminant entry into the building through openings, such as seepage of SPL or contaminated groundwater, chemical odors, or elevated readings on a field screening instrument.

- An opening is connected directly to an external preferential pathway; for instance, a gap around a utility line penetration permits unimpeded vapor entry from the permeable backfill in the utility line trench.

The most effective way to evaluate a building for significant foundation openings is to gain access to the building and visually inspect the foundation and basement walls for utility penetrations and overall foundation condition. Remediators should try to access buildings whenever possible so that they can get the best possible information when evaluating significant foundation openings. However, visual inspections are not always possible. Sometimes property owners do not grant access to buildings. It is also possible for finished basements to have coverings on walls and floors (e.g., paneling, carpet, etc.) making openings difficult to see. If the remediator cannot gain access to a building to inspect for significant foundation openings, there are several assessment options presented below that do not require building access.

The Department recommends sealing significant foundation openings to inhibit the pathway (U.S. EPA, 2008, Section 3.2). Proper sealing should be done with durable materials as a long-term solution such that the former openings are no more transmissive to vapors than the rest of the foundation. Although sumps, when dry, are not generally considered to be significant openings, if a sump contains contaminated groundwater it may need to be sealed. Sealing openings is a building repair and is therefore not considered an activity and use limitation.

The recommendations listed below concern the assessment and screening of significant foundation openings. (See Appendix IV--C, Figure IV-C-3 for an illustration.) The evaluation is described in terms of VI screening, but the remediator may also use the data with appropriate attenuation factors (Appendix IV-A) to carry out an SSS risk assessment (Section IV.K.5.). Unless otherwise noted, the methods below cannot be used if contaminated soil, groundwater, or SPL is present within the building. This is not a checklist of required evaluations; rather, if any of the following items is satisfied such that screening values or risk thresholds are not exceeded, then other items do not need to be examined.

Options to assess significant foundation openings that do not require building access include the following.

- If there is no external preferential pathway, then the horizontal proximity distances discussed in Section IV.E are applicable to the potential VI source. Vertical proximity distances do not apply because they are based on attenuation across an intact slab.

- Soil data may be screened using generic soil-to-groundwater numeric values. Groundwater data may be screened with used aquifer MSCs. These screening values are acceptable even if contaminated soil or groundwater is present inside the building.

- Near-source soil gas samples may be collected in the source area. This data should be screened with sub-slab screening values or modeled.

- Modeling of soil, groundwater, or near-source soil gas data may be performed by assuming that no slab is present as a conservative scenario (as described in Appendix IV-B).

Options to assess significant foundation openings when building access is available and possible include the following.

- Sub-slab soil gas samples may be obtained if the building does not have a dirt floor. Sub-slab data should be screened with indoor air screening values.

- If foundation openings are sealed, then soil and groundwater data may be screened with standard screening values, near-source soil gas data may be screened with near-source soil gas screening values, and sub-slab soil gas data may be screened with sub-slab screening values (Sections IV.F and IV.G).

- Indoor air screening can be used at any time, even when contaminated soil, groundwater, or SPL is present within the building.

E. Use of Proximity Distances

The remediator may use horizontal and vertical proximity distances from existing or planned future inhabited buildings to identify potential VI sources (Figure IV-6). To accomplish this step, existing and/or future inhabited buildings are located and proximity distances from each of these buildings are delineated. Then, relying on the results of site characterization and/or postremediation sampling, any areas of contaminated groundwater at the water table and volumes of contaminated unsaturated zone soil that exceed applicable screening values within a proximity distance from an existing or future inhabited building are identified (Figure IV-4). Areas of SPL and areas predicted to exceed the screening values in a fate-and-transport analysis are identified. If there is no SPL present or soil or groundwater screening values are not exceeded within these proximity distances, then no VI sources are present to address under the SHS.

If there is contamination both within a proximity distance (e.g., Figure IV-4) and near a potential preferential pathway (e.g., Figure IV-3), then the remediator evaluates each area of contamination separately. There may be potential VI sources in both locations. The process outlined in Figure IV-6 would be repeated for each area of contamination and each potential vapor migration route. The use of proximity distances should also account for future plume migration as determined in a fate-and-transport analysis.

A proximity distance is the distance between an existing or future inhabited building and contaminated groundwater or soil within which VI could pose a risk. Proximity distances are a function of the mobility and persistence of the chemical as well as, in the case of petroleum substances, the depth of the source and the characteristics of the subsurface materials. There are distinct proximity distances for petroleum and non-petroleum regulated substances:

- For contamination associated with non-petroleum substances present in soil and/or groundwater, a horizontal proximity distance of 100 feet applies between the building and SPL or soil or groundwater screening value exceedances; and

- For soil and/or groundwater contamination associated with petroleum substances and related hydrocarbons, a horizontal proximity distance of 30 feet and a vertical proximity distance of five feet apply between the building and soil or groundwater screening value exceedances. For petroleum SPL, a further vertical proximity distance of 15 feet applies between the SPL and foundation level.

A vertical proximity distance is not applicable for non-petroleum substances. Proximity distances are based on the attenuation of vapors caused by diffusion through soil. A non-petroleum vertical proximity distance would be deeper than bedrock and groundwater at many sites, and it would not account for vapor advection through fractures.

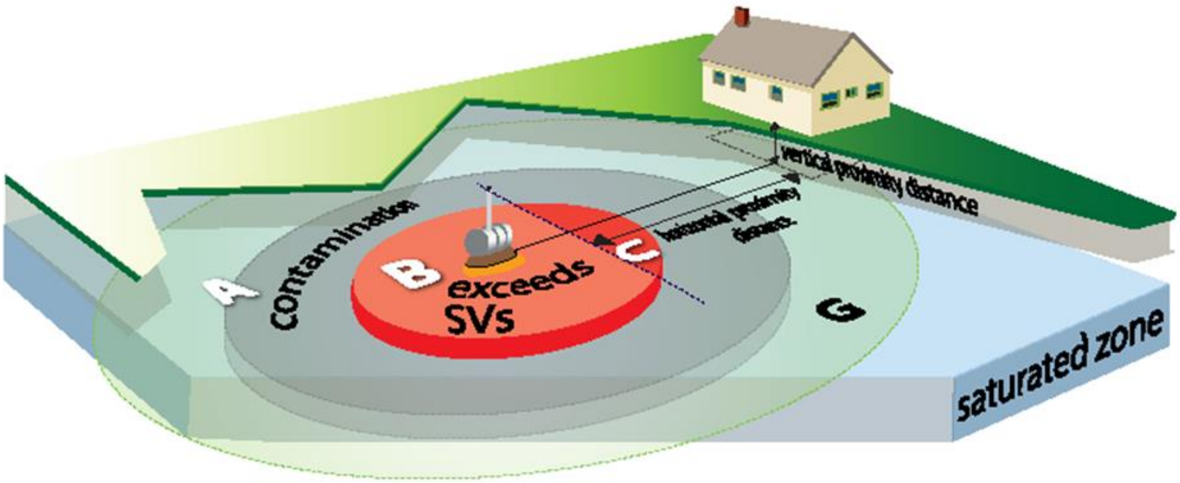
Note: The petroleum proximity distances apply to any petroleum substance, not just the hydrocarbons listed on the Petroleum Short List from the LRP Technical Guidance Manual. (Note that 1,2-dibromoethane, 1,2-dichloroethane, and MTBE are not petroleum hydrocarbons.) Petroleum substances are either aliphatic or aromatic compounds. Aliphatic compounds are composed of straight-chained, branched, or cyclic compounds and can be saturated (alkanes) or unsaturated (alkenes, alkynes, and others). Aromatic compounds have one or more conjugated, benzene or heterocyclic rings within their structures.

Petroleum substances are treated differently than non-petroleum substances in setting proximity distances because their high rates of biodegradation play a key role in diminishing the effects of VI (U.S. EPA, 2013, 2015b; ITRC, 2014). Petroleum hydrocarbons typically biodegrade under both anaerobic and aerobic conditions, with aerobic degradation occurring much more rapidly. Since soil oxygen content is generally higher in surface and shallow sub-surface soils, vapors from petroleum hydrocarbons biodegrade rapidly as they migrate upward through the soil column, reducing their concentrations prior to migrating into inhabited buildings. The Department defines an acceptable soil or soil-like material as having greater than 2% oxygen for purposes of applying proximity distances for petroleum substances. Measurement of soil oxygen content is not required unless there is reason to believe the soil is anaerobic (see Appendix IV-C for a recommended methodology). For instance, in the case of a large SPL plume or a large building overlying SPL, oxygen may be depleted and the 15-foot vertical proximity distance might not be protective for VI.

If only petroleum substances have been detected, the remediator determines the horizontal and vertical distance of the building foundation to the groundwater plume or soil contamination. If a current or future inhabited building is greater than or equal to 30 horizontal feet from an area of petroleum substance SPL or screening value exceedance, then there is adequate distance for aerobic biodegradation to occur to reduce the vapor concentrations to acceptable levels. Likewise, if there is greater than or equal to five feet of acceptable soil or soil-like material vertically between the bottom of a current and/or future inhabited building foundation and the top of the dissolved phase contaminated groundwater plume or unsaturated zone area of soil petroleum screening value exceedance, then there is adequate distance for biodegradation to occur to reduce the vapor concentrations to acceptable levels. The minimum vertical proximity distance is 15 feet for petroleum SPL, at least five feet of which should be acceptable soil or soil-like material. Vertical distances are calculated using the maximum groundwater elevation and the top of the measured or inferred SPL (smear zone or residual NAPL). If neither the horizontal nor vertical proximity condition is met, the remediator must evaluate VI further.

An example of the application of proximity distances is shown in Figure IV-4. (The assessment described here is not limited to USTs or petroleum hydrocarbons.) Zone A is the area of contamination identified in the site characterization. Zones B and C include groundwater contamination that exceeds screening values, and Zone G represents the horizontal proximity distance from Zones B and C. Zone C is the area within the horizontal proximity distance from the existing building, so it is the only portion of groundwater contamination that could pose a VI problem. Therefore, Zone C is a potential VI source, at least for non-petroleum substances, that requires additional assessment.

Figure IV-4: Use of Proximity Distances to Evaluate Potential VI Sources



The vertical proximity distance can be applied to the petroleum portion of the contamination. If this release contains only petroleum, then the contamination in groundwater is not of VI concern because groundwater is entirely below the vertical proximity distance line. The brown and orange zones below the tank represent contaminated soil that exceeds screening values, with the brown zone being the portion of contaminated soil that is above the vertical proximity distance. However, the contaminated soil is entirely beyond the horizontal proximity distance from the building. Therefore, if the contamination consists only of petroleum hydrocarbons, then there is no potential VI source and no further VI evaluation would be required for the currently occupied building.

F. Soil and Groundwater VI Screening

This section describes the development and application of soil and groundwater screening values to properly collected characterization and attainment data. Remediators may choose from the following soil and groundwater screening options.

Soil or Groundwater Screening	Additional Considerations
Soil concentrations < SVSOIL	Not available if SPL is present or if there is a significant foundation opening that has not been sealed.
Soil concentrations < generic soil-to-groundwater numeric value	Available with significant foundation openings. Not available if SPL is present.
Groundwater concentrations < SVGW	Not available if groundwater is less than five feet below foundation level, if SPL is present, if contaminated groundwater enters an external preferential pathway, or if there is a significant foundation opening that has not been sealed.
Groundwater concentrations < used aquifer groundwater MSC	Available if groundwater is less than five feet below foundation level, if contaminated groundwater enters an external preferential pathway, or if there is a significant foundation opening. Not available if SPL is present.

When evaluating VI for the Converted Residential Category using the generic soil-to-groundwater numeric values or the used aquifer groundwater MSCs, the non-residential values should be used since the current use of the property, and therefore the exposure parameters, are non-residential. A summary of screening value restrictions and the reasoning for the restrictions is provided in Figure IV-9.

1. Soil and Groundwater Screening Values

There are two sets of groundwater VI screening values: (1) at depths less than five feet below the building foundation, they are the Act 2 groundwater MSCs, and (2) at depths greater than or equal to five feet below the foundation, they are the values provided in Table IV-1. The soil VI screening values are provided in Table IV-2. Both Tables IV-1 and IV-2 are located on the Department's Vapor Intrusion web page. The derivation of these values is explained in Appendix IV-A. Table IV-6 describes important conditions for collecting soil and groundwater data to be used for VI screening.

The groundwater VI screening values (SV_{GW}) for depths less than five feet below foundation level are the used aquifer groundwater MSCs (Chapter 250, Appendix A, Table 1). The groundwater screening values for depths greater than or equal to five feet below foundation level are the higher of the groundwater MSCs and the calculated groundwater screening values based on empirical attenuation factors. The groundwater MSCs are considered suitable VI screening values because groundwater with concentrations at or below the MSCs is acceptable for use inside buildings (e.g., cooking, showering, cleaning, etc.). The maximum groundwater elevation should be compared to the 5-ft. depth criterion when selecting the applicable groundwater SVs (Table 1 or MSCs). Because the water table elevation changes over time, the VI investigation should recognize that soil in the intermittently saturated zone may be a VI source.

The soil VI screening values (SVSOIL) are the higher of the generic soil-to-groundwater numeric values (Chapter 250, Appendix A, Table 3B) and calculated soil screening values. Soil screening values may be applied at any depth below a building foundation. The calculated soil screening values are established using the acceptable risk-based indoor air concentrations and model-derived attenuation factors. The generic soil-to-groundwater numeric values are considered appropriate for VI screening because soil contamination that is unable to impact aquifers in excess of groundwater MSCs is also unlikely to pose an excess inhalation risk. Furthermore, VI sources associated with contaminated soil are typically not directly beneath buildings and they do not have an infinite lateral extent, making the assumptions of the model for calculating soil screening values conservative.

If a preferential pathway or significant foundation opening restricts the use of soil or groundwater screening values (Section IV.D), the remediator may still utilize groundwater MSCs and generic soil-to-groundwater numeric values for VI screening (unless SPL is present). These values may be applied even if contamination is present within the building (e.g., contaminated groundwater in a sump or contaminated soil in a dirt basement floor).

2. Soil and Groundwater Screening Methods

The presence of residual SPL in soil or mobile SPL in groundwater prevents the use of soil or groundwater screening values (Figure IV-5). (Although Figure IV-5 illustrates a UST, the criteria indicated are not limited to tank cases or petroleum hydrocarbon contaminants.) Screening values for soil and groundwater may be used to address VI for buildings beyond the appropriate horizontal proximity distance from SPL (Figure IV-6). If there is a preferential pathway or a significant foundation opening, then additional restrictions may apply (Section IV.D). The remainder of this subsection assumes that neither SPL nor preferential pathways prevent the use of soil and groundwater screening values. Potential sampling locations are illustrated in Appendix IV-C, Figures IV-C-1-3.

For purposes of screening soil and groundwater data to evaluate the VI pathway using one or a combination of remediation standards, the concentration of a regulated substance is not required to be less than the limits relating to the PQLs for a regulated substance in accordance with 25 Pa. Code § 250.701(c).

VI can be addressed by screening either characterization data or postremediation data for soil and groundwater. The soil and groundwater sampling results combined with applicable proximity distances are used in the screening analysis to determine if any potential VI sources are present (see Figure IV-4). Important conditions for screening are listed in Table IV-6. Among these are that groundwater must be sampled at or near the water table because it will be the source of vapors that can migrate to buildings.

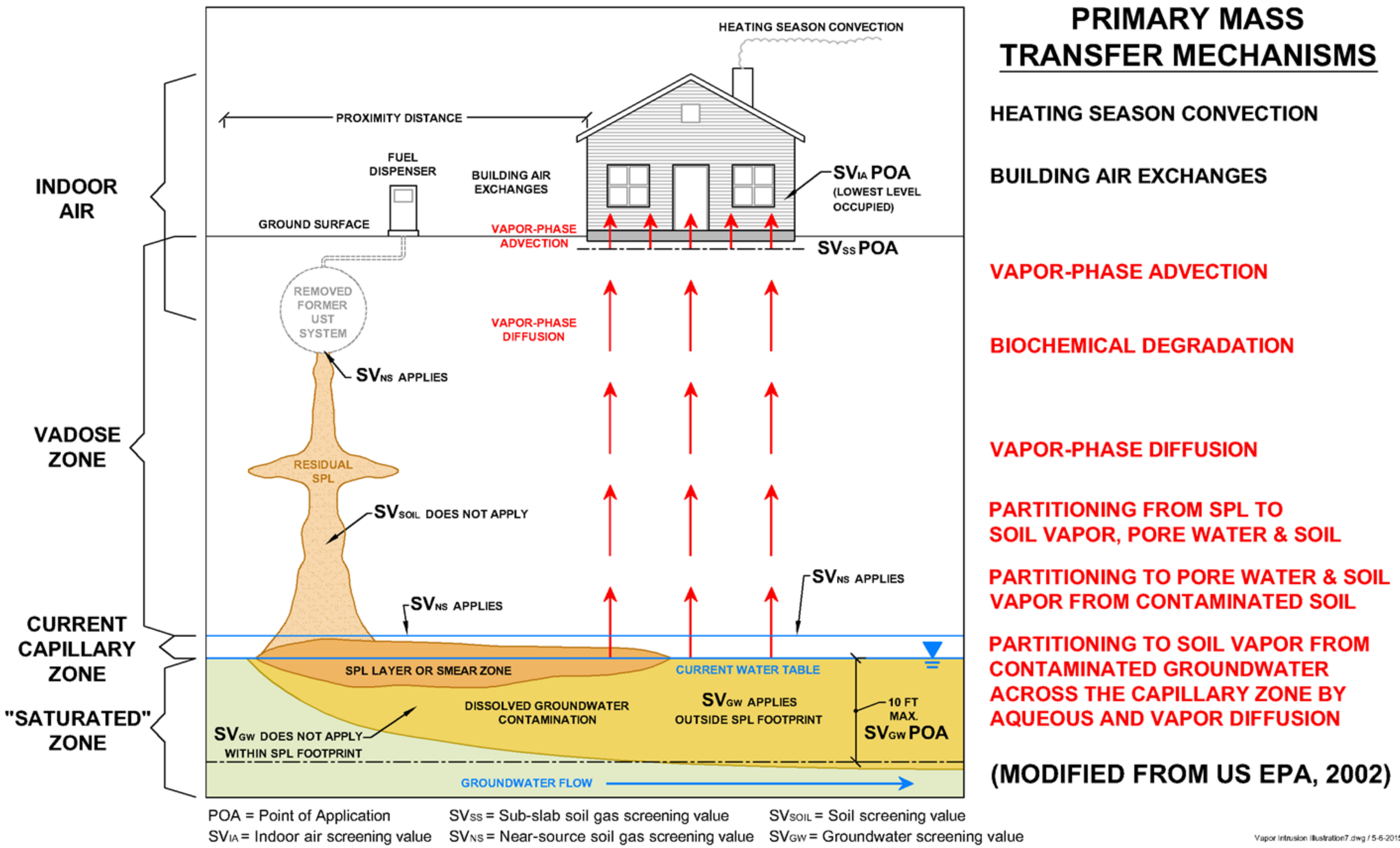
Proper characterization of soil and groundwater contamination is required at all Act 2 sites and this data alone may be sufficient for the VI assessment. If the site soil and groundwater characterization data are below MSCs without remediation being performed, then the site characterization data may be used for VI screening (Tables IV-6 and IV-7). No potential VI source exists if the applicable characterization data does not exceed soil and groundwater VI screening values (SVSOIL, SVGW). If the characterization data exceed MSCs but the remediator intends to pursue the SHS (i.e., by means of remediation), then the characterization data should be used to identify potential VI sources. If there are none, then no further VI evaluation is necessary.

When a potential VI source is remediated, VI screening may be performed with the soil or groundwater attainment data in accordance with the sampling methodologies and related statistical tests of Chapter 250, Subchapter G (Table IV-7). Note, however, that the groundwater data evaluated for VI is within the horizontal proximity distance from current or planned future inhabited buildings, not just at the point of compliance. For example, when at least eight consecutive quarters of groundwater attainment data have been collected, the remediator may apply the 75%/10x test to monitoring wells on the property and the 75%/2x test for off-site monitoring wells for VI screening (§ 250.707(b)(2)(i)). Fewer than eight consecutive quarters of data may be screened for no exceedances with Department approval pursuant to § 250.704(d).

For soil remediated *in situ*, the POA is throughout the volume of soil originally determined to exceed the soil screening value(s) (i.e., the potential VI source). For soil excavated and removed from the site, the POA is the margins of the excavation.

The number and locations of groundwater monitoring wells are selected on the basis of their representativeness with respect to water quality in the relevant portion of the plume. For groundwater on developed properties, the POA is throughout the area of a plume that has been identified as a potential VI source prior to VI assessment or remediation. For groundwater on undeveloped properties or in undeveloped portions of properties where future inhabited buildings may be constructed, the POA is throughout the area of a plume that has been identified as a potential VI source prior to VI assessment or remediation and is not within an area subject to an AUL restricting construction of future inhabited buildings.

Figure IV-5: Effect of Separate Phase Liquid on the Applicability of Screening Values



G. Alternative VI Assessment Options

The purpose of the VI assessment options is to gather and evaluate enough information to adequately determine whether a potential VI source is present that must be addressed under the SHS. Remediators may choose from the following alternative assessment options.

Alternative Assessment Option	Additional Considerations
Near-source soil gas concentrations < SVNS	Not available if contaminated groundwater or SPL enters a preferential pathway, if there is a significant foundation opening, if an external preferential pathway penetrates the building foundation, or if a potential VI source is less than five feet below foundation level.
Near-source soil gas concentrations < SVSS	Available for preferential pathways and significant foundation openings, and available for a potential VI source less than five feet below foundation level, but not if it is less than five feet below grade.
Sub-slab soil gas concentrations < SVSS for existing buildings	Not available if an external preferential pathway penetrates the building foundation or if there is a significant foundation opening that has not been sealed.
Sub-slab soil gas concentrations < SVIA for existing buildings	Available if a preferential pathway penetrates the foundation or there is a significant foundation opening.
Indoor air concentrations < SVIA at existing buildings	No restrictions.
Vapor intrusion modeling using acceptable input parameters	Not available for soil or groundwater where an external preferential pathway or SPL is present. Not available for near-source soil gas if an external preferential pathway is present.

A summary of screening value restrictions and the reasoning for the restrictions is provided in Figure IV-9.

1. Soil Gas and Indoor Air Screening Values

The near-source soil gas screening values (SVNS) are provided in Table IV-3, the sub-slab soil gas screening values (SVSS) in Table IV-4, and the indoor air screening values (SVIA) in Table IV-5. All three of the Tables are located on the Department's Vapor Intrusion web page. The derivation of these values is explained in Appendix IV-A. Table IV-6 describes important conditions for collecting soil gas and indoor air data to be used for VI screening. Detailed information on sampling methodologies is provided in Appendix IV-C.

The near-source soil gas screening values are based on attenuation factors derived from modeling and endpoint concentrations equal to the acceptable indoor air screening values. Near-source soil gas is measured within or directly above an unsaturated zone soil source or directly above the capillary fringe for a groundwater source. Screening near-source soil gas data against near-source soil gas screening values is an option when a preferential pathway does not penetrate the building foundation (Section IV.D). Vapor concentrations measured in near-source soil gas are theoretically the highest possible concentrations because they are directly adjacent to the source.

The sub-slab soil gas screening values are based on EPA's empirical attenuation factors and endpoint concentrations equal to the acceptable indoor air screening values. As a result, screening sub-slab soil gas data against sub-slab screening values cannot be done in the presence of a preferential pathway that penetrates the building foundation (Section IV.D). Sub-slab samples are collected immediately below the foundation, and their proximity to the receptor makes them a reliable indicator of potential exposures. Sub-slab sampling may also be done beneath intact paved areas large enough to be representative of future inhabited buildings without basements.

The indoor air screening values (SV_{IA}) are calculated using the inhalation risk equations in EPA's risk assessment guidance. Indoor air data represent conditions that are as close to the receptor as possible and, therefore, provide the most accurate representation of concentrations at the point of exposure. Indoor air can be influenced by other vapor sources inside or outside of the structure not attributable to soil or groundwater contamination. This can lead to false positive indoor air detections which increases uncertainty in VI investigations. The likelihood of false negative indoor air detections is relatively low. If the remediator suspects that there are indoor sources of vapor contamination at the site, indoor air sampling is not recommended.

2. Soil Gas and Indoor Air Screening Methods

Near-source soil gas, sub-slab soil gas, and indoor air data may be acquired during the site characterization phase or following soil or groundwater remediation. VI sampling requirements and statistical tests are not specified in 25 Pa. Code Chapter 250. Therefore, the number of sample points for addressing VI is determined based on the CSM, professional judgment, and the guidance in this document. DEP recommends a minimum of two sample locations per building for sub-slab soil gas, and indoor air sampling and at least two near-source soil gas sample locations at the source. Potential sampling locations are illustrated in Appendix IV-C, Figures IV-C-1-3.

The characterization data and CSM are used to determine the size and location of the area of potential VI sources. For most sites, sampling should be biased toward the most contaminated areas or the most appropriate locations for the sample type. When a large number of samples is necessary, the sample locations should be determined by an appropriate randomization method (e.g., systematic random sampling, stratified random sampling, etc.) as described in the RCRA SW-846 manual (U.S. EPA, 2007, Chapter 9). These decisions are made on a case-by-case basis. Other important conditions for collecting data for the VI evaluation are listed in Table IV-6 and Appendix IV-C.

The presence of SPL does not prevent the use of near-source soil gas or sub-slab soil gas screening values (Figure IV-5) unless the SPL has entered an external preferential pathway or significant opening. Indoor air screening values are available even in circumstances when SPL, an external preferential pathway, and/or a significant opening are present.

The POA for near-source soil gas is at least five feet below grade (Figure IV-1). If near-source soil gas samples are collected at least five feet below foundation level, then the data may be screened using near-source soil gas screening values (SV_{NS}). If near-source soil gas samples are collected less than five feet below foundation level, then the data may be screened using sub-slab soil gas screening values (SV_{SS}). Acceptable soil or soil-like material should be present between the sampling depth and the building foundation.

For near-source soil gas above a groundwater source, the number and locations of soil gas vapor probes are selected on the basis of their representativeness with respect to water quality in the relevant portion of the plume. When the water table occurs in soil, the POA for near-source soil gas is nominally within one foot of the top of the capillary fringe or as close to this interval as sampling can reasonably be performed given typical fluctuations in groundwater levels. Theoretical capillary fringe thicknesses for different soil types are provided in Appendix IV-C, Table IV-C-1. When the water table occurs within bedrock, the POA for near-source soil gas is within one foot of the soil-bedrock interface.

Sub-slab and indoor air samples should be biased toward areas of the building with the greatest expected VI impact. Indoor air samples should be collected in the basement, if present, or the lowest occupied floor. DEP recommends obtaining a concurrent ambient air sample (in addition to at least two indoor samples) to account for potential background contamination from outside the building.

The indoor air data collected for screening purposes should be collected when the daily average outdoor temperature is at least 15°F (8°C) below the minimum indoor temperature in the occupied space and when the heating system is operating normally. Indoor air sampling can be performed during warmer seasons, but that data should be used for informational purposes only and should not be used to screen out the VI pathway. If a building is not heated, then indoor air samples collected at any time of the year may be used for screening.

The remediator may initially characterize VI with a minimum of two rounds of near-source soil gas, sub-slab soil gas, or indoor air sampling (Table IV-7). This data will normally be collected during the site characterization, but it can also be obtained following soil or groundwater remediation or during attainment monitoring. The two sampling events should occur at least 45 days apart for statistical independence.

When preparing a sampling plan many factors should be considered (Appendix IV-C). Two sample locations and two sampling rounds will not be sufficient at all sites and for all buildings. Spatial and temporal variability of VI data is significant, and small data sets have the potential of under-representing true mean concentrations and inhalation risks. Larger buildings will likely require more sample locations as source concentrations, vapor entry rates, and indoor ventilation rates will vary across the structure. If an as-yet undeveloped area is being evaluated, then there will need to be enough near-source soil gas points to encompass future building construction. Because petroleum hydrocarbons tend to pose a relatively low risk for VI owing to bioattenuation, DEP regards chlorinated VOCs as a greater concern for potential under-sampling.

If the near-source soil gas, sub-slab soil gas, or indoor air characterization data are equal to or less than the screening values (SV_{NS}, SV_{SS}, SV_{IA}), then no potential VI sources are present to address under the SHS. (However, be aware of potential restrictions associated with preferential pathways, as described above.) If there are screening value exceedances, then the remediator has two options to continue evaluating the VI pathway. One option is to collect sufficient near-source soil gas, sub-slab soil gas, or indoor air data to apply statistical screening tests (Table IV-7). The other option is to select another assessment or remedial alternative (Figure IV-6). For example, if sub-slab sample results exceed screening values, then indoor air samples could be collected and screened, a mitigation system could be installed, or a risk assessment could be performed under the SSS. In this case, the remediator should not collect near-source soil gas samples because they are farther from the point of exposure.

To screen near-source soil gas, sub-slab soil gas, and indoor air data using statistical tests, at least eight data points must be obtained at the existing or planned future building. This data can be a combination of sample locations and sampling rounds as long as there are at least two rounds collected at all of the same points (e.g. two rounds of sampling at four locations or four rounds of sampling at two locations). Sample locations should be biased toward areas with the greatest expected VI impact. The following soil and groundwater statistical tests of § 250.707(b) may be applied to the collective data from the near-source soil gas, sub-slab soil gas, or indoor air sampling at each building:

- Seventy-five percent of all samples shall be equal to or less than the applicable VI screening value with no individual sample exceeding ten times the screening value on the property (75%/10x test) and two times the screening value beyond the property boundary (75%/2x test).

- As applied in accordance with EPA-approved methods on statistical analysis of environmental data, as identified in 25 Pa. Code § 250.707(e), the 95% upper confidence limit of the arithmetic mean shall be at or below the applicable VI screening value (95% UCL test). The minimum number of samples is specified by the method documentation.

As an example, if there are two sub-slab sampling points in an onsite building that have been sampled four times, the 75%/10x test may be applied to those eight sets of analytical results. These tests should not be used for combinations of near-source and sub-slab data or soil gas and indoor air data. Data should be collected concurrently from all sample locations at the building.

Near-source soil gas, sub-slab soil gas, and indoor air sampling rounds should be performed in subsequent quarters or twice per quarter. Samples should be collected at least 45 days apart. DEP may allow alternative sampling frequencies with prior written approval.

3. Vapor Intrusion Modeling

VI modeling can be used to predict indoor air concentrations in current or future buildings. Modeling of any kind has an inherent amount of uncertainty involved, but, if acceptable input parameters are used with measured data, it can be a useful tool. The J&E model is currently the most widely used and accepted VI model available (Appendix IV-B). The J&E model does have its limitations, namely it does not account for bioattenuation of petroleum hydrocarbons in its predictions. As a result, other models, such as BioVapor, can be used to predict indoor air concentrations at petroleum VI sites. Each model has its own set of conservative default input parameters that should be used when applicable. However, some parameters such as soil type, depth to the source, and building size can be adjusted to site-specific conditions.

Soil and groundwater data cannot be used for modeling if an external preferential pathway or SPL is present. In addition, near-source soil gas data may not be modeled when there is an external preferential pathway. However, near-source data may be collected above SPL and modeled. The J&E model also may be applied when a building has significant foundation openings, such as a dirt floor, as described in Appendix IV-B.

For sites that are completely or partially undeveloped, many of the modeling input parameters will have to be estimated. The remediator can use information from building plans, if available, and conservative parameter values. A list of input parameters that can be adjusted based on site conditions is provided in the modeling guidance presented in Appendix IV-B.

Pennsylvania versions of EPA's J&E model spreadsheets are available on DEP's website. They should be used for Act 2 and storage tank corrective action J&E modeling. These versions have DEP default parameter inputs as well as physical/chemical properties and toxicological values from Chapter 250, Appendix A, Table 5A. It is important to remember that when using VI modeling under the SHS, the desired output is a predicted indoor air concentration.

This modeled concentration should be used in the evaluation of VI by comparing it to the associated indoor air screening value. The J&E model can calculate risk values, but these should not be used for SHS evaluations. Use of risk calculations to evaluate VI is considered to be a risk assessment, which is a tool to be used under the SSS, and is subject to additional reporting requirements and fees. If calculated risk values are used in the VI analysis, then the site is being remediated under a combination of standards and all associated fees and requirements of both standards will apply.

H. Mitigation and Activity and Use Limitations

Properly installed and maintained mitigation measures eliminate or greatly reduce VI exposure and therefore remain protective regardless of changes in subsurface concentrations or toxicity levels. Many areas of Pennsylvania have high levels of naturally occurring radon gas, which can pose a significant public health threat. VI mitigation systems not only address potential VI concerns associated with the release of regulated substances at remediation sites, but also provide additional public health benefits associated with reducing the significant threat caused by naturally occurring radon gas. However, mitigation systems may not be feasible in all cases. The feasibility of using a mitigation system to address VI impacts for existing buildings and planned future buildings will depend on the specific details of the site, the building, and the design of the system. Mitigation most commonly involves the installation of an active sub-slab depressurization system (similar to a fan-driven radon abatement system) (U.S. EPA, 2008).

For residential buildings, standard radon-type mitigation systems should be installed by individuals or firms certified by DEP for radon mitigation pursuant to 25 Pa. Code Chapter 240 of the regulations (Pennsylvania DEP, 1997). Standard residential systems do not need to be designed or approved by a Licensed Professional Engineer. The remediator is not required to perform indoor air confirmation sampling. Active sub-slab depressurization systems can be tested by measuring pressure differentials to demonstrate depressurization throughout the slab or by collecting one or more indoor air samples that do not exceed screening values. The system should be tested following its installation, if a significant modification or repair is made, after a change in ownership, or upon request by the Department. Performance and testing guidelines for these systems are provided in Appendix IV-C, Section IV-C.9.

Other engineering controls that mitigate VI, such as the installation of a vapor barrier, can be used to prevent VI. Vapor barriers should be designed and manufactured for use in VOC mitigation. The material should be chemically resistant and have demonstrated low permeability for the VOCs present. Moisture barriers typically do not meet these criteria. Vapor barriers should be installed and tested pursuant to the manufacturer's recommendations.

The following AULs can be used to maintain the attainment of the SHS.

- Using mitigation as a means of eliminating or reducing vapor migration
- Committing to mitigation (as described below) of currently planned future inhabited buildings on the property.
- Committing to evaluate potential VI sources at the time currently planned future inhabited buildings are constructed. The results of the evaluation should be submitted to DEP for review.
- Prohibiting construction of basements or future residential and/or nonresidential inhabited buildings in a specified area of the property where the VI pathway may be complete.

If there are no plans for future construction of inhabited buildings at the site, the remediator may still choose to use an AUL to address possible future VI issues. In this case, controls would not be required to maintain the SHS, but the remediator may wish to have additional protection for unplanned uses. Any combination of the above four conditions may be utilized. For example, Figure IV-4 depicts the proximity distance evaluation for a current building (Section IV.E). Groundwater contamination in Zones B and C and the soil contamination zone in orange also represent potential VI sources at the site if a future inhabited building is constructed within the applicable proximity distances from these areas. Zone G, indicated by the outer dotted perimeter, is the area within the horizontal proximity distance from the potential VI source (Zones B and C) which exceeds soil and/or groundwater screening values. The remediator could evaluate VI within Zone G, for instance, with near-source soil gas sampling or modeling. Alternatively, the remediator could incorporate AULs requiring future evaluation if a new building is constructed, preemptive mitigation of new buildings, or the prohibition of occupied buildings within Zone G.

As required by the Uniform Environmental Covenants Act (Act 68 of 2007, 27 Pa. C.S. §§ 6501–6517, “UECA”) and the accompanying regulations (25 Pa. Code Chapter 253), engineering and institutional controls needed to address the VI pathway to demonstrate attainment of the SHS or SSS are to be in the form of an environmental covenant, unless waived by DEP. The environmental covenant should include language that requires the property owner to maintain the VI mitigation system. In most cases the environmental covenant does not need to include language requiring periodic indoor air sampling or reporting to DEP. However, mitigation systems that have electric motors or other moving parts, such as sub-slab depressurization systems, will eventually break down or wear out and will need periodic monitoring to ensure they are operating properly. DEP should be notified in the event of a property transfer, if there is a problem with the system, or upon request by DEP.

Natural attenuation resulting in decreasing concentrations of soil and groundwater contamination over time can occur at sites with releases of substances that naturally degrade in soil. At sites for which an environmental covenant was used to address the VI pathway from potential VI source(s), it may include a provision that allows for termination of the covenant or the AULs related to VI if the remediator can demonstrate to DEP that the AUL(s) is/are no longer necessary under current site conditions to comply with the selected standard.

The following language is provided as a guide for environmental covenants with only one AUL related to VI:

> *This Environmental Covenant may be terminated if: (1) an evaluation is performed that demonstrates that mitigation to address a complete or potentially complete vapor intrusion pathway is no longer necessary and appropriate, and (2) the Department reviews and approves the demonstration.*

Alternatively, the following language is provided as a guide for environmental covenants with multiple AULs including AULs unrelated to VI:

> *This Environmental Covenant may be modified with respect to the VI AUL if: (1) an evaluation is performed that demonstrates that mitigation to address a complete or potentially complete vapor intrusion pathway is no longer necessary and appropriate, and (2) the Department reviews and approves the demonstration*

I. Remediating and Reassessing the VI Pathway

Under some circumstances mitigation may not be practical or cost effective. The remediator may choose to perform further soil and/or groundwater remediation to address the VI pathway. Following the remediation, additional data must be collected for VI screening. This can include new soil or groundwater attainment data, or it can consist of soil gas or indoor air sampling data. The postremediation data is evaluated following the process illustrated in Figure IV-6 and described in Sections IV.F and IV.G.

The timing of the remediation is an important consideration. If there is an excess VI risk but remediation is a long-term action (such as a pump-and-treat system), then excess inhalation risks may exist for an unacceptably long time. In such cases the remediator is responsible for implementing interim measures to protect human health.

J. Addressing 25 Pa. Code Chapter 250 Requirements

The final step in the process flowchart on Figure IV-6 is to address the requirements of 25 Pa. Code Chapter 250 with respect to VI. This step is necessary to demonstrate compliance with the SHS in order to receive liability protection under Act 2. The submitted report should include a description of the CSM for VI with a preferential pathway assessment. The flowchart endpoint can be reached in the following three ways, and compliance should be documented in either the FR (Chapter 250) or the site characterization and/or remedial action completion reports (Chapter 245):

- **Soil and Groundwater Screening.** The remediator may screen soil and groundwater concentration data within proximity distances of existing or planning buildings. If no potential VI sources are identified, then no further analysis is necessary. Maps and cross sections that show the spatial relationship between soil and groundwater data, any SPL, any potential preferential pathways, and existing or planned future inhabited structures should be used to document that no potential VI sources are present. Applicable proximity distances should be shown on these exhibits. Soil and groundwater data should be tabulated and compared to applicable screening values. If statistical methods for screening the data are used, they should be explained.

- **Alternative Assessment Options.** The remediator may evaluate the VI pathway by screening near-source soil gas, sub-slab soil gas, or indoor air data, or by performing modeling. If the site data satisfy the screening criteria, then no further analysis is necessary. Sampling locations relative to potential VI sources and existing or planned future inhabited buildings should be shown on maps. The methodology for collecting the samples should be described and the results tabulated with applicable screening values. If statistical methods for screening the data are used, they should be explained. Refer to Appendix IV-B for recommended modeling documentation.

- **Mitigation and Environmental Covenants.** The remediator may address the VI pathway by installing a mitigation system or implementing activity and use limitations in an environmental covenant. Installation of the mitigation system must be documented, for instance, with plans, manufacturer specifications, and the installer’s certification. Testing to demonstrate the system’s effectiveness should be performed (Appendix IV-C) and the results described in the report. If mitigation is successful, no further analysis is required. The conditions to be included in a covenant to maintain the remedy should be detailed in the report.

When a potential VI source in soil or groundwater is remediated, new samples should be collected to reevaluate the VI pathway and data should be presented as described above. If the remediator chooses the SSS to address VI, then the remediator should follow the process and reporting described in Section IV.K.

K. Evaluating the VI Pathway Under the Site-Specific Standard

1. Overview

A remediator may perform a SSS VI evaluation for one of three reasons:

- The remediator has selected the SSS for substances of VI concern in soil and/or groundwater;
- Soil and groundwater attain the SHS MSCs, but the VI pathway is not satisfactorily addressed by the SHS VI assessment process described previously in this guidance;
- The remediator wishes to evaluate VI for substances to which the SHS process cannot be applied, such as mercury, cyanide, or organics without inhalation toxicity values.

The SSS VI evaluation process shares many elements with the SHS process, but the screening values are not the same and a human health risk assessment is an option. The SSS VI process is outlined in Figure IV-7. It is important to note that the purpose of Figure IV-7 is to illustrate how all of the steps in the VI evaluation process under the SSS fit together. Figure IV-7 should not be used as your sole guide for performing a VI evaluation; rather, it should be used in conjunction with the text of this guidance. The principal steps of a VI evaluation under the SSS are:

- Develop the CSM and assess the presence of preferential pathways.
- Identify potential VI sources from exceedances of SHS soil and groundwater screening values within proximity distances and/or the occurrence of SPL.
- Screen near-source soil gas, sub-slab soil gas, or indoor air data.
- Perform a cumulative human health risk assessment, which may include modeling.
- Mitigate buildings using activity and use limitations.
- Remediate the soil and/or groundwater contamination and reassess the pathway.
- Address the 25 Pa. Code Chapter 250 SSS requirements.

In most cases, all of the above steps will not be necessary, and the remediator is not required to follow the process sequentially. For instance, buildings with a potentially complete VI pathway may be mitigated without the collection of soil gas or indoor air data.

The SHS VI screening values presented in this guidance are based on a carcinogenic target risk level of 10^{-5} and a non-carcinogenic hazard quotient of 1.0. These screening values are not appropriate for use in risk assessments being performed under the SSS because the SHS target risk levels may not be sufficiently conservative to account for cumulative risks to receptors from multiple contaminants and/or multiple pathways. However, screening can be performed under the SSS for VI according to Section IV.K.4 below.

2. Preferential Pathway Evaluation

The remediator must assess potential preferential pathways and significant foundation openings as part of the SSS CSM development. The presence of a preferential pathway or significant opening may limit the use of proximity distances, screening values, and modeling.

The conditions listed in Section IV.D to identify and evaluate preferential pathways and significant openings also apply under the SSS. Specifically, contamination in soil and groundwater that exceeds SHS screening values within 30 horizontal and five vertical feet of a preferential pathway constitutes a potential VI source (Figure IV-3). Acceptable soil or soil-like material is qualified by no exceedances of SHS soil screening values. However, soil, groundwater, near-source soil gas, sub-slab, and indoor air sample data should be screened with appropriate site-specific screening values as described in Section IV.K.4.

3. Use of Proximity Distances

The remediator may utilize proximity distances to identify potential VI sources, as described in Section IV.E. For non-petroleum substances, the horizontal proximity distance is 100 feet, and for petroleum hydrocarbons it is 30 feet. When dissolved or adsorbed petroleum hydrocarbons are at least five feet below a building foundation and petroleum SPL is at least 15 feet below a building foundation, they are not considered to be a potential VI source. These vertical proximity distances must encompass acceptable soil or soil-like material.

Potential VI sources are established by the presence of SPL and exceedances of SHS soil and groundwater screening values within the applicable horizontal proximity distance. Appropriate site-specific screening values are explained in Section IV.K.4. For petroleum vertical proximity distances to apply, there must be acceptable soil or soil-like material (i.e., no exceedances of SHS soil screening values) in the upper five feet.

4. Site-Specific Standard VI Screening

Screening of soil, groundwater, near-source soil gas, sub-slab soil gas, and indoor air data is available under the SSS. This step in the evaluation allows substances to be eliminated prior to performing a risk assessment. Samples should be collected pursuant to the guidance in Table IV-6 and Appendix IV-C. An assessment of external preferential pathways, significant foundation openings, and the presence of SPL needs to be performed prior to screening as these are conditions that can limit the use of screening values.

If no limiting conditions exist, then soil and groundwater data may be screened using appropriate screening values. If limiting conditions are present, near-source soil gas, sub-slab soil gas, and indoor air may be screened with the following exceptions (Section IV.G and Figure IV-9):

- Near-source soil gas screening values are not available if there is a source less than five feet below the building foundation, if SPL or contaminated groundwater has entered a preferential pathway, if an external preferential pathway penetrates the building foundation, or if there is a significant foundation opening. Despite these limitations, if the potential VI source is at least five feet below grade, then near-source soil gas data may be screened with sub-slab screening values.

- Sub-slab soil gas screening may not be performed if an external preferential pathway penetrates the building foundation or in the presence of a significant foundation opening. In those cases, the data may be screened with indoor air screening values.

The Department permits remediators to define potential VI sources using SHS soil and groundwater screening values, even if the substances and media will be attaining the SSS. However, when screening soil or groundwater attainment data to eliminate substances from a risk assessment, the remediator must use SSS screening values as described below.

The SHS VI screening values listed in Tables IV-1 through IV-5 may not be used as is, without adjustment, for SSS screening. The SHS criteria are based on a 10^{-5} target cancer risk and a 1.0 target hazard quotient, and on groundwater MSCs and soil-to-groundwater numeric values (Appendix IV-A). Attainment for the SSS is demonstrated for cumulative risks to receptors from all substances, media, and pathways.
VI evaluations using a combination of standards are discussed in Section IV.C.3.

As illustrated in Figure IV-8, substance-by-substance SSS VI risk screening values can be determined using either of the following methods:

- Select the appropriate values for soil, groundwater, near-source soil gas, sub-slab soil gas, or indoor air from Tables IV-1 through IV-5, or used aquifer groundwater MSCs and generic soil-to-groundwater numeric values if limiting conditions apply (see Section IV.F and Figure IV-9). Reduce each screening value by a factor of 10.

- Use the current EPA residential or industrial indoor air Regional Screening Level (RSL) values (based on a target cancer risk of 10^{-6} and a target hazard quotient of 0.1) (U.S. EPA, 2018a). RSLs based on a 10^{-5} cancer risk may be used for screening when it can be demonstrated that VI is the only complete exposure pathway for a receptor. RSLs may be used for screening indoor air data or for screening near-source or sub-slab soil gas data by using the following attenuation factors (refer to Appendix IV-A):

Sample Type	Attenuation Factor		
	Residential	**Non-Residential**	**Converted Residential**
Sub-slab soil gas	0.026	0.0078	0.026
Near-source soil gas	0.005	0.001	0.005

The methodology for soil and groundwater screening is described in Section IV.F.2, and the methods for near-source soil gas, sub-slab soil gas, and indoor air are provided in Section IV.G.2. Screening may be applied to characterization and postremediation data. A sufficient number of sample locations and rounds must be collected to satisfactorily evaluate the pathway. DEP recommends a minimum of two sample locations and two sampling rounds for screening.

For the SSS, the only acceptable screening criterion is no exceedances of the applicable screening values. Substances that screen out using either one-tenth of the SHS VI screening values or the EPA RSLs do not need to be included in a VI risk assessment.

5. Performing a VI Risk Assessment and Modeling

In a risk assessment, the VI pathway should be considered when developing the CSM. The CSM should use a qualitative fate and transport analysis to identify all current and future potentially complete and incomplete exposure pathways, including source media, transport mechanisms, and all potential receptors (25 Pa. Code § 250.404). The risks associated with all complete exposure pathways must be combined for individual receptors in order to evaluate the total cumulative risk to each receptor. For example, if ingestion of contaminated soil, dermal contact with contaminated groundwater, and inhalation of vapor-phase contamination via VI are all complete exposure pathways for the same receptor, the calculated risk values for each of these pathways must be combined to evaluate the total risk to the receptor. For the SSS, the cumulative excess risk for known or suspected carcinogens may not be greater than 10^{-4} and the hazard index may not exceed one for systemic toxicants (25 Pa. Code § 250.402).

Current toxicity values should be used in a SSS risk assessment (25 Pa. Code § 250.605). Therefore, if a toxicity value has been updated since the last revision of the SHS screening values, that new information must be included in a cumulative risk assessment. This provision is consistent with DEP's discretion in allowing screening to substitute for a risk assessment.

VI modeling is one option for SSS risk assessments. DEP's modeling guidance is provided in Appendix IV-B. For SSS modeling, the user inputs soil, groundwater, or near-source soil gas concentrations into the Pennsylvania versions of EPA's J&E models. The desired output is the incremental risks for each substance, not the predicted indoor air concentrations. The model risk results are then incorporated into the cumulative risk assessment.

The second option is to use indoor air, sub-slab soil gas, or near-source soil gas data for the risk assessment. Soil gas data must be converted to estimated indoor air concentrations using the conservative attenuation factors tabulated in Section IV.K.4.

Inhalation risks are calculated using standard equations. (See Appendices IV-A and IV-B)

The VI risk assessment must be submitted in a risk assessment report meeting the procedural and substantive requirements of Act 2. For regulated storage tank sites, the risk assessment is provided in the site characterization and/or remedial action completion reports. Human health risk assessment guidance is found in Section III.H. Screening of chemicals of concern may follow the methodology described in Section IV.K.4.

6. Mitigation and Remediation

If site contamination does not screen out using the SSS screening values or the cumulative risks are excessive, then the remediator may choose to mitigate the VI pathway or remediate the VI sources. The remediator can also select these options before screening field data or carrying out a risk assessment. Mitigation and remediation require submittal of a cleanup plan.

Current and planned future inhabited buildings may be mitigated to eliminate the VI pathway (Section IV.H). Mitigation measures that prevent the migration of vapor, such as vapor barriers or sub-slab depressurization systems, are considered to be engineering controls. The standard mitigation approach is an active sub-slab depressurization system (U.S. EPA, 2008). Performance and testing guidelines are provided in Appendix IV-C. Measures taken that limit or prohibit exposure are considered to be institutional controls. Engineering or institutional controls used to mitigate the VI pathway must be addressed in the postremediation care plan and must be memorialized in an environmental covenant.

Remediation of soil and/or groundwater is also an alternative to address the VI pathway (Section IV.I). Postremediation data must be collected and evaluated through screening or a risk assessment. If remedial action is not completed promptly, then the remediator may be responsible for employing interim measures to protect human health.

7. Using an OSHA Program to Address VI

VI can be difficult to evaluate when vapors from soil or groundwater sources enter industrial (or commercial) facilities that use the same chemical(s) in their processes. DEP does not regulate indoor air. Rather, worker exposure to chemical vapors associated with an onsite industrial process is regulated by the Occupational Safety and Health Administration (OSHA). It is nearly impossible to accurately isolate and measure the VI component of the indoor air that can be attributed to soil and groundwater contamination using indoor air sampling. As a result, workers who are not properly trained to work in areas that contain these vapors can still be exposed to soil or groundwater related vapors due to VI.

Therefore, an OSHA program can be used to address VI as an institutional control within the SSS. The remediator should demonstrate that the substances in the soil or groundwater contamination they are evaluating are currently being used in a regulated industrial process inside the inhabited building(s) and that OSHA regulations are fully implemented and documented **in all areas of the building(s)**. This means that a hazard communications plan is in place, including the posting of Safety Data Sheets [SDSs; formerly known as Material Safety Data Sheets (MSDSs)], so that workers and others who might be exposed to all chemicals of concern have full knowledge of the chemicals' presence, have received appropriate health and safety training, and have been provided with the appropriate protective equipment (when needed) to minimize exposure. Remediators should not use an OSHA program to evaluate risk from VI in cases where the regulated substances being evaluated for the VI pathway are not used in the work place. It is also expected that a quantitative analysis of indoor air data using occupational screening values will be included in the VI assessment. Data is needed to show that OSHA worker protection measures are satisfied and also to demonstrate compliance and attainment of the SSS. If OSHA implementation cannot be documented, then an OSHA program cannot be used as a means of addressing VI. A checklist is included in Appendix IV-D to help remediators and reviewers ensure that the OSHA program is adequately documented. All items on the checklist should be provided to demonstrate that a complete OSHA program is present to provide protection. Additional guidance regarding the use of industrial hygiene/occupational health programs to address the VI pathway can be found in EPA's *OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air* (U.S. EPA, 2015a).

The use of an OSHA program to address VI is an institutional control because it limits exposure through the implementation of the OSHA requirements. If the future owner does not use the same chemical(s) in their industrial process as the previous owner and/or does not fully implement an OSHA program for the same chemical(s), then VI would need to be reevaluated by the new owner.

8. Addressing Chapter 250 Requirements

The final step in the process flowchart on Figure IV-7 is to address the requirements of Chapter 250 with respect to VI. This step is necessary to demonstrate compliance with the SSS under Act 2. The submitted report should include a description of the CSM for VI with a preferential pathway assessment. The flowchart endpoint can be reached in the following four ways. Compliance should be documented in Act 2 (Chapter 250) or storage tank corrective action (Chapter 245) reports:

- **Soil and Groundwater Screening.** The remediator may screen soil and groundwater concentration data within proximity distances to existing or currently planned inhabited buildings. If no potential VI sources are identified, then no further analysis is necessary. Documenting this conclusion requires the production of maps and cross sections that show the spatial relationship between soil and groundwater data, any SPL, any potential preferential pathways, and existing or planned future inhabited structures. Applicable proximity distances should be shown on these exhibits. Soil and groundwater data should be tabulated and compared to applicable screening values. This information is submitted in the remedial investigation and FR or the site characterization and remedial action completion reports, as appropriate.

- **Alternative Assessment Options.** The remediator may evaluate the VI pathway by screening near-source soil gas, sub-slab soil gas, or indoor air data. If the site data satisfy the screening criteria, then no further analysis is necessary. Sampling locations relative to potential VI sources and existing or planned future inhabited buildings should be shown on maps. The methodology for collecting the samples should be described and the results tabulated with applicable screening values. Supporting information is submitted in the remedial investigation and FR or the site characterization and remedial action completion reports, as appropriate.

- **Risk Assessment.** If VI screening values are not applicable or they are exceeded, then a human health risk assessment may be performed. If the site-specific risk thresholds (cumulative 10^{-4} cancer risk and hazard index of 1.0) are satisfied, no further analysis is required. Risk assessment requirements are described in 25 Pa. Code § 250.409 and Section III.H. Documentation is supplied in a risk assessment report or a risk assessment submitted as part of a site characterization report and remedial action completion report, as appropriate. The risk evaluation may include modeling, as described in Appendix IV-B.

- **Mitigation and Activity and Use Limitations.** The remediator may address the VI pathway by installing a mitigation system or implementing AULs in an environmental covenant. Submittal of a cleanup plan is required when an engineering control is used to mitigate the exposure pathway for a current receptor. Installation of the mitigation system must be documented, for instance, with plans, manufacturer specifications, and the installer's certification. Testing to demonstrate the system's effectiveness should be performed (Appendix IV-C) and the results described in the report. The conditions to be included in a covenant to maintain the remedy or eliminate the pathway should also be detailed in a postremediation care plan. Documentation for mitigation systems and covenant remedies is provided in the FR or remedial action completion report, as appropriate.

When a potential VI source in soil or groundwater is remediated, new samples are collected to reevaluate the VI pathway. That data is presented as described above for the SSS or through the SHS process, as appropriate.

Figure IV-6: Statewide Health Standard Vapor Intrusion Assessment Process

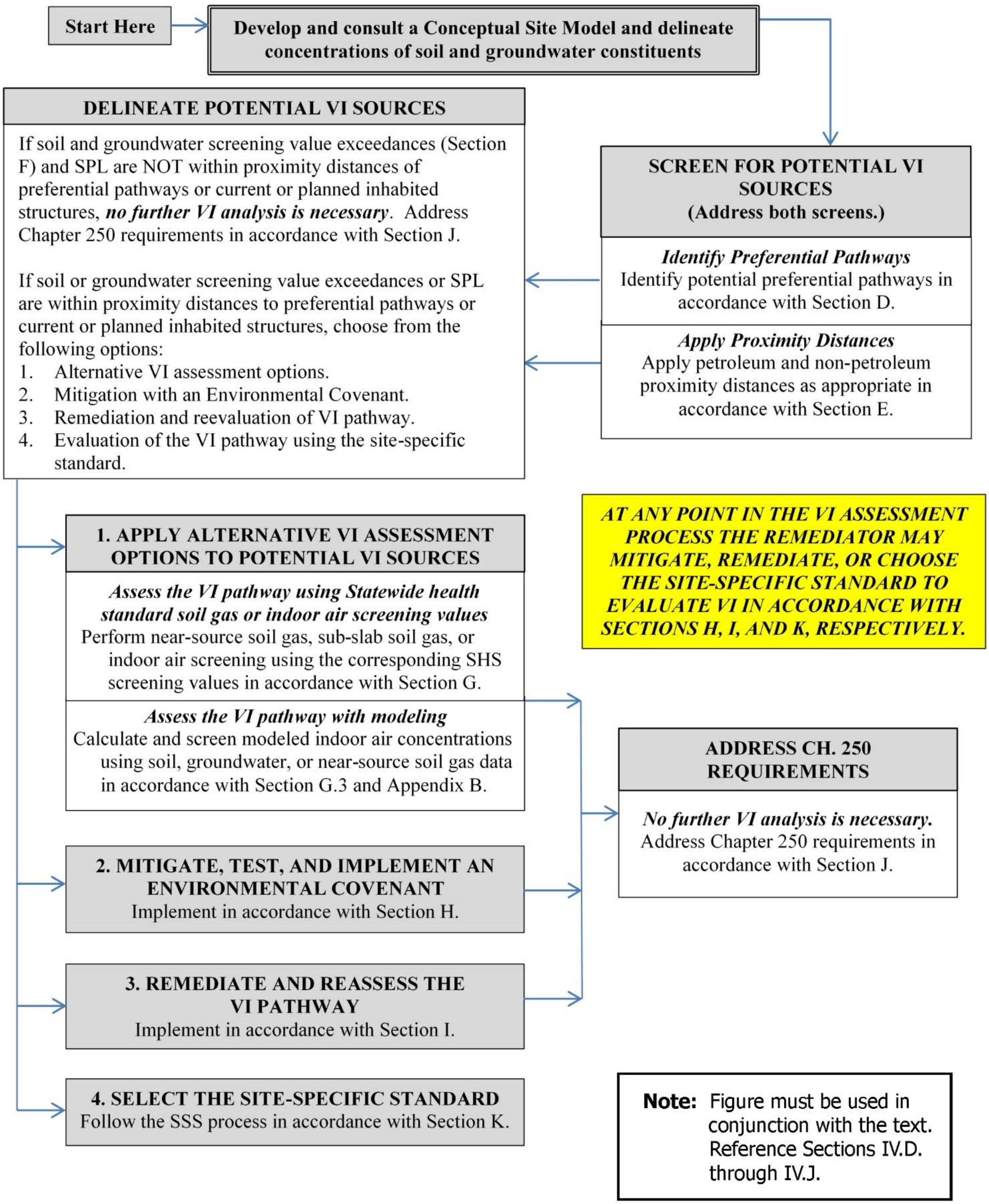
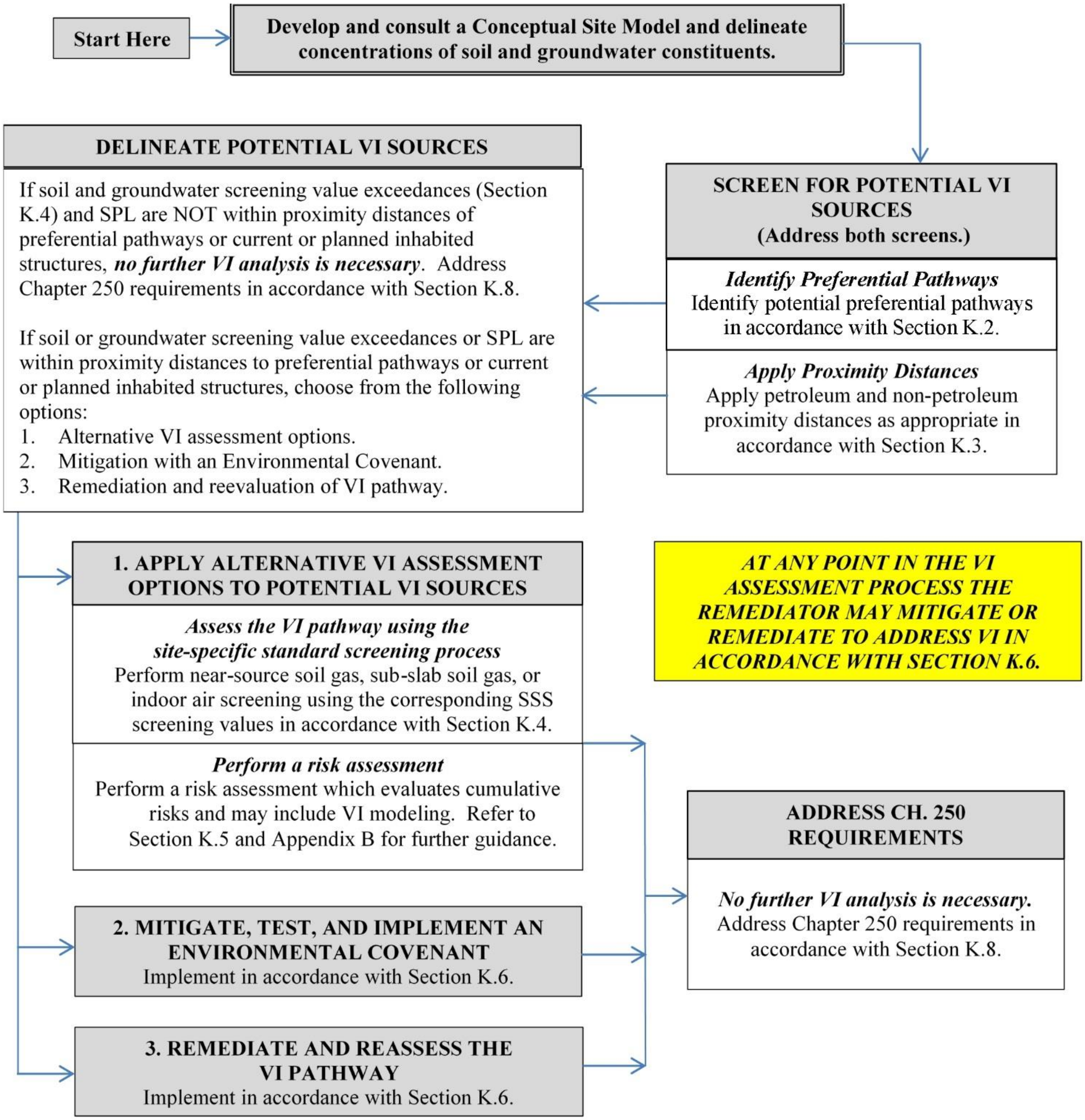
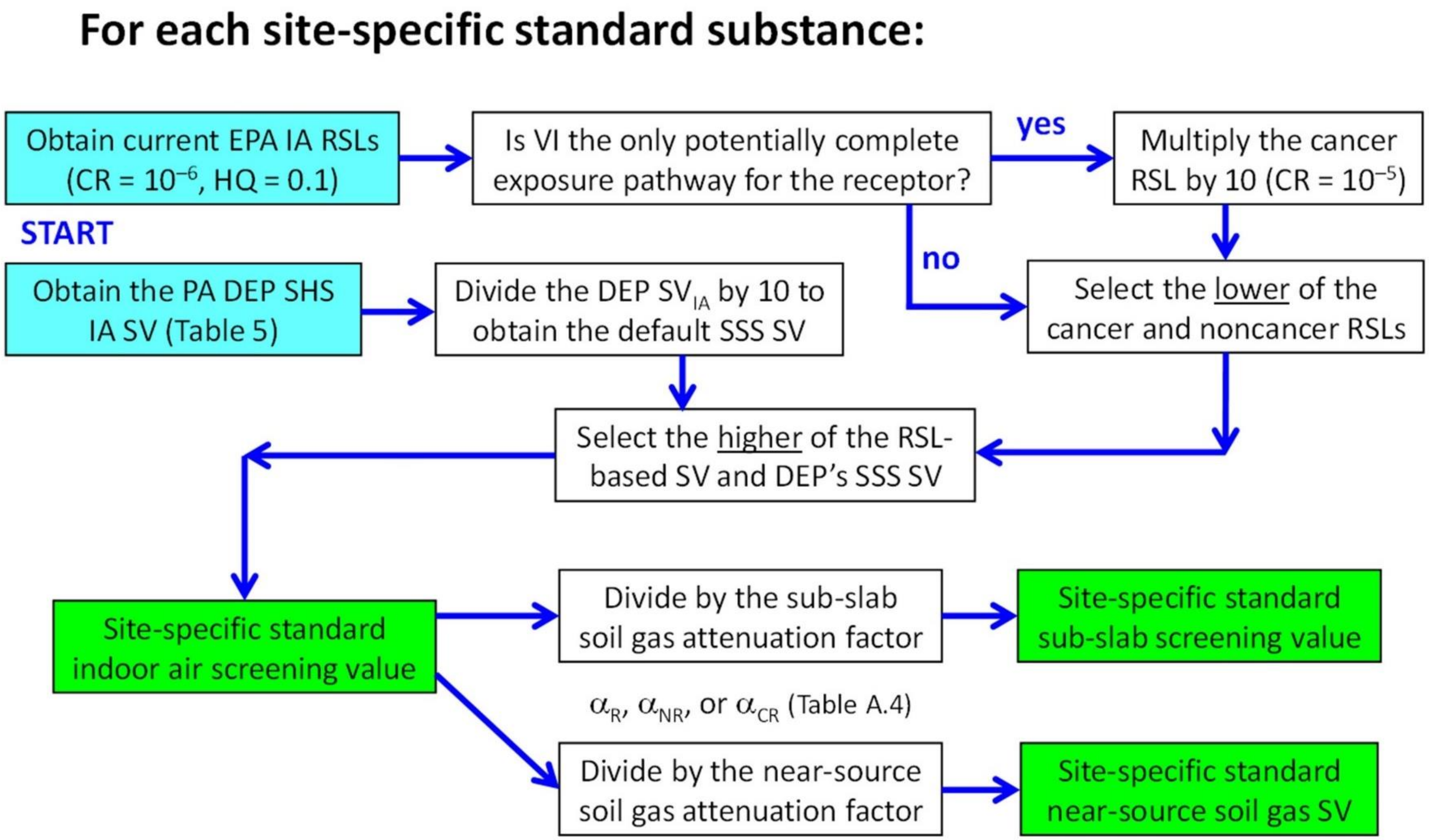


Figure IV-7: Site-Specific Standard Vapor Intrusion Assessment Process



Note: Figure must be used in conjunction with the text. Reference Section IV.K.

Figure IV-8: Process to Determine Site-Specific Standard Vapor Intrusion Screening Values



Note: Figure must be used in conjunction with the text. Reference Section IV.K.4.

Figure IV-9: Screening Value Use Restrictions

Source	Data Type	Screening Value	Screening Value Use Restriction	Reason for Restriction
Groundwater within proximity distances	**Groundwater**	SV_{GW}	1. Presence of SPL within appropriate horizontal proximity distance 2. Presence of a significant foundation opening 3. Contaminated GW enters an external preferential pathway 4. GW < 5 feet below foundation level	1. SV_{GW} values or the used aquifer GW MSCs cannot be used in the presence of SPL because both values assume no SPL is present. 2. SV_{GW} values cannot be used in the presence of significant foundation openings because the calculated SV_{GW} values assume the presence of a slab. 3. SV_{GW} values cannot be used when GW enters a preferential pathway because the calculated SV_{GW} values assume attenuation through soil. 4. SV_{GW} values cannot be used when GW < 5 feet below foundation level because the calculated SV_{GW} values require at least 5 feet of soil. • NOTE: For site-specific standard screening, use 1/10th of the Table 1 or1/10th of the MSC values.
		Used Aquifer GW MSC	1. Presence of SPL within appropriate horizontal proximity distance	
Soil within proximity distances	**Soil**	SV_{SOIL}	1. Presence of SPL within appropriate horizontal proximity distance 2. Presence of a significant foundation opening	1. SV_{SOIL} values and the generic soil-to-GW numeric values cannot be used in the presence of SPL because both values assume no SPL is present. 2. SV_{SOIL} values cannot be used in the presence of a significant foundation opening because the calculated SV_{SOIL} values assume a slab is present. • NOTE: For SSS screening, use 1/10th of the Table 2 or 1/10th of the MSC values.
		Generic Soil-to-GW Numeric Value	1. Presence of SPL within appropriate horizontal proximity distance	
Groundwater or Soil within proximity distances	**Near-Source Soil Gas**	SV_{NS}	1. Contaminated GW or SPL enters a preferential pathway 2. Presence of a significant foundation opening 3. External preferential pathway penetrates the building foundation 4. Potential VI source is < 5 feet below foundation level	1. SV_{NS} values cannot be used when contaminated GW or SPL enters an external preferential pathway because the SV_{NS} values assume attenuation through soil. 2. SV_{NS} values cannot be used in the presence of a significant foundation opening because the SV_{NS} values assume the presence of a slab. 3. SV_{NS} values cannot be used if an external preferential pathways penetrates the building foundation because the SV_{NS} values assume the presence of a slab. 4. SV_{NS} values cannot be used if the potential VI source is < 5 feet bleow foundation level because the SV_{NS} values assume 5 feet of soil between the source and the foundation. 5. A comparison of near-source soil gas data to SV_{SS} values cannot be performed if the potential VI sourse is < 5 feet below grade because shallow soil gas data can be unreliable. • NOTE: For SSS screening, use 1/10th of the Table 3 values or use EPA indoor air RSLs with an appropriate attenuation factor.
		SV_{SS}	1. Potential VI source is < 5 feet below grade	
	Sub-Slab Soil Gas	SV_{SS}	1. Presence of a significant foundation opening 2. Preferential pathway penetrates the building foundation	1. The comparison of sub-slab data to SV_{SS} is not available in the presence of a significant foundation opening because the calculation of the SV_{SS} values assumes the presence of an intact slab. 2. The comparison of sub-slab data to SV_{SS} is not available if an external preferential pathway penetrates the building foundation because the SV_{SS} values presume the presence of soil between the source and foundation. • NOTE: For SSS screening, use 1/10th of the Table 4 values or use EPA indoor air RSLs with an appropriate attenuation factor.
		SV_{IA}	No Restrictions	
	Indoor Air	SV_{IA}	No Restrictions	• NOTE: For SSS screening, use 1/10th of the Table 5 values or use EPA indoor air RSLs.

Note: Figure must be used in conjunction with the text. Reference Sections IV.F. and IV.G.

L. References

American Petroleum Institute (API), 2005, Collecting and Interpreting Soil Gas Samples from the Vadose Zone, Publication No. 4741, Washington, DC.

American Petroleum Institute (API), 2010, BioVapor User's Manual, Washington, DC.

American Society for Testing and Materials (ASTM), 2007, Standard Test Method for Particle-Size Analysis of Soils, D422-63(2007)e2, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2008, Standard Practice for Radon Control Options for the Design and Construction of New Low-rise Residential Buildings, E1465-08a, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2009, Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens, D7263-09, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2010a, Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method, D2937-10, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2010b, Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, D2216-10, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2011a, Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), D2487-11, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2011b, Standard Guide for Assessing Depressurization-Induced Backdrafting and Spillage from Vented Combustion Appliances, E1998-11, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2012a, Standard Practice for Active Soil Gas Sampling in the Vadose Zone for Vapor Intrusion Evaluations, D7663-12, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2012b, Standard Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method, D1298-12b, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2013a, Standard Test Method for Measurement of the Permeability of Unsaturated Porous Materials by Flowing Air, D6539-13, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2013b, Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings, E2121-13, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2014, Standard Test Method for Estimation of Mean Relative Molecular Mass of Petroleum Oils from Viscosity Measurements, D2502-14, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2015a, Standard Practice for Analysis of Reformed Gas by Gas Chromatography, D1946-90(2015)e1, West Conshohocken, PA.

American Society for Testing and Materials (ASTM), 2015b, Standard Guide for Application of Engineering Controls to Facilitate Use or Redevelopment of Chemical-Affected Properties, E2435-05(2015), West Conshohocken, PA.

California Environmental Protection Agency (EPA), 2011a, Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air, Sacramento, CA.

California Environmental Protection Agency (EPA), 2011b, Vapor Intrusion Mitigation Advisory, Sacramento, CA.

California Environmental Protection Agency (EPA), 2015, Advisory—Active Soil Gas Investigations, Sacramento, CA.

Folkes, D., W. Wertz, J. Kurtz, and T. Kuehster, 2009, Observed spatial and temporal distributions of CVOCs at Colorado and New York vapor intrusion sites, Ground Water Monitoring & Remediation, 29, 70-80.

Guo, Y., C. Holton, H. Luo, P. Dahlen, K. Gorder, E. Dettenmaier, and P. Johnson, 2015, Identification of alternative vapor intrusion pathways using controlled pressure testing, soil gas monitoring, and screening model calculations, Environmental Science & Technology, 49, 13,472-13,482.

Hawaii Department of Health (DoH), 2014, Technical Guidance Manual for the Implementation of the Hawaii State Contingency Plan—Soil Vapor and Indoor Air Sampling Guidance, Honolulu, HI.

Hers, I., R. Zapf-Gilje, L. Li, and J. Atwater, 2001, The use of indoor air measurements to evaluate intrusion of subsurface VOC vapors into buildings, Journal of the Air & Waste Management Association, 51, 1318-1331.

Hers, I., R. Zapf-Gilje, P. C. Johnson, and L. Li, 2003, Evaluation of the Johnson and Ettinger model for prediction of indoor air quality, Ground Water Monitoring & Remediation, 23, 119-133.

Holton, C., H. Luo, P. Dahlen, K. Gorder, E. Dettenmaier, and P. C. Johnson, 2013, Temporal variability of indoor air concentrations under natural conditions in a house overlying a dilute chlorinated solvent groundwater plume, Environmental Science & Technology, 47, 13,347-13,354.

The Interstate Technology & Regulatory Council (ITRC), 2007, Vapor Intrusion Pathway: A Practical Guideline, Washington, DC.

The Interstate Technology & Regulatory Council (ITRC), 2014, Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management, Washington, DC.

Jarvela, S., K. Boyd, R. Gadinski, M. DiVincenzo, and T. Karlicek, 2003, Tranguch gasoline site case history, International Oil Spill Conference Proceedings, 637-642, April 2003.

Johnson, P.C., and R. A. Ettinger, 1991, Heuristic model for predicting the intrusion rate of contaminant vapors into buildings, Environmental Science & Technology, 25, 1445-1452.

Luo, H., P. Dahlen, P.C. Johnson, T. Peargin, and T. Creamer, 2009, Spatial variability of soil-gas concentrations near and beneath a building overlying shallow petroleum hydrocarbon–impacted soils, Groundwater Monitoring & Remediation, 29, 81-91.

Massachusetts Department of Environmental Protection (DEP), 1995, Guidelines for the Design, Installation, and Operation of Sub-slab Depressurization Systems.

Massachusetts Department of Environmental Protection (DEP), 2011, Interim Final Vapor Intrusion Guidance, Boston, MA.

McHugh, T.E., T.N. Nickels, and S. Brock, 2007, Evaluation of spatial and temporal variability in VOC concentrations at vapor intrusion investigation sites, in Proceedings of Air & Waste Management Association, Vapor Intrusion: Learning from the Challenges, September 26-28, Providence, RI, 129-142.

New Jersey Department of Environmental Protection (DEP), 2013, Vapor Intrusion Technical Guidance, Trenton, NJ.

New York Department of Health (DoH), 2006, Guidance for Evaluating Soil Vapor Intrusion in the State of New York, Troy, NY.

Pennell, K.G., M. Kangsen Scammell, M.D. McClean, J. Ames, B. Weldon, L. Friguglietti, E.M. Suuberg, R. Shen, P.A. Indeglia, and W.J. Heiger-Bernays, 2013, Sewer gas: An indoor air source of PCE to consider during vapor intrusion investigations, Groundwater Monitoring & Remediation, 33, 119-126.

Pennsylvania Department of Environmental Protection (DEP), 1997, Pennsylvania Radon Mitigation Standards, Bureau of Radiation Protection, Harrisburg, PA, 294-2309-002.

Pennsylvania Department of Environmental Protection (DEP), 2014, User’s Manual for the Quick Domenico Groundwater Fate-and-Transport Model, Bureau of Environmental Cleanup and Brownfields, Harrisburg, PA.

Persily, A. K., and J. Gorfain, 2009, Analysis of Ventilation Data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study, NIST Interagency/Internal Report (NISTIR) 7145-R.

Provoost, J., L. Reijnders, F. Swartjes, J. Bronders, P. Seuntjens, and J. Lijzen, 2009, Accuracy of seven vapour intrusion algorithms for VOC in groundwater, Journal of Soils and Sediments, 9, 62-73.

Provoost, J., A. Bosman, L. Reijnders, J. Bronders, K. Touchant, and F. Swartjes, 2010, Vapour intrusion from the vadose zone—seven algorithms compared, Journal of Soils and Sediments, 10, 473-483.

Schuver H., Lutes C., Kurtz J., Holton C., Truesdale R. S., 2018, Chlorinated vapor intrusion indicators, tracers, and surrogates (ITS): Supplemental measurements for minimizing the number of chemical indoor air samples - Part 1: Vapor intrusion driving forces and related environmental factors, Remediation, 28, 7-31.

Taylor, C. A., and H. G. Stefan, 2008, Shallow groundwater temperature response to urbanization and climate change in the Twin Cities Metropolitan Area: Analysis of vertical heat convection effects from the ground surface, University of Minnesota, St. Anthony Falls Laboratory, Minneapolis, MN, Project Report No. 504.

U.S. Department of Agriculture (USDA), 1993, Soil Survey Manual, Soil Conservation Service, USDA Handbook 18.

U.S. Environmental Protection Agency (EPA), 1991, Handbook: Sub-Slab Depressurization for Low Permeability Fill Material—Design and Installation of a Home Radon Reduction System, EPA/625/6-91/029.

U.S. Environmental Protection Agency (EPA), 1993, Radon Reduction Techniques for Existing Detached Houses—Technical Guidance (Third Edition) for Active Soil Depressurization Systems, EPA 625/R-93/011.

U.S. Environmental Protection Agency (EPA), 1994a, Model Standards and Techniques for Control of Radon in New Residential Buildings, Air and Radiation (6604-J), EPA 402-R-94.

U.S. Environmental Protection Agency (EPA), 1994b, Radon Prevention in the Design and Construction of Schools and Other Large Buildings, Office of Research and Development, EPA/625/R-92/016.

U.S. Environmental Protection Agency (EPA), 2001, Building Radon Out: A Step-by-Step Guide on how to build Radon-Resistant Homes, Office of Air and Radiation, EPA/402-K-01-002.

U.S. Environmental Protection Agency (EPA), 2004, User’s Guide for Evaluating Subsurface Vapor Intrusion into Buildings, Office of Emergency and Remedial Response, Washington, DC.

U.S. Environmental Protection Agency (EPA), 2006, Guidance on Systematic Planning Using the Data Quality Objectives Process, EPA QA/G-4, Office of Environmental Information, Washington, DC, EPA/240/B-06/001.

U.S. Environmental Protections Agency (EPA), 2007, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846).

U.S. Environmental Protection Agency (EPA), 2008, Indoor Air Vapor Intrusion Mitigation Approaches, Office of Research and Development, Cincinnati, OH, EPA/600/R-08-115.

U.S. Environmental Protection Agency (EPA), 2009, Risk Assessment Guidance for Superfund (RAGS), Volume 1: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment), Office of Superfund Remediation and Technology Innovation, Washington, DC, EPA-540-R-070-002.

U.S. Environmental Protection Agency (EPA), 2010, Temporal Variation of VOCs in Soils from Groundwater to the Surface/Subslab, APM 349, Office of Research and Development, Washington, DC, EPA/600/R-10/118.

U.S. Environmental Protection Agency (EPA), 2011a, Toxicological Review of Trichloroethylene, National Center for Environmental Assessment, Washington, DC, EPA/635/R-09/011F.

U.S. Environmental Protection Agency (EPA), 2011b, Exposure Factors Handbook, Office of Research and Development, Washington, DC, EPA/600/R-09/052F.

U.S. Environmental Protection Agency (EPA), 2012a, Conceptual Model Scenarios for the Vapor Intrusion Pathway, Office of Solid Waste and Emergency Response, Washington, DC, EPA 530-R-10-003.

U.S. Environmental Protection Agency (EPA), 2012b, EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings, Office of Solid Waste and Emergency Response, Washington, DC, EPA 530-R-10-002.

U.S. Environmental Protection Agency (EPA), 2012c, Fluctuation of Indoor Radon and VOC Concentrations Due to Seasonal Variations, Office of Research and Development, Washington, DC, EPA/600/R/12/673.

U.S. Environmental Protection Agency (EPA), 2013, Evaluation of Empirical Data to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds, Office of Underground Storage Tanks, Washington, DC, EPA 510-R-13-001.

U.S. Environmental Protection Agency (EPA), 2014a, Vapor Intrusion Screening Level (VISL) Calculator, User's Guide, Office of Superfund Remediation and Technology Innovation, Washington, DC.

U.S. Environmental Protection Agency (EPA), 2014b, Human Health Evaluation Manual, Supplemental Guidance: Update of Standard Default Exposure Factors, Office of Solid Waste and Emergency Response, Washington, DC, OSWER Directive 9200.1-120, February 6, 2014.

U.S. Environmental Protection Agency (EPA), 2015a, OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air, Office of Solid Waste and Emergency Response, Washington, DC, OSWER Publication 9200.2-1154.

U.S. Environmental Protection Agency (EPA), 2015b, Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites, Office of Underground Storage Tanks, Washington, DC, EPA 510-R-15-001.

U.S. Environmental Protection Agency (EPA), 2015c, Assessment of Mitigation Systems on Vapor Intrusion: Temporal Trends, Attenuation Factors, and Contaminant Migration Routes under Mitigated and non-Mitigated Conditions, Office of Research and Development, Washington, DC, EPA/600/R-13/241.

U.S. Environmental Protection Agency (EPA), 2015d, Simple, Efficient, and Rapid Methods to Determine the Potential for Vapor Intrusion in the Home: Temporal Trends, Vapor Intrusion Forecasting, Sampling Strategies, and Contaminant Migration Routes, Office of Research and Development, Washington, DC, EPA/600/R-15/070.

U.S. Environmental Protection Agency (EPA), 2016a, Toxicological Review of Trimethylbenzenes, National Center for Environmental Assessment, Washington, DC, EPA/635/R-16/161Fa.

U.S. Environmental Protection Agency (EPA), 2016b, Petroleum Vapor Intrusion Modeling Assessment with PVIScreen, Office of Research and Development, Washington, D.C., EPA/600/R-16/175.

U.S. Environmental Protection Agency (EPA), 2017, Documentation for EPA's Implementation of the Johnson and Ettinger Model to Evaluate Site Specific Vapor Intrusion into Buildings, Version 6.0, Office of Superfund Remediation and Technology Innovation, Washington, DC.

U.S. Environmental Protection Agency (EPA), 2018a, Regional Screening Levels for Chemical Contaminants at Superfund Sites—Generic Tables, Washington, DC.

U.S. Environmental Protection Agency (EPA), 2018b, Vapor Intrusion Screening Level (VISL) Calculator, User's Guide, Washington, DC (online).

U.S. Environmental Protection Agency (EPA), 2018c, Regional Screening Levels for Chemical Contaminants at Superfund Sites—User's Guide, Washington, DC.

Yao, Y., R. Hen, K. G. Pennell, and E. M. Suuberg, 2011, Comparison of the Johnson–Ettinger vapor intrusion screening model predictions with full three-dimensional model results, Environmental Science & Technology, 45, 2227-2235.

M. Tables

Tables IV-1 through IV-5 are located on the vapor intrusion web page of the DEP website.

Table IV-6: Collection of Data for Vapor Intrusion Screening

Sample	Conditions for VI Data Collection
Soil	• Collect an appropriate number of samples to characterize the source(s) and/or demonstrate attainment. • The samples are from unsaturated soil. • No SPL is present.
Groundwater	• Install an appropriate number of monitoring wells to characterize the source(s) and/or demonstrate attainment. • Sample from properly constructed monitoring wells. • Sample at or near the water table. • Monitoring well screens cross the water table. • The wetted length of the well screen should be no more than 10 feet. • If the depth to water below the foundation is less than 5 feet then MSC-based screening values should be used. • Acceptable soil or soil-like material exists between the water table and the building foundation. • No SPL is present.

Sample	Conditions for VI Data Collection
Near-Source Soil Gas	• Account for potential spatial variability in the sampling design based on the soil and groundwater data. • Collect at least two rounds of samples from at least two locations. • Locate sample points where they will be most representative of soil gas in potential VI sources and preferential pathways (if applicable). • The sample depth is within about 1 foot of the top of the capillary fringe for groundwater sources, considering the effects of water table fluctuations. • Sample above bedrock when the water table is within bedrock. • Sample within or no more than 1 foot above vadose zone soil sources. • Sample at least 5 feet below grade. • Acceptable soil or soil-like material exists between the source and the building foundation. • Refer to Appendix IV-C.
Sub-Slab Soil Gas	• Account for potential spatial variability in the sampling design. • Collect at least two rounds of samples from at least two locations. • Bias sample points towards areas of greatest expected impact. • Refer to Appendix IV-C.
Indoor Air	• Account for potential spatial variability in the sampling design. • Collect at least two rounds of samples from at least two locations. • Sample in the lowest occupied floor (basement and/or first floor). • Sample when the daily average outdoor temperature is at least 15°F (8°C) below the minimum indoor temperature of the occupied space. • Refer to Appendix IV-C.

Table IV-7: Application of Statewide Health Standard Vapor Intrusion Screening Criteria

Characterization Data	Vapor Intrusion Screening Conditions
Soil Characterization	• Soil attains the Statewide health standard on the basis of the characterization data without remediation. • Use all applicable soil characterization data for VI screening. • If there are no exceedances of VI soil screening values (SV_{SOIL}), then the VI evaluation is complete.*
Groundwater Characterization	• Groundwater attains the Statewide health standard on the basis of the characterization data without remediation. • Use all applicable groundwater characterization data for VI screening. • Collect at least two rounds of data. • If there are no exceedances of vapor intrusion groundwater screening values (SV_{GW}), then the VI evaluation is complete.*
Near-Source Soil Gas, Sub-Slab Soil Gas, or Indoor Air Characterization	• The remediator may characterize and screen soil gas or indoor air with a limited number of sampling rounds. • Sample at least two locations and perform a minimum of two sampling events. • Collect samples at least 45 days apart. • If there are no exceedances of VI screening values (SV_{NS}, SV_{SS}, SV_{IA}) then the VI evaluation is complete. *
Attainment Data	**Vapor Intrusion Screening Conditions**
Soil Attainment	• Use all applicable soil attainment data. • The attainment requirements for soil in Sections 250.702, 250.703, and 250.707(b)(1) of the regulations may be utilized for vapor intrusion soil screening (e.g., 75%/10x test).

Characterization Data	Vapor Intrusion Screening Conditions
Groundwater Attainment	• Use all applicable groundwater attainment data. • When eight or more consecutive quarters of data are available then the attainment requirements for groundwater in 25 Pa. Code §§ 250.702, 250.704, and 250.707(b)(2)(i) of the regulations may be utilized for vapor intrusion groundwater screening (e.g., 75%/10x test on the property and 75%/2x test beyond the property boundary). • Fewer than eight rounds of data may be screened with DEP approval pursuant to 25 Pa. Code § 250.704(d) of the regulations. The VI evaluation is complete if all concentrations are less than or equal to the groundwater screening values (SV_{GW}). • The alternate groundwater attainment statistical method found at 25 Pa. Code § 250.707(b)(2)(ii) of the regulations may be applied to VI screening when the minimum number of samples specified by the documentation of the method have been collected.

Table IV-7: Application of Statewide Health Standard Vapor Intrusion Screening Criteria (cont.)

VI Monitoring Data	Vapor Intrusion Screening Conditions
Near-Source Soil Gas, Sub-Slab Soil Gas, or Indoor Air Monitoring	• Soil gas and indoor air monitoring is performed on a quarterly basis or twice per quarter with samples collected at least 45 days apart. • The Department may approve alternative sampling frequencies. • Near-source and sub-slab soil gas samples are collected from all of the same probes in each event. • Indoor air samples are collected at all of the same locations in each event. • There is a minimum of two sampling rounds. • Statistical tests for screening are applied to the collective data from all near-source soil gas, sub-slab soil gas, or indoor air locations and rounds at each building or portion of a building with a potential VI impact. • Statistical tests may be used when there is a combination of at least eight sample locations and sampling rounds of any given type (near source soil gas, sub-slab soil gas, or indoor air) at each current or planned future building. • The following statistical test may be applied when screening VI data: Seventy-five percent of all samples are equal to or less than the applicable screening value with no individual sample exceeding ten times the screening value on the property (75%/10x test) and two times the screening value beyond the property boundary (75%/2x test). • An alternative statistical method may be applied to VI screening when the minimum number of samples specified by the documentation of the method have been collected: As applied in accordance with EPA approved statistical methods, the 95% UCL of the arithmetic mean is at or below the applicable screening value.

* The use of screening values may be restricted due to the presence of SPL, external preferential pathways, or significant foundation openings. See Sections IV.F and IV.G and Figure IV-9 for additional information on screening value use.

APPENDICES

Appendix IV-A: Methodology for Developing SHS Vapor Intrusion Screening Values

DEP has calculated screening values (SVs) for regulated substances of VI concern for use with the SHS. These SVs may be applied to appropriately collected data for indoor air, sub-slab soil gas, near-source soil gas, soil, and groundwater. The methods used to develop the SVs are explained in the following sections.

The SVs for subsurface media are derived using attenuation factors (α). An attenuation factor is the ratio between the contaminant concentration in indoor air and the equilibrium soil gas concentration in the unsaturated zone or sub-slab area ($\alpha \equiv C_{IA}/C_{SG}$).

DEP's approach is to first calculate indoor air SVs (SV_{IA}), then to determine sub-slab soil gas, near-source soil gas, soil, and groundwater SVs based on attenuation factors established for each of those POA.

As there are distinct attenuation factors for residential (α R) and nonresidential (α NR) structures, DEP carries out separate calculations for SVs that apply to buildings constructed for residential use that have been converted to a purely nonresidential use. These attenuation factors (α CR) are equal to the residential factors under the assumption that vapor flow rates and indoor air exchange rates are comparable to residential structures. The converted residential SVs are derived from the nonresidential indoor air SVs.

The VI screening values are provided in Tables IV-1-5 on the Department's Vapor Intrusion web page. They will be updated periodically using current scientific information when the 25 Pa. Code Chapter 250 MSCs are revised, consistent with the 25 Pa. Code § 250.11.

1. Indoor Air

Indoor air represents the point of exposure for inhalation of volatile chemicals in the VI pathway. The POA for indoor air screening is the basement or lowest occupied level of the building.

Contaminants that pose a risk for VI either have a boiling point less than 200°C or a Henry's law constant greater than or equal to 1×10^{-5} atm-m^3/mol and a molecular weight less than 200 g/mol. Certain regulated substances meet these criteria but currently have no inhalation toxicity values; they are listed in Table IV-A-1 on the Department's Vapor Intrusion web page. DEP has not published VI SVs for most of these chemicals. SHS VI evaluations are not available for substances without SVs. The remediator may choose to evaluate VI using the SSS for these chemicals. In addition, DEP does not consider the polycyclic aromatic hydrocarbons (PAHs) in Table IV-A-1 to be of VI concern because of their high boiling points, relatively low Henry's law constants, and very low vapor pressures.

In the case of 1,3,5-trimethylbenzene, DEP has chosen 1,2,4-trimethylbenzene as a surrogate for inhalation toxicity (U.S. EPA, 2016a). These two substances have similar chemical and toxicological characteristics.

Indoor air SVs (SV_{IA}) are determined from the inhalation risk equations in U.S. EPA (2009). This method is equivalent to that used by EPA for RSLs and in the VISL Calculator (U.S. EPA, 2014a, 2018b, 2018c). SVs for systemic toxicants ($SV_{IA(nc)}$) and carcinogens ($SV_{IA(c)}$) are calculated in units of micrograms per cubic meter (μg/m^3).

For systemic toxicants (non-carcinogens) the indoor air SV is:

$$SV_{IA(nc)} = \frac{THQ \times RfC_i \times AT_{nc} \times (365\,\frac{days}{yr}) \times (24\,\frac{hr}{day})}{ET \times EF \times ED} \times \frac{1{,}000\ \mu g}{mg}$$

For carcinogens, the indoor air SV is:

$$SV_{IA(c)} = \frac{TR \times AT_c \times (365\,\frac{days}{yr}) \times (24\,\frac{hr}{day})}{IUR \times ET \times EF \times ED}$$

For substances classified as mutagens, except for vinyl chloride and trichloroethylene, the residential carcinogenic indoor air SV is:

$$SV_{IA(c,m,R)} = \frac{TR \times AT_c \times (365\,\frac{days}{yr}) \times (24\,\frac{hr}{day})}{IUR \times ET \times EF \times AED}$$

For vinyl chloride, the residential carcinogenic indoor air SV is:

$$SV_{IA(c,vc,R)} = \frac{TR}{\frac{IUR \times ET \times EF \times ED}{AT_c \times (365\,\frac{days}{yr}) \times (24\,\frac{hr}{day})} + IUR}$$

For trichloroethylene, the residential carcinogenic indoor air SV is:

$$SV_{IA(c,TCE,R)} = \frac{TR \times AT_c \times (365\,\frac{days}{yr}) \times (24\,\frac{hr}{day})}{(IUR_k \times AED + IUR_l \times ED) \times ET \times EF}$$

As TCE has a mutagenic mode of action for the kidneys, the residential carcinogenic SV is calculated using distinct IUR values for kidney cancer and non-Hodgkin lymphoma and liver cancer (U.S. EPA, 2011a).

The nonresidential indoor air carcinogenic SVs for mutagens are determined using the non-mutagenic equation $SV_{IA(c)}$ given above.

The variables and exposure factors in the above equations are defined in Table IV-A-2. Certain conditions are explained in § 250.307(h) of the regulations.

Residential and nonresidential indoor air SVs are defined as the lower of the applicable systemic, carcinogenic, and mutagenic values. The toxicity parameters used are from Chapter 250, Appendix A, Table 5A (Table IV-A-5 on the Department's Vapor Intrusion web page).

Table IV-A-2: Inhalation Risk Variables

Symbol	Term	Residential	Nonresidential
THQ	Target Hazard Quotient, systemic toxicants	1.0	1.0
RfCi	Inhalation Reference Concentration (mg/m^3)	Table IV-A-5	Table IV-A-5
ATnc	Averaging Time for systemic toxicants (yr)	30	25
ET	Exposure Time (hr/day)	24	8
EF	Exposure Frequency (days/yr)	350	250
ED	Exposure Duration (yr)	30	25
TR	Target Risk, carcinogens	1 x 10–5	1 x 10–5
IUR	Inhalation Unit Risk ($(\mu g/m^3)^{-1}$)	Table IV-A-5	Table IV-A-5
ATc	Averaging Time for carcinogens (yr)	70	70
AED	Combined Age-Dependent Adjustment Factor and Exposure Duration (yr)	76	N/A
IURk	TCE IUR, residential, kidney cancer ($(\mu g/m^3)^{-1}$)	1.0 x 10–6	N/A
IURl	TCE IUR, residential, non-Hodgkin lymphoma and liver cancer ($(\mu g/m^3)^{-1}$)	3.0 x 10–6	N/A

2. Sub-Slab Soil Gas

The POA for sub-slab soil gas screening is immediately beneath the slab or basement of a building. In some circumstances, samples may be collected from behind basement walls or below intact paved areas large enough to be representative of future inhabited buildings. Sub-slab SVs (SV_{SS}) are defined using attenuation factors from U.S. EPA (2012b, 2015a). These SVs have units of micrograms per cubic meter ($\mu g/m^3$).

EPA derived a sub-slab attenuation factor (α_{SS}) from a statistical evaluation of 431 paired sub-slab and indoor air sampling data at over 400 residential buildings at 12 sites. The data was limited to chlorinated VOCs. The empirical attenuation factors are defined as $\alpha_{SS} = C_{IA}/C_{SS}$.

EPA's recommended residential attenuation factor is $\alpha_{SS,R} = 0.026$, the 95th percentile of the screened data. DEP has adopted this attenuation factor for all chemicals, including petroleum hydrocarbons, as a conservative approach. This residential factor also applies to nonresidential buildings that were originally constructed for residential use ($\alpha_{SS,CR}$) or that have mixed residential and commercial uses.

For nonresidential buildings that were constructed purely for nonresidential use (e.g., commercial, industrial, and institutional buildings), DEP adjusts EPA's attenuation factor to account for a higher air exchange rate in such structures. The 10th percentile air exchange rates for residential and commercial buildings are 0.18 and 0.60 air changes per hour, respectively (U.S. EPA, 2011b, Ch. 19). These are conservative rates, particularly for modern nonresidential buildings which typically have values exceeding 1 hr^{-1}. The adjusted nonresidential sub-slab attenuation factor is:

$$\alpha_{SS,NR} = (0.026) \times \frac{0.18\ hr^{-1}}{0.60\ hr^{-1}} = 0.0078$$

Sub-slab SVs are calculated directly from the indoor air SVs using the applicable attenuation factor:

$$SV_{SS} = \frac{SV_{IA}}{\alpha_{SS}}$$

3. Near-Source Soil Gas

Near-source soil gas samples are collected proximal to the source to minimize the influence of variable effects such as soil moisture, atmospheric conditions, and leakage from the surface into the sample that can bias shallow soil gas measurements. For groundwater and SPL the POA is immediately above the capillary zone throughout the area of the plume. For soil in the vadose zone the POA is within or immediately above the contaminated soil. Screening may be applied when at least a 5-foot vertical section of acceptable soil or soil-like material is present between the bottom of the building foundation and the depth where the near-source soil gas sample is obtained. (If a near-source soil gas sample is collected less than 5 feet below the foundation it may be screened using sub-slab soil gas SVs.) Near-source soil gas SVs (SV_{NS}) are defined using attenuation factors derived from modeling as explained below. These SVs have units of micrograms per cubic meter ($\mu g/m^3$).

DEP estimated a near-source soil gas attenuation factor (α_{NS}) by running numerous J&E model simulations (Johnson and Ettinger, 1991; U.S. EPA, 2004). DEP utilized EPA's advanced soil model (version 3.1, February 2004) to determine soil gas source concentrations corresponding to specified indoor air SVs. The simulations encompassed 12 to 16 different chemicals, the full suite of soil types, and water-filled porosities ranging from residual saturation to the EPA default values in the J&E manual. DEP made conservative assumptions of a shallow source (5 feet) and a high vapor flow rate (Q_{soil} = 5 L/min). EPA's default building characteristics for a small, slab-on-grade building were retained. The models had low, 10th percentile values for the air exchange rate (0.18 hr^{-1} residential, 0.60 hr^{-1} nonresidential; U.S. EPA, 2011b, Ch. 19).

The results of this modeling indicated that there is relatively little variability in the soil gas attenuation factor for different conditions. The silt soil type has the highest attenuation factor because of its low residual water content and relatively high air-filled porosity. Representative factors are $\alpha_{NS,R}$ = 0.005 and $\alpha_{NS,NR}$ = 0.001 for residential and nonresidential scenarios. To further assess these values DEP examined the soil gas data in EPA's VI database (U.S. EPA, 2012b). Of 46 buildings at four sites with paired deep soil gas (> 10 feet) and indoor air measurements, only one exceeded the modeled attenuation factor of 0.005. (This exception had a calculated attenuation factor of 0.0075.)

Near-source SVs are calculated directly from the indoor air values using the applicable attenuation factor:

$$SV_{NS} = \frac{SV_{IA}}{\alpha_{NS}}$$

4. Soil

Soil samples may be collected in the unsaturated zone as part of the site characterization or a demonstration of attainment following remediation. The POA is throughout the area of contamination. Screening may be applied to samples collected at any depth below the building foundation and above the water table. SPL should not be present. Soil SVs (SV_{SOIL}) are defined as the higher of a calculated SV and the generic soil-to-groundwater pathway numeric value for a used aquifer in 25 Pa. Code Chapter 250. Soil SVs have units of milligrams per kilogram, dry basis (mg/kg).

The calculated SVs are based on equilibrium partitioning of the contaminant between the sorbed phase on soil, the dissolved phase in pore water, and the vapor phase in the pore space. This relationship is given in § 250.308(a)(3) of the regulations, with the dilution factor set to 1:

$$\mathrm{SV}'_{\mathrm{SOIL}} = \left(f_{\mathrm{oc}} K_{\mathrm{oc}} + \frac{\theta_{\mathrm{w}}}{\rho_{\mathrm{b}}}\right) C_{\mathrm{pw}} \times \frac{1\ \mathrm{mg}}{1{,}000\ \mu\mathrm{g}}$$

where SV'_{SOIL} is the calculated SV for soil (mg/kg) and C_{pw} is the concentration in pore water (µg/L). The other parameters are defined in Table IV-A-3. The value of f_{oc} is from § 250.308(a)(3). The dry bulk density used is representative of typical soil types (U.S. EPA, 2004, 2017). DEP defines θ_w equal to 0.1 to represent relatively dry conditions, close to residual saturation, beneath a building.

The pore water concentration is related to the pore vapor concentration (C_{pv}) by Henry's law:

$$C_{\mathrm{pw}} = \frac{C_{\mathrm{pv}}}{H'} \times \frac{1\ \mathrm{m}^3}{1{,}000\ \mathrm{L}}$$

where Cpv has units of micrograms per cubic meter (µg/m^3). *H′* is calculated at a soil temperature of 16°C (61°F) (Appendix IV-B).

The value of the pore vapor concentration is determined from the SV_{IA} by means of soil attenuation factors:

$$C_{\mathrm{pv}} = \frac{\mathrm{SV}_{\mathrm{IA}}}{\alpha_{\mathrm{SOIL}}}$$

The soil attenuation factors were determined through testing with the J&E model as described in Section IV-A.3 of this appendix, but with a source depth of 0.5 feet, directly below the slab. The corresponding factors are $\alpha_{SOIL,R}$ = 0.01 and $\alpha_{SOIL,NR}$ = 0.002.

The soil SVs are limited by the residual saturation value of 10,000 mg/kg as defined in § 250.305(b).

Each calculated SV is compared to the generic soil-to-groundwater pathway numeric value for a used aquifer with total dissolved solids less than or equal to 2,500 mg/L (25 Pa. Code Chapter 250, Appendix A, Table 3B), and DEP defines the higher of the two values as the soil SV for VI (SV_{SOIL}). The generic soil-to-groundwater numeric values are considered appropriate for VI screening because soil contamination that is unable to impact aquifers in excess of groundwater MSCs is also unlikely to pose an excess inhalation risk. DEP also recognizes that the infinite source assumption used to calculate SVs is very conservative, that soil contamination commonly occurs outside the footprint of potentially impacted buildings, and that these SVs do not account for the natural biological degradation of petroleum hydrocarbons in soil vapor.

Table IV-A-3: Soil Partitioning Parameters

Symbol	Description	Value
f_{oc}	fraction organic carbon in soil	0.0025
K_{oc}	organic carbon partitioning coefficient (L/kg)	Table IV-A-5
θ_w	water-filled porosity of soil	0.1
ρ_b	dry bulk density of soil (kg/L)	1.5
H'	Henry's law constant at soil temperature	Table IV-A-5

5. Groundwater

Groundwater data that have been collected as part of the site characterization or a demonstration of attainment may be used for VI screening. The POA is throughout the area of the groundwater plume. Certain conditions apply to groundwater screening. Groundwater samples are collected from properly constructed monitoring wells screened across the water table, and the wetted length of the well screen should be no more than 10 feet. SPL is not present. When using screening values for groundwater that is at least 5 feet below the foundation, acceptable soil or soil-like material should be present between the groundwater and the foundation.

Groundwater SVs (SV_{GW}) for depths less than 5 feet below the foundation are defined by the groundwater MSCs for a used aquifer. Groundwater SVs for depths of 5 feet below the foundation and greater are defined as the higher of calculated SVs based on empirically determined attenuation factors and the groundwater MSCs for a used aquifer. SVs have units of micrograms per liter (µg/L).

EPA developed a database of 774 paired groundwater and indoor air sampling data at over 600 residential buildings located at 24 sites (U.S. EPA, 2012b). The data was limited to chlorinated VOCs. EPA performed a statistical evaluation of the database, and they recommended an attenuation factor of 0.001. This value is the 95th percentile of the screened data. The groundwater attenuation factor is defined as $\alpha_{GW} = C_{IA}/C_{GW}$.

The Department has reexamined EPA's database by considering two additional factors. One is the uncertainty in the groundwater temperatures selected for each site. In some instances the assigned temperatures may have been underestimated. The other is that EPA's evaluation included some data from buildings over shallow groundwater (less than 5 feet below the foundation). DEP reanalyzed the database with a range of plausible annual average groundwater temperatures and without the shallow groundwater data.

DEP has derived a residential groundwater attenuation factor of 0.0009 for groundwater that is at least 5 feet below the foundation. DEP has adopted this attenuation factor for all chemicals, including petroleum hydrocarbons, as a conservative approach. This residential factor ($\alpha_{GW,R}$) also applies to nonresidential buildings that were originally constructed for residential use ($\alpha_{GW,CR}$) or that have mixed residential and commercial uses.

For nonresidential buildings that were constructed purely for nonresidential use (e.g., commercial, industrial, and institutional buildings), DEP adjusts the residential attenuation factor to account for a higher air exchange rate in these structures. The 10th percentile air exchange rates for residential and commercial buildings are 0.18 and 0.60 air changes per hour, respectively (U.S. EPA, 2011b, Ch. 19). The adjusted nonresidential groundwater attenuation factor is:

$$\alpha_{\mathrm{GW,NR}} = (0.0009) \times \frac{0.18\ \mathrm{hr}^{-1}}{0.60\ \mathrm{hr}^{-1}} = 0.0003$$

Calculated groundwater SVs ($\mathrm{SV}'_{\mathrm{GW}}$) are determined from the indoor air SVs using the applicable attenuation factor and a conversion from soil gas to a dissolved concentration via Henry's law:

$$\mathrm{SV}'_{\mathrm{GW}} = \frac{\mathrm{SV}_{\mathrm{IA}}}{\alpha_{\mathrm{GW}}} \times \frac{1}{(1{,}000\ \mathrm{L/m^3})H'}$$

where H' is the nondimensional Henry's law constant at the groundwater temperature (Table IV-A-5 on the Department's VI web page). DEP calculates the Henry's law constant at a groundwater temperature of 16°C (61°F) (Appendix IV-B).

DEP compares each calculated SV to the groundwater MSC for a used aquifer with total dissolved solids less than or equal to 2,500 mg/L (Chapter 250, Appendix A, Table 1). DEP defines the groundwater SV for VI ($\mathrm{SV}_{\mathrm{GW}}$) for depths of 5 feet below the foundation and greater as the maximum of the calculated SV ($\mathrm{SV}'_{\mathrm{GW}}$) and the MSC, limited by the aqueous solubility (S). DEP regards the groundwater MSCs as suitable for VI screening at any depth because they are acceptable for water used inside homes, including inhalation exposures.

6. Building Foundation Openings

The sub-slab soil gas and groundwater attenuation factors are derived from EPA's database of residential VI sampling. DEP recognizes that many of the buildings used in EPA's study likely had typical foundation openings such as sumps, French drains, floor drains, and gaps around utility penetrations. (For instance, over three-quarters of the homes included in the sub-slab attenuation factor analysis had basements, and EPA did not filter the data for the presence of foundation openings.) For this reason, DEP considers the attenuation factors and screening values to be applicable to buildings with common openings. For a small house with a sump and an open, interior French drain, the size of these openings would not be more than a few percent of the foundation area. DEP's threshold for significant openings, which preclude the use of the attenuation factors and SVs, is 5% of the foundation area (Section IV.D.2).

DEP establishes attenuation factors for near-source soil gas and soil based on J&E model simulations. These tests assume a conservative, high vapor flow rate into the building, which would be representative of vapor entry through typical foundation openings. Therefore, the near-source soil gas and soil attenuation factors and SVs are also applicable to buildings that do not have foundation openings exceeding 5% of the foundation area.

7. Attenuation Factor Summary

The attenuation factors used to calculate the VI SVs are listed in Table IV-A-4. The sub-slab and groundwater attenuation factors are based on EPA's empirical database (U.S. EPA, 2012b). The near source soil gas and soil attenuation factors are defined from DEP's modeling studies.

Table IV-A-4: Attenuation Factors

Sample Type	α R	α NR	α CR
Sub-slab soil gas	0.026	0.0078	0.026
Near-source soil gas	0.005	0.001	0.005
Soil	0.01	0.002	0.01
Groundwater	0.0009	0.0003	0.0009

R: residential building
NR: nonresidential building
CR: residential building converted to nonresidential use

The near-source and sub-slab soil gas attenuation factors may also be used within a SSS risk assessment for estimating indoor air concentrations (Section IV.K.4) or for calculating SVs from EPA's indoor air RSLs (Section IV.K.5).

Appendix IV-B: Vapor Intrusion Modeling Guidance

DEP recommends the use of EPA's J&E model (U.S. EPA, 2004) for analyzing VI with the SHS and SSS. Remediators may use DEP's versions of the model which are based on EPA's advanced model version 3.1 spreadsheets. These versions are posted on DEP's website, and they will be updated periodically with the most recent toxicological and other model input parameters.

This appendix describes key assumptions and limitations of the J&E model, acceptable adjustments to default input values, and the use of alternative models for petroleum hydrocarbons.

1. Background

The J&E model solves for the transport of vapor-phase contaminants into a building above the source (Johnson and Ettinger, 1991; U.S. EPA, 2004, 2017). There are three spreadsheets for the different source types: groundwater, soil, and soil gas. The model calculates the vaporization of dissolved or adsorbed contaminants, the diffusion of these vapors toward the surface, their advection through the foundation or slab into the occupied space, and their dilution in indoor air. The calculations rely on five sets of parameters integral to this process and the inhalation risk assessment:

- source description (e.g., depth)
- chemical properties
- toxicological properties
- capillary fringe and vadose zone properties (e.g., soil type)
- building characteristics (e.g., air exchange rate).

The J&E model is an approximation that is dependent on many parameters, not all of which are well known. It is not easily calibrated; therefore, the user should input conservative values to avoid underestimating inhalation risks. Users submitting J&E models to DEP are expected to be familiar with EPA's *User's Guide* and should understand the model's assumptions and limitations (U.S. EPA, 2004, 2017).

Several studies have compared J&E model results to field data (Hers *et al.*, 2003; Provoost *et al.*, 2009, 2010) and to numerical analyses (Yao *et al.*, 2011). This research indicates that J&E gives reasonable, conservative results in most cases, within about one order of magnitude. These studies reinforce the need to use J&E with caution because the model is highly sensitive to some parameters. It is essential to have adequate site data and a strong CSM when modeling VI.

The objective of VI modeling is to determine if an Act 2 standard is attained. Although the EPA spreadsheets can calculate screening values, models submitted to DEP should not be used in this manner. Users must instead input the contaminant concentration on the DATENTER worksheet to calculate the incremental risk. The DEP versions give results in two forms, depending on the Act 2 standard selected for the contaminant.

For SHS evaluations, the user compares the predicted indoor air concentration on the RESULTS sheet to the SHS indoor air screening value (SV_{IA}) (Table IV-5 on the Department's VI web page).

For SSS risk assessments, the user obtains the incremental carcinogenic and noncarcinogenic inhalation risks from the RESULTS sheet, determines the cumulative risks for all SSS contaminants of concern, and compares the cumulative risks to the Act 2 thresholds (Section IV.K.5).

Under appropriate conditions in the SSS, predicted indoor air concentrations can be compared to occupational limits (OSHA PELs) (Section IV.K.7).

2. Assumptions

Users are referred to EPA's J&E *User's Guide* for a complete description of the model (U.S. EPA, 2004, 2017). It has several critical assumptions and limitations that all users must be aware of.

- The source extent is horizontally and vertically infinite. Source mass does not diminish with time. These are conservative assumptions.
- No SPL is present for soil and groundwater modeling.
- The solution is one-dimensional, accounting only for vertical vapor transport; lateral migration of vapors is ignored.
- Soil properties are homogeneous.
- There is no biodegradation of contaminant vapors in the vadose zone, a conservative assumption.
- There are no preferential pathways between the source and the building.
- The system is in steady state; that is, vapor transport is in equilibrium.
- The model does not account for the combined effects of multiple contaminants.

In addition, see U.S. EPA (2004, 2017) Section 2.4.

3. J&E Model Parameter Adjustments

Key input parameters and allowable changes to these values for VI modeling are explained in this section. The Department's conservative default model parameter values, as input on the DATENTER sheet of the J&E spreadsheet, are given in Table IV-B-1. Most input values used are EPA's defaults.

EPA developed their J&E model as a screening tool, and they recommend against using it to predict a unique indoor air concentration or risk (U.S. EPA, 2017). However, because DEP accepts J&E model results as a single line of evidence when sufficient supporting information is available, users should bias inputs (including source concentrations) to upper range values, not average or central tendency values.

Table IV-B-1: Adjustable J&E Model Input Parameters and Default Values

Parameter	Symbol	Residential	Nonresidential
Average soil/groundwater temperature (°C)	T_s	Table IV-B-2	Table IV-B-2
Depth below grade to bottom of enclosed space floor[1] (cm)	L_F	10 / 200	15 / 200
Depth below grade to source (cm)	L_{WT}, L_t, L^s	150	150
Thickness of soil strata (cm)	h	150	150
Capillary and vadose zone USDA soil types		sandy loam	sandy loam
Soil dry bulk density[2] (g/cm^3)	ρ_b	1.62	1.62
Soil total porosity[2]	n	0.387	0.387
Soil water-filled porosity[2]	θ_w	0.1	0.1
Enclosed space floor thickness (cm)	L_{crack}	10	10
Enclosed space floor length (cm)	L_B	1000	1000
Enclosed space floor width (cm)	W_B	1000	1000
Enclosed space height[3] (cm)	H_B	244 / 366	244 / 366
Indoor air exchange rate (hr^{-1})	E_R	0.18	0.60
Average vapor flow rate into building[4] (L/min)	Q_{soil}	5	5

Notes to Table IV-B-1

1 Default is 15 cm for a slab-on-grade building and 200 cm for buildings with basements.
2 The values shown are for a sandy loam. Models must use the J&E default values associated with the selected soil type unless soil samples are tested for physical characteristics.
3 Default is 244 cm for slab-on-grade buildings and 366 cm for buildings with basements.
4 Adjust default based on building size; see text.

- **Source concentration (C_W, C_R, C_g):** The user enters an appropriate contaminant concentration for groundwater (C_W, µg/L), soil (C_R, µg/kg), or soil gas (C_g, $\mu g/m^3$). Source data should conform to the conditions in Table IV-6. Input concentrations should generally be the maximum from recent sampling in the source area near current or future buildings (see Appendix IV-C, Figures IV-C-1-3). If sufficient data are available, a 95% UCL of the mean may be a suitable value. The data selected for determining the source concentration may have been collected for the site characterization and/or the demonstration of attainment. When the vapor source is a groundwater plume, fate-and-transport modeling may be used to estimate groundwater concentrations at downgradient receptors if monitoring well data is unavailable. The groundwater model should be calibrated, conservative, and applied in a manner consistent with DEP's Quick Domenico (QD) user's guide (Pennsylvania DEP, 2014). For the soil gas J&E model only near-source soil gas data may be used, and the source may include SPL.

- **Building foundation:** The default foundation type is slab-on-grade construction. The type of foundation establishes the value of the depth below grade of the enclosed space floor (L_F). For slab-on-grade foundations the EPA default is L_F = 10 cm (0.3 feet); for basements it is L_F = 200 cm (6.6 feet). This value may be altered with supporting documentation for the site building.

- **Depth below grade to source (L_{WT}, L_t, L_s):** The default value is 150 cm (5 feet). The user enters the actual minimum depth based on the site characterization and/or monitoring data. For groundwater, it should be the seasonally high water table depth of the contaminated aquifer (L_{WT}). For soil, it should be the depth to the top of contaminated soil (L_t). DEP recommends using the shallowest depth that either exceeds the soil screening value (SV_{SOIL}) or that is contaminated as indicated by field screening. For soil gas the source depth is the top of the screen in the soil gas probe (L_s).

  Acceptable soil or soil-like material should be present between the building foundation and the contaminant source. Acceptable soil or soil-like material will not have the following characteristics: obvious contamination (staining or odors), field instrument readings in the head space above soil samples greater than 100 ppmv, evidence of SPLs, or exceedances of soil screening values (refer to Section IV.B of the guidance). The thickness of acceptable soil or soil-like material may be less than 5 feet.

  Where there is a basement, the source must be entirely below the foundation as J&E does not model lateral vapor transport. Soil or groundwater with concentrations exceeding screening values cannot be in contact with the foundation. J&E simulates vapor diffusion through homogeneous, isotropic porous media. Therefore, it cannot determine vapor migration through fractured bedrock. If the water table is below the bedrock interface, then the model groundwater source depth (L_{WT}) should be input as the depth to bedrock. A continuous layer of acceptable soil or soil-like material should be present between the bedrock surface and the building foundation.

- **Depth below grade to bottom of contamination (L_b):** A finite source calculation is allowed for the soil model if the depth to the bottom of the contaminated soil has been delineated.

- **Soil/groundwater temperature (T_S):** Long-term average subsurface temperatures depend on the average air temperature of the locale and the nature of the surface material. Ground temperatures are higher in developed areas with buildings and pavement than where the land is undeveloped. DEP has compiled shallow groundwater temperature data collected during low-flow purging of monitoring wells at sites in the Southeast Region of Pennsylvania. In addition, DEP has examined continuous soil temperature data from three U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS), Soil Climate Analysis Network stations (Mahantango Creek, PA; Rock Springs, PA; and Powder Mill, MD). Each data set was compared to air temperature data collected from weather stations during corresponding periods. This information was supplemented with the study by Taylor and Stefan (2008).

  Average shallow subsurface temperatures are typically ~4°C higher than local air temperatures. DEP recommends using a model soil/groundwater temperature that is 4°C greater than the long-term average air temperature for the region. Thirty-year average temperatures for 1986–2015 available from the National Oceanic and Atmospheric Administration's (NOAA) NOWData application ranged from 50°F to 56°F (10–14°C) for Pennsylvania. Therefore, estimated regional average soil/groundwater temperatures are 14–18°C (Table IV-B-2).

Table IV-B-2: Pennsylvania Shallow Soil and Groundwater Temperatures

Northwest Region	**Northcentral Region**	**Northeast Region**
14°C	15°C	14°C
Southwest Region	**Southcentral Region**	**Southeast Region**
15°C	16°C	18°C

Users may input a site-specific soil and groundwater temperature based on data from a local weather station. The long-term average air temperature should be increased by 4°C for input as T_S. Discrete groundwater temperature measurements collected over a short period of time may not be representative of long-term conditions.

- **Soil type:** It is the user's responsibility to assess soil boring logs to select an appropriate soil type for input to the model. Field logging of borings should be performed by a qualified environmental professional (i.e., a geological scientist or a soil scientist). Where the soil is heterogeneous or there are different interpretations of the soil type, professional judgment must be used, but the best practice is to select the soil type with the greatest VI potential. This may require sensitivity testing of the model. The user may define up to three soil layers in the model if sufficient data has been obtained to support this option. The soil type entry in DEP's model versions is a sandy loam as a conservative default.

  EPA categorized soil using the U.S. Department of Agriculture's Soil Conservation Service (SCS) (now the NRCS) soil types. To select the soil type, the environmental professional interprets boring logs based on the Unified Soil Classification System (ASTM, 2011a) in terms of the SCS classifications. A gradation analysis of soil samples is the best means to select the proper soil type in J&E (ASTM, 2007). Table IV-B-3 can also assist the user with this selection, and Figure IV-B-1 shows the SCS soil types in terms of the proportions of clay, silt, and sand.

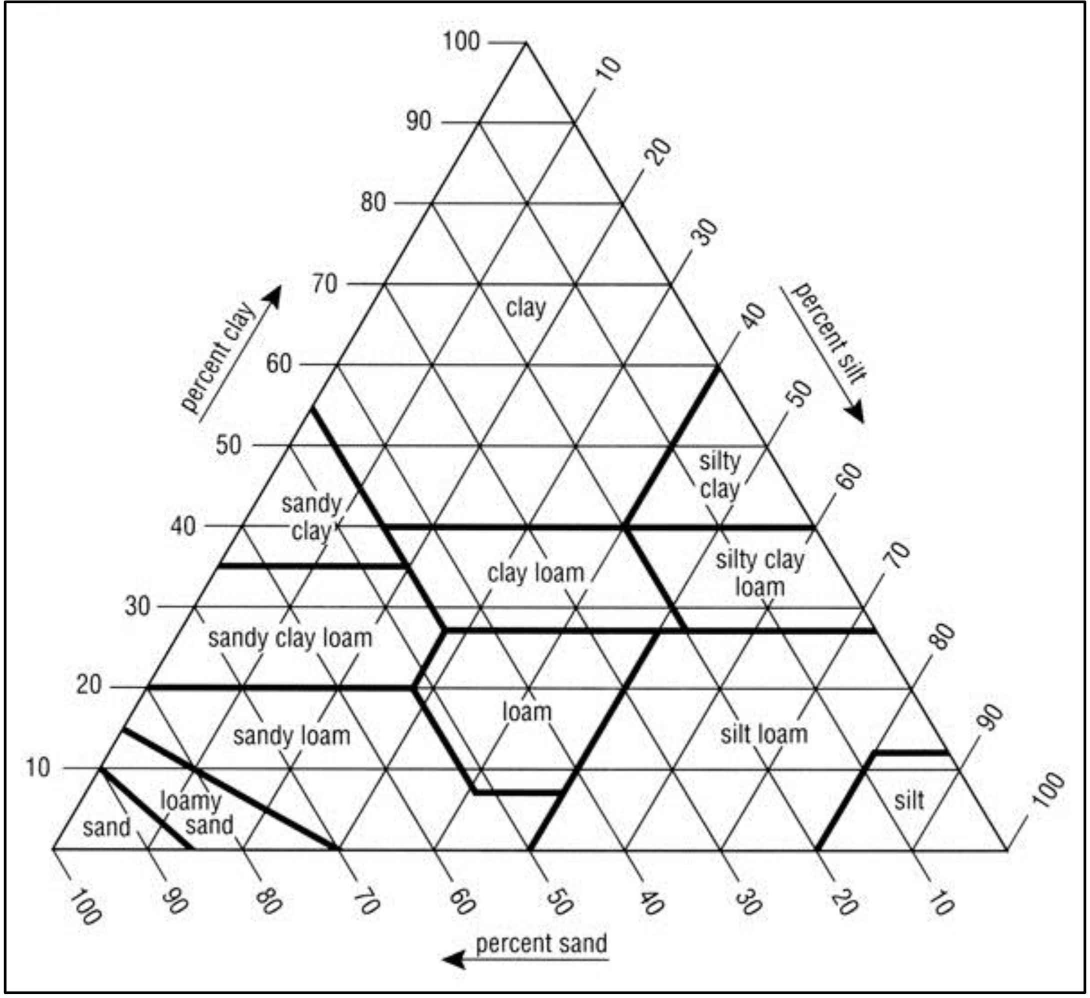
  If artificial fill is present, then the user must be cautious in applying the J&E model to the site. The fill might have characteristics sufficiently close to a USDA soil type to be acceptable for modeling; if so, the user can choose an appropriate soil type with justification in the report.

Table IV-B-3: Guidance for the Selection of the J&E Model Soil Type

Predominant Soil Types in Boring Logs	Recommended Soil Classification
• Sand or Gravel or Sand and Gravel, with less than about 12% fines, where "fines" are smaller than 0.075 mm in size.	Sand
• Sand or Silty Sand, with about 12% to 25% fines	Loamy Sand
• Silty Sand, with about 20% to 50% fines	Sandy Loam
• Silt and Sand or Silty Sand or Clayey, Silty Sand or Sandy Silt or Clayey, Sandy Silt, with about 45 to 75% fines	Loam
• Sandy Silt or Silt, with about 50 to 85% fines	Silt Loam

Source: U.S. EPA (2017), Table 14

Figure IV-B-1: USDA SCS Soil Classification Chart



Source: USDA (1993, Ch. 3).

- **Soil properties:** DEP has adopted the EPA default values for bulk soil density (ρ_b) and total porosity (n), which depend on the soil type. These values should not be altered unless properly collected samples (e.g., in thin-walled tubes) have been analyzed for these parameters (ASTM, 2009, 2010a). DEP does not consider the EPA default water-filled porosity values (θ_w) to be sufficiently conservative because soil beneath buildings is relatively dry. DEP's default value is 0.1 or the residual saturation (θ_r), whichever is greater for the soil type. The user can change θ_w only based on laboratory analyses of the moisture content of properly collected soil samples from underneath the building or an intact paved area large enough to be representative of a future inhabited building (ASTM, 2010b).

- **Fraction of organic carbon (f_{oc}):** The default value is 0.0025 from EPA and § 250.308(a). The user may change this value for soil modeling only with laboratory measurements of f_{oc} in site soils (e.g., U.S. EPA Method 9060A). However, the f_{oc} may be set to zero if the material is not believed to contain any organic carbon.

- **Floor thickness (L_{crack}):** The EPA default value is 10 cm (4 inches). This may be changed by the user if the actual (or planned) slab thickness is known. A dirt floor may be simulated with a value of zero.

- **Building dimensions (L_B, W_B, H_B):** The EPA default residential floor space area is 1,080 ft^2 (100 m^2) for a 10- by 10-m home. Default enclosed space heights (H_B) are 244 cm (8 feet) for slab-on-grade buildings and 366 cm (12 feet) for structures with basements. Note, however, that if indoor air does not communicate efficiently between the basement and the first floor, then the default value is not conservative and it should be reduced. The user may input the actual (or planned) building dimensions.

- **Air exchange rate (ER):** Air exchange rates exhibit a large range for different buildings and seasons. DEP adopts the current 10th percentile residential value of 0.18 hr^{-1} (U.S. EPA, 2011b, Ch. 19). The measured range in a study of 100 office buildings was approximately 0.2–4.5 per hour (Persily and Gorfain, 2009). A 10th percentile nonresidential value is 0.60 hr^{-1} (U.S. EPA, 2011b, Ch. 19). The user should input these 10th-percentile values for residential and nonresidential buildings. The actual air exchange rate of an existing or planned building may be input to the J&E model if it has been measured or is documented in the heating, ventilation and air conditioning (HVAC) system design and settings.

- **Vapor flow rate (Q_{soil}):** The soil gas flow rate into buildings is highly uncertain, and it depends on the material in contact with the foundation, the arrangement of cracks and other foundation openings, the pressure differential, and other factors. The EPA default value is 5 L/min based on tracer gas studies at five sites summarized by Hers *et al.* (2003). In the absence of better information on this parameter, DEP's default Q_{soil} is 5 L/min. If the user changes the building dimensions (LB and WB) then the value of Q_{soil} should be scaled correspondingly. Assuming vapor entry through foundation perimeter cracks, the scale factor is the ratio of the building perimeters. The default perimeter for the 10- by 10-m building is 40 m (130 feet). For example, if the building dimensions are 50 feet by 100 feet, the perimeter is 300 feet, the scale factor is 2.3, and Q_{soil} = 12 L/min.

  Another option is to enter a soil vapor permeability value and allow the model to calculate Q_{soil}. This is permitted only if the user obtains vapor permeability test data for the soil in contact with the foundation (ASTM, 2013a).

Although the prior version of J&E (U.S. EPA, 2004) provided for a calculation of Q_{soil} based on the soil type, this option is no longer available in the DEP and EPA models (U.S. EPA, 2017). The pressure differential (ΔP) and crack width (w) inputs were used only for the Q_{soil} calculation and are therefore disabled in the DEP spreadsheets.

Chemical, physical, and toxicological properties for substances with VI potential are found in the VLOOKUP sheet. DEP's default values are listed in Table IV-A-5 on the Department's VI web page. These default properties and the default residential or nonresidential exposure factors cannot be changed in SHS modeling. (Model-predicted indoor air concentrations for the SHS do not depend on the exposure factors on the DATENTER sheet or the toxicological parameters in the VLOOKUP sheet.)

The EPA J&E model versions do not account for the effect of mutagenic chemicals on the cancer risks for residential exposure scenarios. The inhalation risk equations for mutagens are provided in Appendix IV-A. DEP's versions of the spreadsheets include a mutagenic risk adjustment factor (MRF) that is applied when the exposure time is entered as 24 hr/day. For the default conditions, MRF = 1.4 for trichloroethylene, 3.4 for vinyl chloride, and 2.5 for other mutagens.

4. Site-Specific Standard Parameter Adjustments

Users of the J&E model may change certain chemical and toxicological properties in the VLOOKUP sheet for the SSS.

- **Organic carbon partition coefficient (K_{oc}):** The default values are from Chapter 250, Appendix A, Table 5A. The values may be changed only if the user obtains laboratory test data of soil samples collected at the site.

- **Toxicity parameters (IUR, RfC_i):** The inhalation unit risk (or unit risk factor, URF) and the inhalation reference concentration are from Chapter 250, Appendix A, Table 5A. For a SSS risk assessment, the user should determine if there is more recent toxicity information available. Current values should be substituted for the Chapter 250 values, if available.

Exposure factors are entered on the DATENTER sheet for SSS risk assessments. The default values are listed in Table IV-B-4. Residential factors should not be changed. The user may adjust nonresidential factors based on conditions at the site. For instance, the daily exposure time could depend on the workplace shift length. EPA currently recommends a residential exposure duration of 26 years (U.S. EPA, 2014b), which may be used in SSS models. (DEP's versions of the J&E spreadsheets include a field for the exposure time (ET), allowing it to be altered from the residential default of 24 hr/day.)

Table IV-B-4: J&E Model Default Exposure Factors

Symbol	Term	Residential	Nonresidential
AT_{nc}	Averaging Time for systemic toxicants (yr)	30	25
ET	Exposure Time (hr/day)	24	8
EF	Exposure Frequency (days/yr)	350	250
ED	Exposure Duration (yr)	30	25
AT_c	Averaging Time for carcinogens (yr)	70	70

5. Petroleum Hydrocarbons

DEP can accept the use of models that account for biodegradation when evaluating petroleum hydrocarbon VI. Examples include the American Petroleum Institute's BioVapor (API, 2010) and EPA's PVIScreen (U.S. EPA, 2016b).

BioVapor and PVIScreen have several additional parameters that must be assessed in the modeling. The user should test the model sensitivity to these values.

- **Oxygen boundary condition:** The user should normally select a constant air flow rate (Q_f), and this is typically set equal to the vapor flow rate through the foundation (e.g., Q_{soil} = 5 L/min). If site data is collected to determine vertical profiles of oxygen, carbon dioxide, and methane concentrations, then the user may estimate the depth of the aerobic zone for model input.

- **Baseline soil oxygen respiration rate:** The model scales this rate with the fraction of organic carbon (f_{oc}), which is not typically known for the site. A default value is provided in PVIScreen.

- **Biodegradation rate constants (k_w):** BioVapor selects default first-order, aqueous phase, aerobic decay rates. Actual degradation rates are extremely variable, and PVIScreen accounts for their uncertainty. Vertical profiling of contaminant concentrations in soil gas may allow the user to estimate the decay rates.

EPA produced an NAPL version of the J&E model (U.S. EPA, 2004). This model was limited to residual NAPL in soil; it was not applicable to mobile NAPL on groundwater. DEP has not developed an updated version of EPA's NAPL spreadsheet, and it is not available in EPA's current J&E version (U.S. EPA, 2017). DEP recommends the collection of near-source soil gas data in areas of SPL (NAPL) for purposes of VI modeling.

6. Attenuation Factor Risk Calculations

SSS screening and risk assessments may also be performed under certain conditions with near-source soil gas and sub-slab soil gas data by using conservative attenuation factors (α). An attenuation factor is the ratio between the contaminant concentration in indoor air and the equilibrium soil gas concentration in the unsaturated zone ($\alpha \equiv C_{IA}/C_{SG}$). Therefore, conservative indoor air concentrations may be estimated using a measured or calculated soil gas concentration and an appropriate attenuation factor. Refer to Appendix IV-A for the relevant equations and Table IV-A-4 for DEP's default attenuation factors. The conditions for using near-source soil gas attenuation factors are the same as those listed for the screening values in Section IV, Table IV-6.

Other soil gas attenuation factors may be used with adequate justification for the SSS. For instance, a tracer test could be used to determine a sub-slab attenuation factor (α_{SS}) for the building. The default attenuation factors may be scaled with actual air exchange rates (AER) for the building. DEP's default indoor air exchange rates are 0.18 hr^{-1} for residential properties and 0.60 hr^{-1} for nonresidential facilities. The adjusted attenuation factor (α') is the product of the default attenuation factor and the ratio of the default AER and the actual AER. For example, if a nonresidential building has a measured air exchange rate of 1.2 hr^{-1}, then the sub-slab attenuation factor may be reduced as follows:

$$\alpha'_{SS,NR} = \alpha_{SS,NR} \frac{0.60\ hr^{-1}}{1.2\ hr^{-1}} = (0.0078) \frac{0.60\ hr^{-1}}{1.2\ hr^{-1}} = 0.0039$$

7. Report Contents

The J&E modeling should be fully documented in the submitted report. The information provided should be sufficient for DEP to understand how the modeling was performed and to reproduce the results. The model description should include the following.

- An explanation for how the model is being used to evaluate the VI pathway; that is, for a SHS prediction of indoor air concentrations or a SSS human health risk assessment.
- A list of the contaminants of concern being modeled and the source concentration inputs.
- An explanation of how source concentrations were selected (for example, the maximum groundwater concentrations from monitoring well data).
- A table of all input parameters, such as source depth and soil type.
- The reasoning for any changes to default input values.
- References for any changes to toxicological values in SSS models.
- A table of the predicted indoor air concentrations for each contaminant of concern in SHS reports, or a table of the individual and cumulative inhalation risks in SSS reports.
- A figure showing the source area, the locations of sample points used for the source concentrations, any preferential pathways, and potentially impacted buildings.
- An appendix with J&E worksheet printouts for the modeling. The DATENTER and RESULTS sheets should be provided for each contaminant of concern. One copy of the VLOOKUP sheet should be included.

Appendix IV-C: Vapor Intrusion Sampling Methods

1. Introduction

This appendix provides guidance on sampling and testing procedures to support VI investigations and mitigation. It describes recommendations for collecting VI-related samples, but it is not meant to be a manual with step-by-step instructions for VI sampling requirements. Professional judgment should be exercised during the development of sampling plans considering that every site will have its own unique conditions. Remediators are encouraged to communicate with the DEP Project Manager to determine the best path forward for VI sampling.

The information in Appendix IV-C includes descriptions of the methods and (QA) procedures to be used when collecting and analyzing VI-related samples. DEP's focus is on sampling with Summa canisters and U.S. EPA Method TO-15 analyses. When other methods are used the remediator should refer to alternative sources and consult with the laboratory. This appendix also provides guidance on testing to confirm the effectiveness of sub-slab depressurization systems which are the most commonly used VI mitigation technology for existing buildings.

a) Applicability

The guidance supplied by this appendix applies whenever sampling and analysis of soil gas or indoor air is performed:

- During site characterization;
- During site monitoring following site characterization;
- Following remediation; or
- When mitigation is performed using sub-slab depressurization (SSD) systems.

The information provided herein may be used to address VI sampling or mitigation activities under either the SHS or the SSS or under a combination of these two standards. These procedures also apply regardless of the size or scope of the VI evaluation when sampling and analysis of indoor air or soil gas is performed or a SSD System is used to mitigate VI.

b) Conceptual Site Model Development

A comprehensive CSM is an important tool in the development of a sampling and analysis plan. The CSM is needed to determine the locations and types of samples that are to be taken. More information on the development of a comprehensive CSM can be found in Section IV.C.1.

c) Spatial and Temporal Variability Considerations

When preparing a VI sampling plan it is important to consider the spatial and temporal variability of contamination in soil gas and indoor air. Spatial variability refers to non-uniform concentrations at different locations within or beneath the same building.

Temporal variability involves concentrations that change from one sampling event to the next. Compared to groundwater concentrations, there are many complicating factors that can cause significant variability in vapor data.

Some causes of spatial variability include:

- Distribution of the source in soil or groundwater;
- Natural heterogeneity (different soil types, soil moisture, bedrock fractures);
- Oxygen distribution in the soil (aerobic/anaerobic conditions);
- Subsurface building structures (footers, utilities);
- Surface features (pavement).

Some causes of temporal variability include:

- Wind, barometric pressure, temperature;
- Precipitation, infiltration, soil moisture, frozen ground;
- Building ventilation, heating, cooling;
- Ambient contaminants (indoor and outdoor sources);
- Sampling errors (equipment leaks).

Research studies have been conducted regarding the spatial variability of vapor concentrations by collecting multiple samples beneath, around, or within buildings (e.g., McHugh *et al.*, 2007; Luo *et al.*, 2009; U.S. EPA, 2012b, 2015c). The results of these studies have shown that sub-slab and soil gas concentrations can span orders of magnitude at a given building, even for moderately sized homes. Indoor air concentrations tend to show less variability as indoor air is typically well mixed in homes and smaller nonresidential buildings. Larger buildings may show greater room-to-room variability influenced by spatial heterogeneity of VI in those areas, possible indoor sources, and different ventilation conditions. For the same reasons, a sample collected at one building may not be representative of conditions at a neighboring building.

Accounting for VI spatial variability in the sampling plan is similar to adequately characterizing soil contamination at a site: a sufficient number of sample points must be installed to evaluate representative concentrations. The CSM should be the guide for choosing these locations. The horizontal and vertical distribution of the vapor source relative to the building, the soil and bedrock conditions, likely pathways to and through the foundation, and the building characteristics (construction, ventilation, etc.) should be considered by the environmental professional developing the sampling approach. Based on site-specific conditions, a single sample location may not be adequate.

Repeat sampling of the same location at several study sites has similarly demonstrated substantial changes in vapor concentrations over time (e.g., Folkes *et al.*, 2009; U.S. EPA, 2010, 2012b, 2012c, 2015c, 2015d; Holton *et al.*, 2013; Schuver *et al.*, 2018). Soil gas, sub-slab, and indoor air concentrations have been found to vary by up to three orders of magnitude over periods of months to years. Shallow soil gas tends to have much greater variability than deeper soil gas, making near-source soil gas a more reliable measure of VI. Much of the variability of indoor air data can be attributed to conditions other than VI.

Temporal and spatial variability in soil gas and indoor air sample results is addressed by using a combination of multiple rounds of samples and multiple sample locations. The goal is to collect sufficient data to determine representative concentrations beneath or within the building. Refer to Section IV.G.2. and Table IV-7 for recommendations on the appropriate number of sampling events and sample locations.

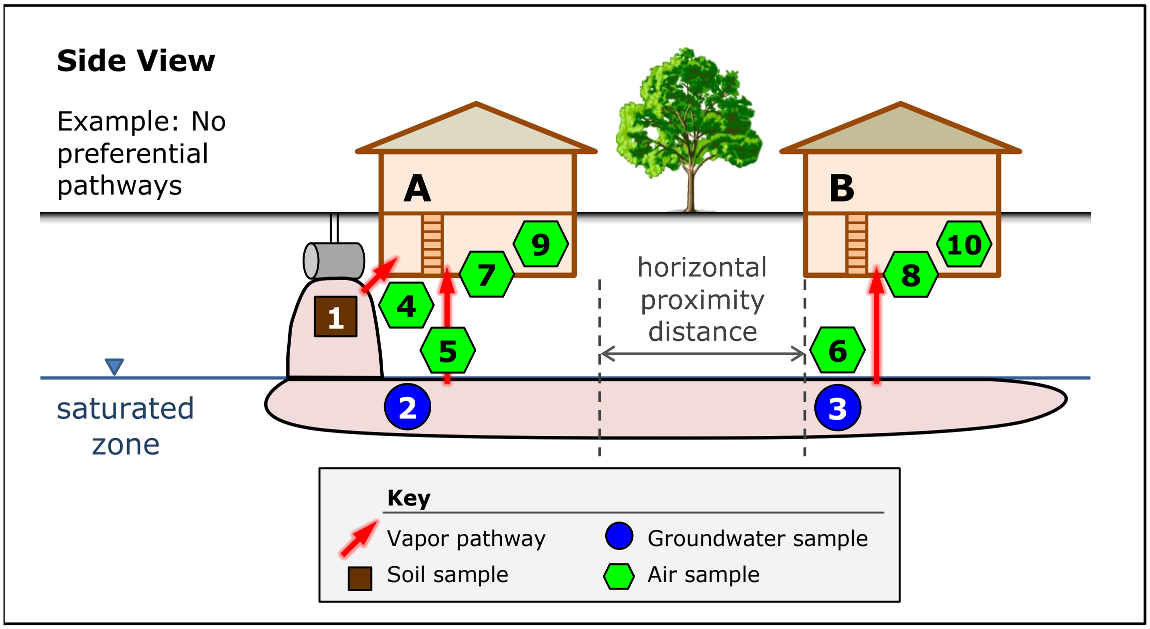
2. Sampling Locations

Figures IV-C-1 through IV-C-3 depict simplified VI scenarios that illustrate sampling location options for the application of screening values and modeling. They include situations without any preferential pathways (Figure IV-C-1), an external preferential pathway (Figure IV-C-2), and a significant foundation opening (Figure IV-C-3). Vertical proximity distances are not considered in these examples. (See Figures IV-3 and IV-4 for additional illustrations of the relationships between sources and buildings in the context of preferential pathways and proximity distances.) The information conveyed in Figures IV-C-1-IV-C-3 must be used in association with the sampling and screening conditions discussed in Sections IV.D, IV.F, IV.G, and IV.K.4., Tables IV-6 and IV-7, and the other parts of this appendix. Refer to Appendix IV-B for further details on using sample data in VI models.

In Figure IV-C-1 a release has contaminated soil adjacent to one building, and the resultant groundwater plume potentially affects it and a downgradient building. Building B is beyond the horizontal proximity distance from the soil contamination, so potential VI from soil only needs to be evaluated for Building A. Potential VI impacts from groundwater beneath Building B should be evaluated with monitoring well data near or upgradient of that building. Note that if the remediator chooses to sample near-source soil gas then distinct samples may be required for the soil and groundwater sources near a given building.

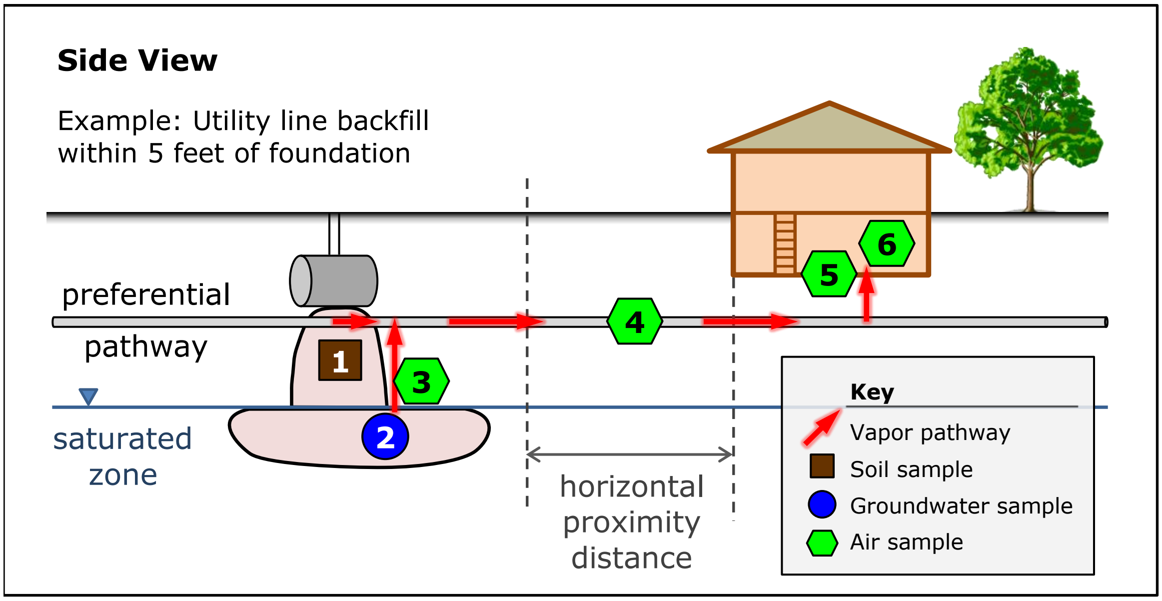
Figure IV-C-2 illustrates an external preferential pathway, such as gravel backfill around a utility line that allows vapors to migrate to a building from a source farther than the horizontal proximity distance. (No significant foundation openings are present.) Modeling is not an assessment option for the pathway to the existing building. The remediator may attempt to collect soil gas samples from within the backfill (location 4); they should be evaluated with sub-slab soil gas screening values. See Section IV.D.1. for additional information.

Figure IV-C-1: Sampling Location Options: Soil and Groundwater Sources



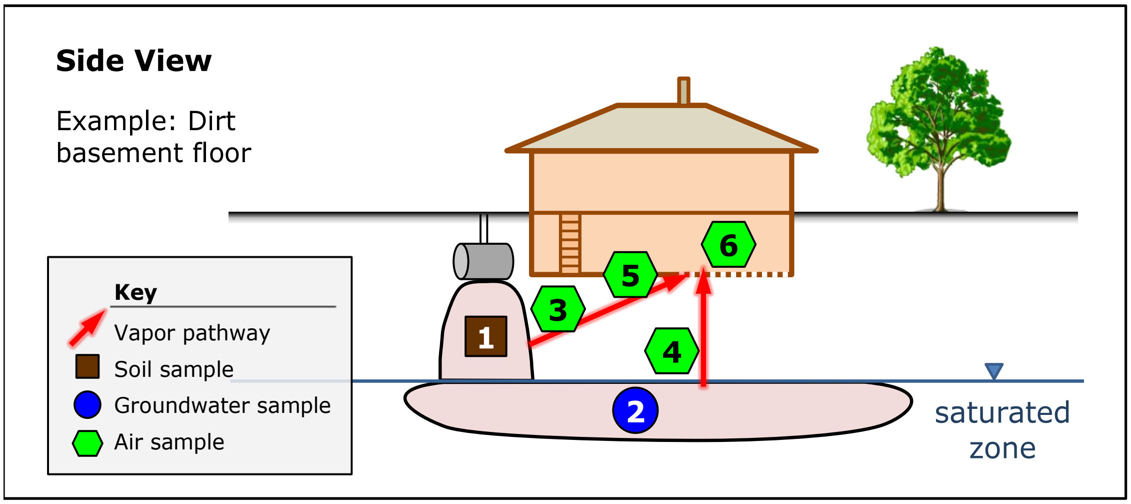
Sample	Description	Screen
1	Soil samples in source area, evaluation of Building A. Restriction: No SPL. Modeling: Yes.	SV_{SOIL}
2	Groundwater samples in source area, evaluation of Building A. Restriction: No SPL. Modeling: Yes.	SV_{GW}
3	Groundwater samples in plume, evaluation of Building B. Restriction: No SPL. Modeling: Yes.	SV_{GW}
4	Near-source soil gas samples at soil source, evaluation of Building A. Modeling: Yes.	SV_{NS}
5	Near-source soil gas samples above groundwater source, evaluation of Building A. Modeling: Yes.	SV_{NS}
6	Near-source soil gas samples above groundwater plume, evaluation of Building B. Modeling: Yes.	SV_{NS}
7	Sub-slab soil gas samples beneath Building A foundation.	SV_{SS}
8	Sub-slab soil gas samples beneath Building B foundation.	SV_{SS}
9	Indoor air samples, evaluation of Building A.	SV_{IA}
10	Indoor air samples, evaluation of Building B.	SV_{IA}

Figure IV-C-2: Sampling Location Options: External Preferential Pathway



Sample	Description	Screen
1	Soil samples in source area. Restriction: No SPL. Modeling: Permitted for future use over source, but not for current use via preferential pathway.	SV_{SOIL}
2	Groundwater samples in source area. Restriction: No SPL. Modeling: Permitted for future use over source, but not for current use via preferential pathway.	SV_{GW}
3	Near-source soil gas samples in source area (soil and/or groundwater). Restriction: No groundwater contamination or SPL migrating through preferential pathway. Modeling: Permitted for future use over source, but not for current use via preferential pathway.	SV_{NS}
4	Soil gas samples within preferential pathway. Restriction: Preferential pathway must contain a permeable material, such as backfill in a utility line trench. Modeling not permitted.	SV_{SS}
5	Sub-slab soil gas samples beneath building foundation. Restriction: Preferential pathway does not penetrate foundation.	SV_{SS}
6	Indoor air samples.	SV_{IA}

Figure IV-C-3: Sampling Location Options: Significant Foundation Opening



Sample	Description	Screen
1	Soil samples in source area. Restriction: No SPL. Modeling: Enter floor thickness of zero (L_{crack} = 0).	SGN*
2	Groundwater samples in source area. Restriction: No SPL. Modeling: Enter floor thickness of zero (L_{crack} = 0).	MSC
3	Near-source soil gas samples in soil source area. Modeling: Enter floor thickness of zero (L_{crack} = 0).	SVSS
4	Near-source soil gas samples above groundwater plume. Modeling: Enter floor thickness of zero (L_{crack} = 0).	SVSS
5	Sub-slab soil gas samples beneath building foundation. Restriction: Foundation slab must be present.	SVIA
6	Indoor air sampling.	SVIA

* Generic soil-to-groundwater numeric value.

Figure IV-C-3 shows sampling locations for a significant foundation opening, such as a section of dirt floor in the basement. In the example the contamination is beneath the building, and there is no external preferential pathway. Soil data can be screened with generic soil-to-groundwater numeric values; groundwater data can be screened with used aquifer MSCs. For screening of near-source soil gas data only sub-slab soil gas screening values should be used. Modeling of soil, groundwater, and near-source soil gas data may be carried out by setting the floor thickness equal to zero (Appendix IV-B). Both sub-slab and indoor air sample data should be screened with indoor air screening values; sub-slab points require an area of intact floor slab. See Section IV.D.2 for further information.

3. Near-Source Soil Gas Sampling

a) Description

Near-source soil gas is sampled from within the vadose zone, specifically from within nominally one (1) foot of the contamination source (contaminated soil or groundwater). For a groundwater source, near-source soil gas samples should be collected within one (1) foot of the top of the capillary fringe if the water table occurs in soil. If the water table occurs in bedrock, the near-source soil gas samples should be collected within one (1) foot of the soil–bedrock interface.

The height of the capillary fringe is not readily determined in the field. The following table provides theoretical estimates from U.S. EPA (2017, Table 13) which may be used as a guide. (Refer also to Appendix IV-B, Section IV-B.3 for additional information on soil type identification.)

Table IV-C-1: Capillary Fringe Height Estimates

Soil Type	L_{cz} (cm)	L_{cz} (ft)
Sand	17	0.6
Loamy Sand	19	0.6
Sandy Loam	25	0.8
Sandy Clay Loam	26	0.9
Sandy Clay	30	1.0
Loam	38	1.2
Clay Loam	47	1.5
Silt Loam	68	2.2
Clay	82	2.7
Silty Clay Loam	130	4.4
Silt	160	5.3
Silty Clay	190	6.3

L_{cz}: capillary fringe thickness

b) Sample Point Installation

Near-source soil gas sampling points can be temporary (used for one sampling event and decommissioned) or semi-permanent (used for multiple sampling events). Recommended resources for soil gas points include API (2005), California EPA (2015), ASTM (2012a), Hawaii DoH (2014), and ITRC (2014).

i) Installation of Temporary Points

Installation and construction of temporary points may be less time and cost sensitive. However, these potential savings may be offset over the life of the project as new points must be installed for each round of sampling. In general, temporary points rely on the use of boring advancement tools for the collection of the soil gas sample and the sealing of the point from the atmosphere. This is accomplished with the compression of the soil along the sides of the boring against the boring advancement tools. Use of temporary points is not recommended but may be necessary due to site conditions or site development. Prior to the utilization of temporary points, the feasibility of the following factors should be carefully considered:

- Proper sealing of the sampling interval from the surface;
- Isolation of the sampling interval within the boring;
- Potential of negative effects of boring advancement using drive-point techniques (e.g., decrease of soil gas permeability due to smearing or compression); and
- Unknown correlation of analytical results for multiple sampling rounds.

ii) Installation and Construction of Semi-Permanent Points

Semi-permanent points are generally constructed in borings advanced using conventional drilling technologies and sealing of the point is accomplished using bentonite or grout in the annulus of the boring. Boring advancement techniques should attempt to minimize disturbance of the vadose zone geologic strata and soil vapor column. Drilling methods that introduce air (e.g., air rotary) or liquid (e.g., mud-rotary) should be avoided.

4. Sub-Slab Soil Gas Sampling

a) Description

Sub-slab soil gas is sampled immediately below the floor slab of a building. The slab can be at grade (slab-on-grade) or below grade (basement).

b) Location

Sub-slab soil gas is located beneath the slab in the porosity of the native soil, ballast stone, or gravel that the building slab was placed over. Sub-slab soil gas sampling locations should be determined based on the specific characteristics of the building being sampled and the objectives of the sampling plan. Whenever possible, sampling locations should be biased toward areas of the building with the greatest expected VI impact, based on a combination of the location of VI sources and building occupancy and use. In general, sampling locations are at least 5 feet from perimeter foundation walls and sampling next to footers, large floor cracks, and apparent slab penetrations (e.g., sumps, floor drains) should be avoided.

c) Sample Point Installation

Sub-slab soil gas sampling points can be temporary (used for one sampling event and decommissioned) or semi-permanent (used for multiple sampling events). The building occupancy, use, and project goals are influential in the determination of which type of sampling point to use. A pre-survey, as described in Section IV-C.8(a)(i) herein, can be completed to assist in determining this information. Generally, installation and construction of temporary points is less time and cost intensive. However, these potential savings may be offset over the life of the project as new points must be installed for each round of sampling.

Sub-slab soil gas sampling points are generally installed inside penetrations through the building slab. Penetrating the floor slab can be accomplished using a hammer drill and bit, a core drill, or direct-push technology. Care should be taken during the floor slab penetration activities to avoid the creation of cracks in the slab. Additionally, the use of water or other lubricants and coolants during the advancement of the floor slab penetration should be compatible with the sampling analyte list and may result in the need for additional point equilibration time (see Section IV-C.8(a)(iv) herein) or the need to develop the sampling point to limit potential interaction of the sample with the water or lubricants.

Recommended resources for sub-slab points include California EPA (2011a), New Jersey DEP (2013), Hawaii DoH (2014), and ITRC (2014).

5. Indoor Air Sampling

a) Sampling Indoor Air

Indoor air sampling is performed when the potential for VI exists through other lines of evidence, and other investigative tools are not able to eliminate the VI pathway. Indoor air sampling may also be considered as a method for mitigation system verification. When compared to the other investigative tools available, indoor air sampling represents the most direct measure of exposure due to the VI pathway however it also can be heavily influenced by background conditions.

Recommended resources for indoor air sampling include New York DoH (2006), California EPA (2011a), New Jersey DEP (2013), Hawaii DoH (2014), and ITRC (2014).

When collecting indoor air samples, it is preferable to collect samples at a time and location that will result in the highest potential concentrations. Samples should be collected from the lowest level of the structure with appropriate accessibility where vapors are expected to enter, including basements, crawl spaces, and where preferential pathways have been identified. Existing environmental data (e.g., groundwater, soil, sub-slab soil gas, etc.), site background information, building construction (e.g., basement, slab-on-grade, or multiple types of foundations, elevator shafts, tunnels, etc.), and building operation details (e.g., number and operation of HVAC systems) as evaluated through the development of the CSM should be considered when selecting locations within the building for indoor air sampling. Indoor air samples may be collected concurrently and collocated with sub-slab soil gas sampling locations, and concurrently with an outdoor ambient air sample.

To characterize contaminant concentrations trends and potential exposures, indoor air samples are commonly collected:

- From the crawl space area;

- From the basement (where vapor infiltration is suspected, such as near sump pumps or indoor wells, or in a central location);

- From the lowest level living space (in centrally located, high activity use areas);

- From multiple tenant spaces if in a commercial setting.

If the pre-survey (Section IV-C.8(a)(i) herein) determines that chemicals of concern for VI are used, handled, or stored in the building being investigated, then those materials should be removed prior to collecting indoor air samples, if possible. The building should be ventilated for at least 24 hours following removal and before sampling. Other lines of evidence may be necessary, such as collocated sub-slab soil gas and indoor air samples, if the materials cannot be removed.

b) Outdoor Ambient Air Sampling

To understand potential background influences during indoor air sampling, an outdoor ambient air sample is commonly collected. This sample provides background concentrations outside of the building being investigated at the time of the indoor air sampling event. The investigator commonly designates a sample location and the site conditions at the time of sampling. The investigator also should be aware of the weather conditions during the sampling event. The sampler should be placed in a secure outside location.

Atmospheric pressure and temperature data from nearby weather reporting stations or through portable meteorological equipment should be collected in conjunction with the ambient air samples. Two web sites that may be useful to the investigator are NOAA's National Weather Service and the Weather Underground.

The following actions are commonly taken to document conditions during outdoor air sampling and ultimately to aid in the interpretation of the sampling results:

- Outdoor plot sketches are drawn that include the building site, area streets, outdoor air sampling location(s), the location of potential interferences (e.g., gasoline stations, dry cleaners, factories, lawn mowers, etc.), compass orientation (north), and paved areas;

- Weather conditions (e.g., precipitation and outdoor temperature) are reported;

- Predominant wind direction(s) during the sampling period are reported using wind rose diagrams; and

- Pertinent observations, such as odors, readings from field instrumentation, and significant activities in the vicinity are recorded.

6. Sampling Soil Gas for Oxygen Content

Note: This section of the guidance is intended only for remediators using the vertical proximity distances for petroleum hydrocarbons.

If the remediator chooses to screen a site using the vertical proximity distances for petroleum hydrocarbons, the acceptable soil or soil-like material should contain greater than 2% oxygen, on a volumetric basis. Oxygen content above this level indicates an aerobic environment that enables biodegradation of petroleum vapors. The investigator can measure the oxygen concentration in the vadose zone at buildings that are potential receptors to demonstrate that the aerobic soil condition is met.

DEP recommends collecting a soil gas sample beneath the building for oxygen content when there is reason to suspect that the soil may be anaerobic (Section IV.E). Only one grab sample collected at a single location is sufficient. A hole should be drilled approximately 12 inches into acceptable soil or soil-like material (i.e., beneath any gravel or similar fill material underlying the slab). Tubing with a probe tip is dropped into the hole, which is then filled with clean sand (e.g., Hawaii DoH, 2014, Section 7.9.3).

When it is not feasible to obtain the soil gas sample beneath the building, a near-slab soil gas sample may be collected. The sample point should be as close to the building as practical, and no farther than 10 feet. It should be located in the area of greatest anticipated soil vapor contamination. The screen depth should be above the top of the soil or groundwater contamination (e.g., smear zone) and below the bottom of the building foundation. The screen should also be at least 5 feet below the ground surface. The investigator may also collect samples at multiple depths to obtain a concentration profile demonstrating biodegradation. The sample probe should be allowed to equilibrate with the subsurface and purged.

In addition to analysis of oxygen (O_2), additional compounds such as carbon dioxide (CO_2) and methane (CH_4) can be measured to document biodegradation. One grab sample is sufficient to demonstrate that the 2% O_2 criterion is satisfied. The sample may be analyzed using a properly calibrated portable instrument. Oxygen should be calibrated at around 2% and 21%. Alternatively, the sample may be collected using a Tedlar bag or a Summa canister and analyzed at a mobile or offsite laboratory using EPA Reference Method 3C.

7. Sampling Separate Phase Liquids

When SPL is present, soil and groundwater screening and modeling are not options available for assessing VI. However, the remediator may obtain a sample of the SPL from a monitoring well to determine if VOCs posing a VI risk are present. This section describes how to evaluate the SPL data for VI.

The SPL sample should be analyzed with U.S. EPA Method 8260C. The results may be reported in units of mass per volume (micrograms per liter, µg/L) or mass per mass (micrograms per kilogram, µg/kg). If the data is reported on a volumetric basis, then the SPL density must be estimated or measured to calculate the mass fraction of each volatile component (e.g., ASTM, 2012b). In addition, the molecular weight of the SPL must be estimated from reference values or an analysis to calculate the mole fraction of each component (e.g., ASTM, 2014).

The vapor concentration (C_v) of each volatile component over the SPL, in units of micrograms per cubic meter ($\mu g/m^3$), equals:

$$C_v = \frac{x_i (VP)(MW)}{RT} \times (10^9)$$

Where x_i is the calculated liquid phase mole fraction of the component in the SPL, and the other quantities are defined in Table IV-C-2. (The 10^9 factor converts from units of g/L to $\mu g/m^3$.)

Table IV-C-2: SPL Vapor Phase Parameters

Symbol	Description	Value	Units
VP	vapor pressure	VISL	mm Hg
MW	molecular weight	Table IV-A-5	g/mol
R	universal gas constant	62.4	L (mm Hg) mol–1 K–1
T	temperature	Table IV-B-2	K

VISL: U.S. EPA's VISL Calculator spreadsheet (U.S. EPA, 2014a).

The vapor concentrations calculated for each substance of concern in the SPL using the above equation are comparable to near-source soil gas concentrations. Therefore, they may be evaluated with near-source soil gas screening values (Table IV-3 on the Department's VI web page for the SHS) to determine if each chemical poses a potential VI risk. Alternatively, the calculated vapor concentrations may be used with a near-source soil gas attenuation factor in a cumulative risk assessment under the SSS (Appendix IV-B, Section IV-B.6). If the SPL is less than 5 feet below the building foundation, then one should apply sub-slab soil gas screening values (Table IV-4 on the Department's VI web page) and sub-slab soil gas attenuation factors.

As an example, consider SPL that is inferred to be No. 6 fuel oil present beneath a nonresidential building. Analysis of a sample of the SPL finds that benzene is nondetect, with a quantification limit of 50,000 µg/L. The density of the SPL is measured, and the result is 8.1 lb/gal (0.97 kg/L). The molecular weight of benzene is 78 g/mol, and the approximate molecular weight of No. 6 fuel oil is 300 g/mol. Therefore, using these values we first estimate an upper bound on the mole fraction of benzene in the SPL, which equals $x_{benzene} = 2.0 \times 10^{-4}$. Next, given a subsurface temperature of 18°C, the estimated maximum vapor concentration of benzene over the SPL, calculated with the above equation, is $C_v = 82{,}000\ \mu g/m^3$.

The nonresidential SHS near-source soil gas screening value for benzene is $SV_{NS} = 16{,}000\ \mu g/m^3$. The estimated benzene vapor concentration based on the detection limit in this example exceeds the screening value. Therefore, at this analytical accuracy, sampling the SPL cannot rule out benzene as a contaminant of VI concern. Possible alternative investigative approaches include near-source soil gas, sub-slab soil gas, or indoor air sampling.

8. Quality Assurance and Quality Control Procedures and Methods

a) Sampling Procedures and Methods

i) Pre-Sampling Survey

Prior to the installation and construction of indoor air and sub-slab soil gas sampling points and the collection of samples, a pre-sampling survey should be conducted. The survey should include a short interview with a representative of the owner/occupant of the building and a visual review of accessible portions of at least the lowest level of the building (basement or first floor). Results of the survey are documented and supplemented by sketch maps and photographs as necessary. The investigator may also choose to use a photoionization detector (PID) or flame ionization detector (FID) during the survey to screen for the presence of VOCs in the building. (Note: The non-compound specific VOC detection levels of PIDs and FIDs are much higher than compound-specific laboratory reporting limits.) The pre-sampling survey should review building-specific factors that could influence VOC concentrations in indoor air including:

- Building construction characteristics;
- Building features, such as the condition of the floor slab, floor penetrations, and floor cracks;
- Heating and ventilations systems;
- Items within the lowest level of the building that could serve as potential VOC sources (paint cans, solvents, fuel containers, etc.);
- Occupant activities in the building (painting, smoking, etc.); and
- Exterior characteristics and items or occupant activities outside the building that could serve as potential VOC sources (mowing, paving, etc.).

These observations and others should be documented on a building survey form.

For additional information see ITRC (2007), California EPA (2011a), and New Jersey DEP (2013).

ii) Sampling Equipment

Near-source soil gas, sub-slab soil gas, and indoor air samples are commonly collected in passivated stainless steel canisters (e.g., Summa) with laboratory-calibrated flow controllers for U.S. EPA Method TO-15, or other appropriate U.S. EPA methods if TO-15 is not applicable. Other types of sampling containers (e.g., Tedlar bags, glass bulbs, syringes) may be used under certain conditions, but stainless steel canisters are preferred.

Canister volumes should be selected to minimize sample volume while still meeting data quality objectives. Minimizing sampling volumes for near-source soil gas and sub-slab soil gas reduces the potential for ambient air entering around the sampling point and limits the potential for migration of soil gas from relatively long distances away from the sampling point during sample collection. Generally, 1-L canisters are used for near-source soil gas and sub-slab soil gas sample collection and 6-L canisters are used for indoor air and ambient sampling.

Canisters should be connected to the soil gas sampling point using small diameter stainless steel, nylon (Nylaflow type LM), polytetrafluoroethylene (PTFE, Teflon), or polyether ether ketone (PEEK) tubing and stainless steel compression-type fittings. (Other appropriate non-reactive materials may be used. Polyethylene, Tygon, and silicone are not acceptable tubing materials.) The number of connections in the sampling system should be minimized to reduce the number of locations where leaks could occur. Minimizing the length and diameter of the tubing reduces the sample residence time and the required purge volume.

iii) Sampling Point Construction

Near-source and sub-slab soil gas sampling point construction materials should be selected to minimize potential interaction with the sample. The probe should be connected to small diameter tubing; the tubing and all fittings should be clean and dry. The tubing is recommended to be capped or plugged at the surface to isolate the sample from the atmosphere or indoor air.

Sub-slab sample points are sealed in the penetration to eliminate short circuiting of air from inside the building through the slab penetration and into the sample. The materials and methods used to create this seal will depend on site-specific factors such as the condition of the slab and the type and volume of traffic in the building as well as the data quality objectives and planned QA and quality control (QC) protocols. Temporary points may be sealed in the penetration with silicone sleeves, silicone rubber stoppers, sculpting clay, putty, or wax. Semi-permanent points may involve the drilling of nested holes in the slab and the use of hydraulic cement or epoxy to seal the tubing and possibly additional fittings in the penetration below the finished elevation. All materials used for construction and completion of the sub-slab soil gas sampling point should be clean, dry and free of materials that could affect the sampling or analysis.

The diameter of the floor slab penetration should be minimized (generally between 3/8 and 1 inch). The surface and sidewalls of the penetration should be cleaned with a stiff bristle brush to remove material created by the advancement of the penetration. Removal of this material is important to limit entrainment of dust in the sub-slab soil gas sample and to promote adherence of the sealing materials to the sidewalls of the penetration or the surface of the slab. Care should be taken to limit interaction with the sub-slab soil gas beneath the slab if a vacuum is used to remove dust during/after advancement of the penetration. If a vacuum is used, additional point equilibration time may be necessary.

Some manufacturers offer alternative sub-slab soil gas sampling point equipment that relies on driving (hammering) a specialized barbed-metal fitting into the slab penetration. The metal fitting is sealed inside the slab penetration by the compression of a sleeve of flexible tubing between the fitting's barbs and the sidewalls of the penetration. These "hammer-in" points may be considered for use during VI investigations.

For indoor and outdoor air sampling, the sampling port should be placed in the breathing zone, approximately 3 to 5 feet above the floor. Mount the canister on a stable platform or attach a length of inert tubing to the flow controller inlet and support it such that the sample inlet will be at the proper height.

Ambient air samples should be collected at breathing zone height (if possible) and in close proximity to the building being tested. For nonresidential buildings, the investigator may elect to collect the ambient air sample near representative HVAC intake locations (i.e., on the roof). Other locations for ambient sampling could be upwind of the building to be sampled. The ambient air sample should have the same sample collection time and be analyzed in the same manner as the interior sample collection method.

iv) Equilibration

After installation, near-source and sub-slab soil gas points should be allowed to equilibrate to natural conditions. This is commonly a minimum of 2 hours up to 24 hours.

v) Leak Testing/Detection for Subsurface Sample Collection

Leakage during soil gas sampling may dilute samples with ambient air resulting in data that underestimates actual site concentrations or causes false negatives. A shut-in check (sampling assembly integrity) and a leak check (surface seal integrity) can be conducted to determine whether leakage is present and then corrected in the field prior to collecting the sample. Recommended resources for leak testing include ASTM (2012a), California EPA (2015), New Jersey DEP (2013), Hawaii DoH (2014), and ITRC (2014).

A shut-in test of the sampling train is recommended to be completed at each location and during each sampling event to verify aboveground fittings do not contain leaks. A shut-in test consists of assembling the above-ground apparatus (valves, lines, and fittings downstream of the top of the probe), and evacuating the lines to a measured vacuum of about 15 inches mercury (200 inches water or 50,000 Pascals), then shutting the vacuum in with closed valves on opposite ends of the sample train. The vacuum gauge is observed for at least 1 min, and if there is a loss of vacuum greater than 0.5 inches mercury (7 inches water or 2000 Pascals), the fittings should be adjusted as needed to maintain the vacuum.

Leak check tests are recommended for near-source and sub-slab soil gas points after construction and equilibration. One method employs a shroud placed over the point. An inert tracer gas (such as helium) is released into the shroud with a target concentration of 10–20%. With the canister valve closed, a soil gas sample is collected from the sample point and measured with a portable helium detector. A leak is occurring when the helium concentration is greater than 10% of the concentration within the shroud. In this case, the leak must be fixed and the leak check repeated.

Helium is the preferred tracer as it is readily available, non-toxic, and easily measured in the field provided high methane levels are not present (false positives). Helium may also be analyzed in the Summa canister sample at the laboratory.

Note: Balloon-grade helium may contain hydrocarbons that could interfere with sample analysis.

vi) Purging

Purging occurs after the sampling system has been assembled (i.e., the canister has been connected to the flow controller and the sampling point has been connected to the canister/flow controller). A "T" fitting can be placed in the sampling train to allow for purging of the connected sampling system. The purging leg of the "T" is commonly isolated from the rest of the sampling train using a valve. There are several acceptable methods for purging the system. For example, either a graduated syringe or a personal sampling pump can be used.

Purge rates for near source and sub-slab soil gas samples should be less than 200 mL/min to limit the potential for short-circuiting or desorbing VOCs from soil particles. Purging volumes should be about three times the volume of the total sampling system (i.e., the sampling point and tubing connected to the sampling canister).

If water is encountered in the soil gas sampling point or observed in the sample tubing during purging, then sampling of the point should not be performed. Commonly, when water is encountered during purging an effort is made to evacuate the water from the soil gas sampling point and then allow a minimum of 48 hours before reattempting purging and sampling.

vii) Sampling Rates

Sampling rates for near-source and sub-slab soil gas samples should be less than 200 mL/min. Sample rates are determined by the laboratory-calibrated flow controller attached to the canister.

Vacuum levels during sampling should not exceed 7.5 inches mercury (100 inches water or 25,000 Pascals). If low permeability materials are encountered during point installation or if there are issues during purging or sampling that suggest low permeability, testing should be performed to measure flow rates and vacuum levels in the near-source soil gas sampling point to determine acceptable purging and sampling flow rates.

Indoor air and ambient air samples are typically collected over a 24-hour period; however, in a nonresidential setting an 8-hour sampling period may be used to coincide with the hours of operation and thus the period of exposure. The sampling flow rate should always be less than 200 mL/min.

With near-source or sub-slab soil gas sampling, the sample duration should be determined by sample volume, but it is recommended to be at least 15 minutes.

If water is observed in the sample tubing during sampling, then sampling should be discontinued. Commonly, when water is encountered during sampling an effort is made to evacuate the water from the soil gas sampling point and then allow a minimum of 48 hours before reattempting purging and sampling.

viii) Sample Recordation

The field sampling team should maintain a sample log sheet summarizing the following:

- Sample identification;
- Date and time of sample collection;
- Sample location;
- Identity of sampler;
- Sampling methods and devices;
- Volume and duration of sample;
- Canister vacuum before and after sample is collected; and
- Chain of custody protocols and records used to track samples from sampling point to analysis.

b) Data Quality Objective (DQO) Process, Sampling and Data Quality Assessment Process

The DQO process (U.S. EPA, 2006) allows a person to define the data requirements and acceptable levels of decision errors prior to data collection. The DQO process should be considered in developing the sampling and analysis plan, including the QA plan. The implementation phase includes sampling execution and sample analysis. The assessment phase includes Data Quality Assessment (DQA). (See 25 Pa. Code § 250.702(a) of the regulations and Section III.F.1.)

c) QA/QC Samples

Prior to using a canister, the integrity of the canister should be examined for damage due to shipping. The canisters should be received in the field with the laboratory-measured pressure as part of the documentation. Field check the pressure of the canister before collecting the sample. The field-measured pressure should be within 10% of the laboratory recorded value. If this is not the case, the canister should be rejected and another canister used. There may be some minor difference in measured pressures (for instance with changes in altitude and barometric pressure) of less than 5% that does not reflect a canister integrity problem.

On completion of sample collection, the final pressure reading should be recorded. This should be about 5 inches mercury (70 inches water or 20,000 Pascals). The reading should be recorded on the chain of custody or other field documentation. If the final pressure is zero (atmospheric), it should still be recorded and sent to the laboratory for verification.

A field duplicate sample may be collected by using a “T” fitting at the point of collection to divide the sample stream into two separate sample containers.

Trip blanks for canisters are not typically required.

Dependent on the sampling equipment it may be desirable to perform an equipment blank. The sample collection media should be certified clean. Materials used in setting up a sampling train should be VOC-free and stored and transported in a VOC-free environment.

Field method blanks can be used to verify the effectiveness of decontamination procedures and to detect any possible interference from ambient air. If samples are collected using sorbent media, it is recommended that a blank media sample accompany the batch of sample media to the field and be returned to the laboratory for analysis. This demonstrates the media is free from compounds of concern from preparation through shipping and handling.

d) Analytical Methods

A variety of analytical methods are available to measure vapor samples (subsurface vapor, indoor and ambient air), all of which can provide useable data when reported with QA/QC (Table IV-C-3). The laboratory QA/QC will include blanks, calibration, and system performance samples that define and verify the quality of the data reported. The laboratory engaged for air and vapor analysis should have NELAC or similar accreditation for the methods reported. There may be cases where certification for the method that will be used is not available. In this case, a laboratory standard operating procedure should be available and appropriate QA/QC should be reported with the results.

Communicate with the laboratory during the planning stages of the investigation to ensure the appropriate analytical method is used. For the data assessment process, it is suggested at a minimum for the laboratory to provide summary QA/QC results with the data reported. A full validated data package can be requested if necessary.

Table IV-C-3: Analytical Methods for VOCs in Soil Gas, Indoor and Ambient Air Samples

Parameter	Method	Sample Media/Storage	Description	Method Holding Time
Polar & non-polar VOCs	TO-15	canister / ambient temperature	GC/MS	30 days
Low level VOCs	TO-15 SIM	canister / ambient temperature	GC/MS	30 days
Polar & non-polar VOCs and SVOCs to C-28	TO-17	sorbent tube/ chilled < 4°C	GC/MS	30 days
Fixed gases (methane, helium, nitrogen, oxygen, carbon dioxide, carbon monoxide)	USEPA 3C or ASTM 1946	canister or Tedlar bag / ambient temperature	GC/TCD/FID GC/FID	3 days for Tedlar bag 30 days for canister

Key elements for choosing the appropriate method are:

- The contaminants of concern;
- The concentrations that may be encountered during sampling and source strength;
- Screening levels/detection levels and other DQOs;
- Sampling considerations;
- Cost of sampling and analysis.

For U.S. EPA Method TO-15 VOCs the passivated canister is the only container allowed by the method; any other containers (e.g., Tedlar bags) are considered a modification. There is no standard list for TO-15. As a performance-based method, any compound that has sufficient volatility and recoveries may be validated for accreditation and reporting, provided a demonstration of capability is performed. TO-15 is the preferred method used for VI investigations.

Method TO-17 is a sister method to TO-15. Samples are collected with active sampling onto absorbent media. This method offers lower reporting limits and extends the compound list to include semi-volatile compounds. However, this media has a limited capacity, which is further limited if screening is done for a broad range of compounds, and sampling with sorbent media requires more field expertise.

Fixed gases, typically defined as O_2, nitrogen, CH_4, CO_2, and CO, can readily be analyzed using laboratory-based methods that use a thermal conductivity detector for detection, and using field monitoring devices (landfill gas monitors). ASTM D1946 (ASTM, 2015a) and U.S. EPA Method 3C are two of the more common analytical methods and can typically detect concentrations as low as 0.1%. They can also be used to analyze for helium, which is often used as a tracer gas during leak check procedures in subsurface sampling. Analysis for these gases can be run from the same canister as VOCs.

Contact your laboratory for analyte lists and reporting levels applicable to these methods, and reference Section III.G.3 for information regarding PQLs.

e) Data Evaluation

If the project was planned using the DQO process or another standard project planning process, the quantity and quality of data, including the measurement quality objectives, will have been specified in the sampling and analysis plan. All of the data should be examined for these types of issues to ensure the data set is of adequate quality prior to use in evaluating the VI pathway.

9. Active Sub-Slab Depressurization System Testing

Details regarding the application, design, installation, and performance testing of SSD systems and other VI mitigation systems are available in the following references: U.S. EPA (1991, 1993, 1994a, 1994b, 2001, 2008), Massachusetts DEP (1995), Pennsylvania DEP (1997), California EPA (2011b), and ASTM (2008, 2011b, 2013b, 2015b).

a) Description

This section applies to recommended performance testing procedures for active sub-slab depressurization systems installed as engineering controls on buildings where the VI pathway is a potential concern. For existing buildings, active SSD systems are the VI mitigation method preferred by DEP. However, the performance and testing requirements described below may also apply for other active VI mitigation technologies such as sub-membrane depressurization, sub-slab pressurization, and building pressurization systems.

Installation of SSD systems includes the sealing of potential soil vapor infiltration points combined with the use of a fan or blower that creates a continuous negative pressure field (vacuum) beneath the concrete floor slab of the lowest level of the building (basement or first floor). The fan or blower pulls the soil vapor from beneath the slab and vents it to the atmosphere at a height well above the outdoor breathing zone (ITRC, 2014, Appendix J). The presence of a continuous negative pressure field beneath the slab results in the movement of indoor air down into the subsurface, thereby eliminating the VI pathway as a potential concern.

Installation of SSD systems in existing buildings should be performed by qualified professionals, and it is generally completed in the following three steps:

Step 1: Inspection and Design-Support Diagnostic Testing – This step typically includes visual inspection of the lowest level of the building to assess the condition of the foundation, to identify potential soil vapor entry points that require sealing, and to review building-specific design considerations such as the location and type of construction of extraction points, possible discharge piping routes, and exhaust fan locations. This step also includes diagnostic testing to support siting of extraction points, sizing of the exhaust fan/blower and piping, and evaluation of stack effects and the potential for back-drafting of heating systems. The results of the diagnostic tests or communication tests are used to confirm the ability of the SSD to depressurize beneath the entire building.

Step 2: Design and Construction of the SSD System – The mitigation contractor prepares a design applicable to the building characteristics and results of diagnostic testing. Elements of the construction include installation of extraction point(s), exhaust piping, exhaust fans/blowers, and sealing of potential soil vapor entry points.

Step 3: Commissioning of the SSD System – The commissioning step includes post-construction performance testing consisting of pressure differential measurements to demonstrate the system is working as designed. During this step, smoke testing is also performed to confirm operation of the SSD system does not result in back-drafting of combustion appliances (heating systems). Adjustments to or augmentation of the SSD system may be completed during this final installation step. Post-construction performance testing methods completed as part of commissioning of active SSD systems are described below.

b) Performance Testing Methods

The remediator should test the mitigation system after its installation. At a minimum, the testing should follow the manufacturer's or vendor's recommendations. The mitigation system should also be tested if a significant modification or repair is made, after a change in ownership, or upon request by the Department.

The primary method of performance testing of active sub-slab depressurization systems consists of differential pressure field extension tests that provide confirmation of a continuous negative pressure field (vacuum) beneath the concrete floor slab of the lowest level of the building. If the differential pressure field extension tests demonstrate the operating SSD system is providing depressurization throughout the sub-slab, the remediator is not required to perform indoor air confirmation sampling.

Differential pressure field extension tests are performed by operating the SSD system and simultaneously measuring the sub-slab pressure at different locations across the floor slab including, if accessible, building corners and building perimeters. The pressure measurements should be performed by drilling a small hole through the slab (e.g., 3/8-inch diameter) and measuring the differential pressure using a digital micromanometer. In general, for active SSD systems a pressure differential of at least 0.01 inches water (2 Pascals) should be achieved when the heating system is operating and 0.025 inches water (6 Pascals) otherwise (U.S. EPA, 1993). The minimum pressure of 6 Pascals is a guideline that applies mostly to residential structures, but use of a lower threshold may be considered (e.g. for larger commercial structures) on a case-by-case basis if proper justification is provided. As such, a digital micromanometer with sufficient sensitivity is necessary. Smoke testing can be performed as a qualitative test, but it may not be as reliable with low vacuums.

As an alternative to differential pressure testing, the remediator may collect one or more indoor air samples.

Appendix IV-D: OSHA Program Vapor Intrusion Checklist

List the chemical(s) of concern that the facility uses:

Chemical:	CAS Registry Number:
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________

☐ Facility provided Material Safety Data Sheet(s) (MSDS) or Safety Data Sheet(s) (SDS) for the chemical(s) of concern listed above that they have identified as using.

☐ Facility identified where the chemical(s) are used in the facility and how they are used.

☐ The facility has performed air monitoring (industrial hygiene) of the identified chemical(s) of concern.

☐ The facility has provided the results of the air monitoring to the Department.

☐ The air monitoring has been conducted in all areas of the plant or facility.

☐ The facility has provided documentation showing that all employees in the facility have completed safety training associated with the chemicals of concern.

☐ Pictures provided by the facility show PPE and signage use associated with the chemicals of concern. (Items shown below are examples of equipment associated with use of PPE, and may not be the exact items used by the facility.)

Dip Tanks

Lab or process hoods with documentation of annual assessments

Canopy hoods with documentation of annual assessments


Local ventilation with documentation of annual assessments

Use of respirators with employee medical clearances



PPE such as chemical gloves, aprons, Tyvek coverall or clothing




Occupational Exposure Values for Chemicals of Concern

Occupational Safety and Health Administration Permissible Exposure Limits (OSHA PEL) or American Conference of Governmental Industrial Hygienist Threshold Limit Values (ACGIH TLV).

Chemical of Concern	OSHA PEL	ACGIH TLV

OSHA exposure limits are available at: 29 CFR Subpart Z; 29 CFR 1910.1000–1052

https://www.osha.gov/dsg/annotated-pels/index.html

ACGIH TLVs are available from the purchased publication. All of these values should be available from the MSDS/SDS.

Status: (All of the above items must be included for the facility to qualify to use an OSHA program to address VI.)

☐ Qualified: OSHA implementation is documented and can be used to address VI

☐ Not Qualified: OSHA implementation is NOT documented

Consultant or Reviewer:

(Print)____

(Signature)__________________________________ Date:__________________