Guidance on the Assessment of the Soil Vapour to Air Pathway

Submitted to:

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[1] https://csapsociety.bc.ca/wp-content/uploads/ATT-3_-CSAP-Professional-Judgement-May2nd.pdf

Glossary

1,2-DCA	1,2-dichloroethane
BPC	building pressure control
PCOC	potential contaminant of concern
CSIA	compound specific isotope analysis
CSM	conceptual site model
DNAPL	dense non-aqueous phase liquid
EDB	ethylene dibromide
ECD	electron capture detector
FID	flame ionization detector
GC	gas chromatography
HVAC	heating ventilation and air conditioning
J&E	Johnson & Ettinger
IA	indoor air
LNAPL	light non-aqueous phase liquid
MLE	multiple lines of evidence
MTBE	methyl tertiary-butyl ether
NAPL	non-aqueous phase liquid
PHC	petroleum hydrocarbon
PID	photoionization detector
PCE	tetrachloroethylene
PVI	petroleum vapour intrusion
PFAS	poly- and per-fluoroalkyl substances
TBA	tertiary-butyl alcohol
TCE	trichloroethylene
TMB	trimethylbenzene
TPH	total petroleum hydrocarbon
SOP	suggested operating procedure
SSD	sub-slab depressurization
SSV	sub-slab ventilation
VI	vapour intrusion
VOC	volatile organic compound

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Executive Summary

The migration of subsurface contaminant vapours to indoor and outdoor air and inhalation of the vapours is an important exposure pathway for human health in the management of contaminated sites in British Columbia (BC). This *Guidance on Assessment of the Soil Vapour to Air Pathway* has been prepared by ARIS Environmental Ltd. (ARIS) and Golder Associates Ltd. (Golder) for the Society of Contaminated Sites Approved Professionals (CSAP) of BC. The purpose of the guidance is to provide practical and science-based recommendations for practitioners working in BC. This document is intended to update and supplement the 2009 CSAP report entitled *Soil Vapour Advice and Practice Guidelines Development Panel - Stage 1* (CSAP 2009). This guidance document does not override the precluding conditions and Ministry policy described in the most recent versions of BC Environment (ENV) Technical Guidance 4 and Protocol 22.

The guidance is structured into five sections intended to provide practical resources for the vapour intrusion (VI) community on a stand-alone basis as shown in Figure ES1. While Section 4 forms the core of the document with guidance on vapour investigation in BC, other Sections provide information resources that form the current state of science in guidance (Section 2) and our understanding of the conceptual site model for vapour investigation (Section 3), and which may be referred to as needed (i.e., readers can refer to Section 4 directly for the guidance recommendations). The summary and purpose for each section is described here in the Executive Summary with hyperlinks to the relevant sections for ease of access to applicable information as required by the user.

This document is not intended to replace the 2009 CSAP Practice Guideline (CSAP 2009), except for the section on measurement of shallow soil vapours pertaining to assessment of indoor air quality for future conditions (Section 4.4). While this document provides information on sampling methods, mitigation measures and vapour attenuation factors in the literature review (for completeness) in Section 2, it does not provide recommendations on these issues as these topics were beyond the scope of this document (practitioners in BC should consult applicable BC ENV protocols and guidance).

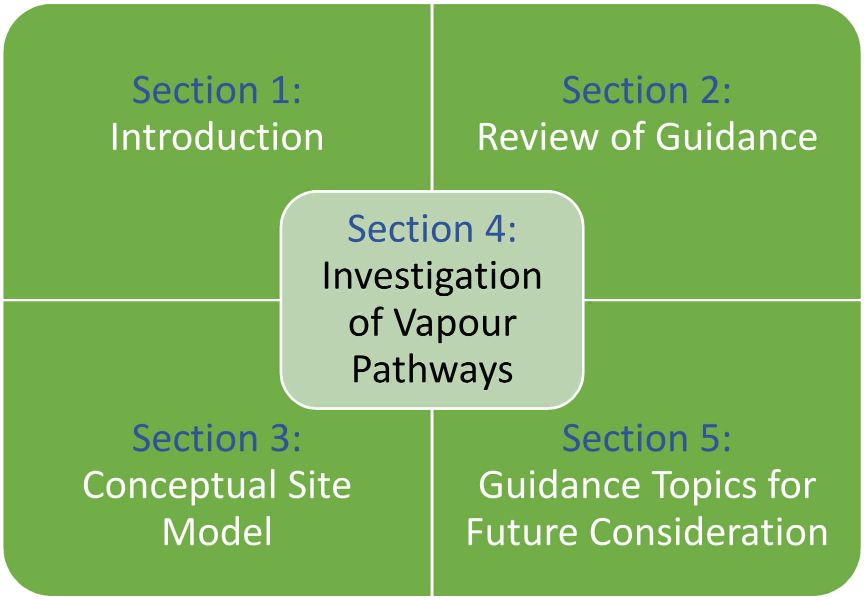

Figure ES1: Structure of the guidance document.

Section 1

Section 1 provides the background and impetus for the creation of this document with an overview of the guidance, which is focussed on the development of new and practical approaches for vapour intrusion assessment, specifically on key topics identified by the practitioners, CSAP members and the Technical Review Committee. The key topics are vapour sampling locations, timing and frequency ("worst-case" conditions), indoor and outdoor air sampling, and shallow soil vapour sampling for a future building scenario, which are addressed in Section 4, in harmonization with available guidance, tools and methods in published literature.

Section 2

For the purpose of harmonization, Section 2 provides a summary of vapour assessment approaches based on a review of 11 key guidance documents from Canada and the US that have been published since CSAP (2009). The review is organized into topics and sub-topics with details provided in a tabular fashion (Appendix A) for each of the 11 guidance documents. The topics that comprise the summaries in Section 2 are the Conceptual Site Model (CSM); vapour sampling locations; vapour sampling frequency; sampling and analysis methods; multiple lines of evidence (MLE); ambient air (indoor and outdoor); vapour intrusion mitigation; and attenuation factors.

It is important to emphasize that Section 2 reflects the summary of the reviewed guidance and other literature, which form the basis and justification for the updated guidance on CSM (Section 3) and vapour investigation pathways (Section 4). As with all site remediation practices, professional judgement is needed to address specific site conditions for vapour assessment, and therefore, the compilation of resources provided in this section is a practical source of information that is organized into specific topics. A high-level summary of the topic can be found in Section 2, and where a greater level of detail and background on a topic is needed, the reader can refer to Appendix A, for locating the relevant documents for that topic.

Section 3

The compilation and synthesis of materials in Section 2 were used to develop the CSM described in Section 3. Based on the information review, the key aspects of the CSM are described as follows:

1. Potential contaminants of concern (PCOCs);
2. Vapour sources;
3. Building and environmental factors;
4. Subsurface factors;
5. Preferential pathways;
6. Spatial and temporal variability; and
7. Current and future land uses.

Subsurface factors including fresh-water lens, interface plume, water table fluctuations, infiltration fronts and soil moisture, soil temperature, preferential pathways, snow and frost, tides, biogenic gases and volatile organic compound (VOC) biodegradation are described with respect to their effect on vapour intrusion potential. The potential importance of transport of VOCs in sewer water and air is described with reference to recent literature, which includes estimation of attenuation factors between groundwater and sewer air, and sewer air and indoor air. Appendix B summarizes key studies and provides recommended methods for sampling sewers.

Spatial and temporal variability in vapour concentrations including data from several intensively monitored research sites are summarized. A conceptual model that describes variability for different media consisting of groundwater, deep soil vapour, sub-slab vapour and indoor air is described and advantages and disadvantage of different media for estimation of exposure concentrations in air are provided. The potential implications of the available measurement data on spatial and temporal variability for obtaining representative near worst-case concentrations are discussed.

Section 4

Based on the CSM and the review of guidance and literature, Section 4 provides recommendations for investigation of vapour pathways, which consists of the following:

1) Vapour assessment approach;
2) Vapour plume stability;
3) Vapour sampling locations and frequency;
4) Shallow soil vapour sampling for a future building;
5) Indoor air assessment methods; and
6) Outdoor air assessment methods.

Two broad approaches for conducting vapour investigations are presented in Section 4.1:

1) A bottom-up approach, where the initial phase of investigation is the characterization of subsurface contamination and testing of soil vapour concentrations (external to building, if present) near the source, which is generally the recommended approach; depending on the results of initial testing, sub-slab and/or indoor testing may be warranted, and
2) A top-down approach, where the initial phase of investigation includes characterization of indoor air quality and sub-slab or shallow soil vapour concentrations, warranted when contamination is in contact with or in close proximity to a building, or when there are indications of higher-risk conditions.

Recommendations are provided for MLE in the implementation of a vapour intrusion investigation. The primary lines of evidence that may be considered in the assessment of vapour intrusion consist of concentration data in soil, groundwater, external soil vapour, sub-slab vapour, indoor air and outdoor air. Secondary lines of evidence include subsurface conditions in addition to concentration data and building conditions. Collecting MLEs can be particularly helpful at complex sites with variable vapour migration pathways, and because many VOCs are ubiquitous in indoor air from background sources.

Section 4.2 describes the assessment of vapour plume stability based on the time to reach approximate steady-state vapour concentrations estimated through the use of models or repeated measurements of vapour concentrations. Section 4.3 provides recommendations for vapour sampling locations based on the investigation stage (e.g., soil vapour, sub-slab vapour, indoor air) and consideration of spatial and temporal variability (Table 3). This section highlights the site-specific nature of the timing and frequency of sampling that accounts for seasonal factors (weather-related and building operations) and their potential impact on vapour source and/or migration, and likelihood of worst-case or applicability to site-specific conditions. Table 4 and a questionnaire are provided as tools in the design and optimization of vapour sampling events for a structured approach. It is expected that this method would generally lead to two to four sampling events at most sites and is intended to provide near worst-case conditions and representative estimates of vapour concentrations for the estimation of indoor and outdoor air concentrations as part of an exposure assessment.

Shallow soil vapour sampling may be warranted when evaluating a future building scenario and the contamination source is at shallow depth, as described in Section 4.4. In the Canadian guidance reviewed (Appendix A), the minimum recommended depth for soil vapour sampling is 1 m, while the US guidance consider 5 ft (1.5 m) as the recommended threshold. Shallow vapour samples are more influenced by ground surface cover, changes in temperature, barometric pressure and there is greater potential for breakthrough of atmospheric air during sampling. Therefore, based on site-specific conditions, tools and methods are provided that include shallow soil vapour sampling, data interpretation and modelling of this scenario to optimize the vapour assessment process.

Indoor air monitoring is generally the last step in a bottom-up approach for characterization of the vapour intrusion pathway, described in Section 4.5. The characterization of indoor air represents the most direct measure of exposure to human receptors; however, there may be background VOC sources in indoor air that confound data interpretation, and there is relatively high temporal variability in indoor air concentrations.

To address potential background VOC sources, an MLE approach is recommended where indoor air, outdoor air and sub-slab vapour samples are analyzed, and where other forensic tools are considered. The locations of indoor air samples are discussed depending on building use, building size and number of storeys. Recommendations for indoor air characterization are presented in Table 5, and a toolbox of methods that may be used to improve indoor air assessments including continuous (real-time) monitoring of VOC concentrations; monitoring of pressure, temperature and other indicators; and building pressure control tests and tracers are considered.

Similar to indoor air monitoring, outdoor air monitoring is generally the last step in a bottom-up approach for vapour assessment, described in Section 4.6. The data objectives for outdoor air monitoring are typically: 1) outdoor air exposure assessment, or 2) characterization of outdoor air as a potential background source to indoor air. Recommendations for outdoor air characterization are presented in Table 6.

Section 5

The review conducted in this guidance indicates the need for further development of approaches, procedures and methods that can be practically implemented at sites. As outlined in Section 5, these include the areas of sustainable vapour mitigation, preferential pathways including sewers, pressure monitoring and building pressure control tests, continuous monitoring of indicator parameters, passive samplers, high purge volume sampling and building foundation assessment, mass flux and discharge assessment, building basements in contact with groundwater, sampling and analysis methods and background sources of VOCs in indoor air. Guidance in these areas is expected to provide for more efficient and sustainable vapour assessment and increase the level of confidence in decision making for site management.

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1.0 INTRODUCTION

The migration of subsurface contaminant vapours to indoor and outdoor air and inhalation of the vapours is an important exposure pathway for human health in the management of contaminated sites in British Columbia (BC). This *Guidance on Assessment of the Soil Vapour to Air Pathway* has been prepared by ARIS Environmental Ltd. (ARIS) and Golder Associates Ltd. (Golder) for the Society of Contaminated Sites Approved Professionals (CSAP) of BC. The purpose of the guidance is to provide practical and science-based recommendations for practitioners working in BC.

The guidance provides a summary of vapour assessment approaches based on a review of key guidance documents from Canada and the US (Section 2 and Appendix A) that have been published since the 2009 CSAP report entitled *Soil Vapour Advice and Practice Guidelines Development Panel - Stage 1* (CSAP 2009). The compilation and synthesis of these guidance were used to provide recommended Conceptual Site Model (CSM) factors (Section 3) and sampling approaches and assessment methods to characterize subsurface vapour and indoor air and outdoor air concentrations (Section 4). An important focus of this guidance is to harmonize the various guidance and advances in published vapour intrusion literature, describe spatial and temporal variability in processes and concentrations and identify assessment approaches and methods that will help to characterize reasonable near “worst-case” conditions.

The report sections consist of the following:

- Section 1: Introduction.
- Section 2: Review of Guidance - Key vapour intrusion guidance and technical papers are reviewed and summarized in a harmonized approach on topics including the CSM, vapour sampling locations and frequency, sampling and analysis methods, multiple lines of evidence, ambient air assessment, mitigation, and attenuation factors.
- Section 3: CSM Development - Key factors for consideration are discussed with regards to vapour potential contaminants of concern (PCOCs), vapour sources, building factors, subsurface factors, spatial and temporal variability, preferential pathways, and current or future development and land use.
- Section 4: Investigation of Vapour Pathways - Recommended assessment approaches, methods for soil vapour assessment, indoor and outdoor air assessment with focus on sampling frequency, and shallow soil vapour sampling for future buildings are discussed.
- Section 5: Overview of Other Potential Vapour Intrusion Issues for Future Consideration – Key aspects of this overview are recommended procedures for monitoring of pressure and concentrations of light gases as additional lines of evidence, and recent advances for building pressure control (BPC) tests, mass flux and discharge estimates, and high purge volume methods among other aspects of vapour intrusion assessment for future consideration.

The topics addressed in the 2009 CSAP Practice Guideline were:

- Identification of Soil Vapour Questions/Issues
- Selection of Potential Contaminants of Concern for Analyses
- Measurement of Shallow Soil Vapours
- Attenuation Factors

- Frequency of Leak Testing During Soil Vapour Sampling

This guidance is not intended to replace the 2009 CSAP Practice Guideline, except for the section on measurement of shallow soil vapours pertaining to assessment of indoor air quality (Section 4.4). While this guidance provides information on sampling methods, mitigation measures and vapour attenuation factors in the literature review in Section 2 (for completeness), it does not provide recommendations on these issues as these topics were beyond the scope of this guidance.

2.0 REVIEW OF GUIDANCE

The key topics on vapour assessment that were selected in the review of guidance were:

- Conceptual Site Model (CSM)
- Vapour sampling locations
- Vapour sampling frequency
- Multiple lines of evidence (MLE)
- Indoor and outdoor air assessment
- Sampling analysis and methods
- Mitigation
- Attenuation factors

The following guidance documents were reviewed in a consistent template with respect to the key topics above and summarized in Appendix A, which consists of eleven tables as follows:

- Table A-1: Health Canada Federal Contaminated Risk Assessment in Canada: Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites, Health Canada (2010).
- Table A-2: California Department of Toxic Substances Control (CA DTSC) Vapor Mitigation Advisory, October, CA DTSC (2011b).
- Table A-3: Science Advisory Board for Contaminated Sites (SABCS) in BC Guidance on Site Characterization for Evaluation of Soil Vapour Intrusion into Buildings, May, SABCS (2011).
- Table A-4: CA DTSC Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air, October, CA DTSC (2011a).
- Table A-5: Interstate Technology and Regulatory Council (ITRC) Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation and Management, October, ITRC (2014).
- Table A-6: United States Environmental Protection Agency (US EPA) Office of Solid Waste and Emergency Response (OSWER) Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air, US EPA (2015a) including Errata dated 29 January 2018.
- Table A-7: CA DTSC Advisory Active Soil Gas Investigations. CA DTSC and Los Angeles and San Francisco Regional WQCBs, July 2015, CA DTSC (2015).
- Table A-8: US EPA Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites, US EPA (2015b).
- Table A-9: Canadian Council for Ministers of the Environment (CCME) Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment. Volumes 1-4, CCME (2016).

- Table A-10: New Jersey Department of Environmental Protection (NJ DEP) Vapor Intrusion Technical Guidance. Site Remediation and Waste Management Program, NJ DEP (2018).
- Table A-11: Washington (State) Department of Ecology (WA Ecology) Guidance for Evaluating Soil Vapour Intrusion in Washington State: Investigation and Remedial Action (2009, revised in 2016 and 2018), WA Ecology (2018).

The objective of Section 2 is to review guidance in other jurisdictions. The review is not intended to override the Ministry policy and precluding conditions described in the most recent versions of BC ENV Technical Guidance 4 (TG 4) and Protocol 22 (P 22) or provide recommendations for provincial guidance and policy in BC. Sections 3 and 4 of this guidance integrate key aspects of the review in Section 2 and knowledge on vapour intrusion with regards to recommended approaches for vapour investigation in BC (readers may refer directly to Section 4 for recommended guidance).

A summary of each key review topic is provided in the sections below.

2.1 Conceptual Site Model

The CSM is described in terms of the type of contamination, vapour sources, building factors, subsurface factors, proximity to contamination source, preferential pathways and other considerations identified in guidance and literature reviewed.

2.1.1 Type of Contamination

Chlorinated or halogenated hydrocarbons and petroleum hydrocarbons represent common PCOCs addressed in all guidance. PCOCs should include breakdown or daughter products where appropriate.

The reviewed guidance documents describe varying approaches for identification of vapour PCOCs, and consequently the suite of chemicals considered between guidance documents are different. Additional vapour PCOCs beyond the common types above are 1,4-dioxane; biphenyl; monochlorobiphenyl and dichlorobiphenyl; and elemental mercury. CCME (2016) indicate both volatile and semi-volatile chemical contaminants should be evaluated; including petroleum hydrocarbons in fuel products, volatile chemicals in coal-tar or creosote, and chlorinated solvents. CA DTSC (2015) describe that hydrogen sulphide and methane may be of concern at sites where biogenic gases are generated.

US EPA (2013) describes volatile chemicals other than petroleum hydrocarbons (PHCs) that may be found in petroleum fuels, such as ethers, alcohols, and other fuel additives (e.g., 1,2,4- and 1,3,5-trimethylbenzene, methyl tertiary-butyl ether (MTBE), tertiary-butyl alcohol (TBA), ethylene dibromide (EDB), and 1,2-dichloroethane (1,2-DCA)). Methane is generated from anaerobic biodegradation of PHCs and other constituents of petroleum fuels (especially ethanol), and organic matter in soil.

With the emergence of poly- and per-fluoroalkyl substances (PFAS) as a significant environmental concern, questions have recently been asked as to whether PFAS are of potential vapour intrusion concern. In research presented by Roth (2019), select PFAS are indicated to meet the US EPA (2015a) criteria for volatile chemicals (based on Henry's Law constant). However, the results of experimental box volatility tests indicated the PFAS analytes detected were not at high enough concentrations to be of a vapour intrusion concern (Roth 2019). In the PFAS guidance developed for CSAP, SLR (2019) notes that "the PFAS of regulatory focus are considered to have limited volatility and are expected to be predominantly associated with air-borne particulate as opposed to being present in the vapour phase". [1]

In the BC regulatory context, Part 1 of the Contaminated Sites Regulation (CSR) defines vapour as gaseous emissions from soil, sediment or water. The substances regulated as vapours in Schedule 3.3 of the CSR, and potentially non-prescribed substances if there is a vapour concern, should be considered as warranted based on the CSM considerations described above.

2.1.2 Vapour Sources

Common vapour sources are non-aqueous phase liquid (NAPL) zones, and soil and groundwater impacted by volatile or semi-volatile chemicals. While some guidance documents describe NAPL as a primary source and a dissolved groundwater plume as a secondary source for soil vapour intrusion (SABCS 2011; US EPA 2015a), this distinction is not considered warranted as groundwater may be contaminated by partitioning from impacted soil or soil vapour, or may not be of concern where there is a dense non-aqueous phase liquid (DNAPL) source below a fresh-water lens. Soil contamination in the unsaturated soil zone or near the groundwater surface (or water table) is a vapour source, but deeper soil contamination that is submerged at a sufficient distance below the groundwater surface is not a vapour contamination source of concern.

Sources of vapour contamination include (US EPA 2015a):

- spills and leaks,
- leaking tanks,
- discharges to sewer lines, septic tanks, and floor drains,
- landfills and other land disposal management units,
- fire-training areas,
- discharge areas, and
- vapour leaks from pressurized tanks and pipelines.

NJ DEP (2018) include a "vapour cloud" as a source. A "vapour cloud" is contamination in soil vapour with no collated contamination in the soil or groundwater; potentially caused by subsurface vapour leaks such as a tank in the unsaturated soil zone (SABCS 2011), or from downward vapour migration through slabs. Contaminated building materials may also be a vapour source.

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[1] PFAS are not currently regulated as vapours in the BC Contaminated Sites Regulation

A building with an indoor vapour contamination source (e.g., dry cleaner) can also result in a subsurface vapour plume (SABCS 2011). The potential for a building to impact subsurface vapour increases when the building has a higher pressure than the subsurface soil.

While the inferred conceptualization is often a steady-state vapour source, the vapour source may evolve and exhibit transient behaviour through both migration of the source zone and associated groundwater and vapour plumes.

2.1.3 Building Factors

Potentially applicable building factors identified in guidance include (NJ DEP 2018; CCME 2016; Health Canada 2010):

- building use (e.g., residential, institutional, day care, school, commercial and industrial uses)
- foundation type and construction (e.g., slab-on-grade, crawlspace, basement, earthen and wooden foundations)
- the depth of the lowest floor below grade (e.g., presence of basements)
- the size and height of the building (the potential for stack effect may increase with increasing height)
- heating ventilation and air conditioning (HVAC) system (e.g., type of heating system and supply and exhaust air)
- potential for stack effect (e.g., temperature differences) or other natural forces (e.g., barometric pressure and wind) that affect building conditions and vapour intrusion
- building pressures (the potential for vapour intrusion increases with increasing building depressurization relative to sub-building soil)
- building ventilation (if vapour intrusion is occurring, concentrations will increase as the fresh air change rate decreases)
- potential vapour entry points (e.g., utility lines that penetrate the foundation, cracks in the walls and floors, sumps and elevator pits)

For aerobically-degrading chemicals (e.g., petroleum hydrocarbons), factors that should be considered (US EPA 2015b; ITRC 2014; NJ DEP 2018) include features that could affect oxygen (O_2) migration or “recharge” to below buildings including the building size; the type and extent of paved surfaces beside buildings; the permeability, moisture content and organic carbon content of soil near buildings; and soil gas advection caused by building or weather conditions.

2.1.4 Subsurface Factors

The following fate and transport mechanisms control indoor air vapour intrusion (generally addressed in most guidance):

- partitioning of vapours from contaminated soil, groundwater, or NAPL into soil vapour gas (unless there is a vapour cloud source)
- diffusion of vapours in vapour- and liquid-phases
- biodegradation
- advection into a building
- mixing of vapours with building indoor air

The broad site characteristics affecting subsurface processes are geology and hydrogeology (CA DTSC 2015). The unsaturated soil zone properties that may be considered in the CSM include soil type, soil heterogeneity, soil moisture, porosity, organic carbon content and soil-air permeability. Site-specific factors considered in guidance (NJ DEP 2018; CCME 2016) include clean water lens, interface plumes, groundwater depth and fluctuations (including tides), surface cover type, snow and frost, soil moisture and infiltration fronts, preferential pathways (addressed in Section 2.1.6) and potential for contaminant degradation. NJ DEP (2018) indicate that a clean water lens may be a barrier to prevent volatilization into overlying buildings when the thickness of the lens is greater than 3 ft (0.91 m) and greater than the annual water table fluctuation.

NJ DEP (2018) highlight the importance of evaluating potential for VOC mass storage in soil within the vadose zone when conducting VI investigation (Yao et al. 2010; Carr 2016), noting that groundwater may not be impacted (i.e., either because of clean-up efforts or because there was an unsaturated zone source). Slow desorption of VOCs from fine-grained and/or organic rich soil zones can result in long-term impacts to shallow soil vapour and potentially cause vapour intrusion.

US EPA (2015a) indicate vapour migration can be impeded by

- high soil moisture
- low-permeability (generally fine-grained) soil
- biodegradation, particularly through aerobic biodegradation of petroleum hydrocarbons and some chlorinated hydrocarbons

US EPA (2015b) describes the factors that affect biodegradation of aerobically-degrading chemicals:

- Vapour source hydrocarbon concentration, flux, and composition of hydrocarbons present including methane.
- Oxygen demand, which is the O_2 required to biodegrade the available hydrocarbons and any other native organic matter present, and O_2 availability.
- Soil type and properties including texture and moisture content.
- Availability of essential micronutrients.
- Ambient temperature in the subsurface.

- The pH of the soil and groundwater.

2.1.5 Proximity to Source

Health Canada (2010) describes that buildings that are within 30 m (vertical or lateral) distance of subsurface contamination should be included in VI investigation. This excludes cases when there are significant surface covers or preferential pathways when larger screening distances may apply. US EPA (2015a) has a similar lateral screening distance, but we note this guidance pertains primarily to chlorinated hydrocarbons.

ITRC (2014) describe a screening approach based on vertical and lateral distances between hydrocarbon source and building; with screening distances developed for two types of petroleum sites:

1) An underground storage tank (UST) or aboveground storage tank (AST) site.

2) A typically larger petroleum industrial site, such as a terminal, refinery or pipeline site.

Identification of buildings to include in VI investigation are within 30 ft (9.1 m) lateral distance of subsurface contamination.

The ITRC (2014) recommended vertical screening distances of non-impacted soil between the source and building are:

- 5 ft (1.5 m): dissolved-phase sources (for both petroleum UST/AST and industrial sites)
- 15 ft (4.6 m): LNAPL sources (petroleum UST/AST sites)
- 18 ft (5.5 m): LNAPL sources (petroleum industrial sites)

Precluding conditions to the application of the above screening distances (and where more detailed assessment would be warranted) include:

- Gasoline containing lead scavengers
- Gasoline containing greater than 10% vol/vol ethanol
- High organic matter content (generally greater than 4% w/w)
- Excessively dry soils (less than 2% by volume or 1.2% by weight moisture)

US EPA (2015b) describe a similar approach, but with a vertical screening distance of 6 ft (1.8 m) for dissolved-phase PHC sources, and additional site investigation criteria and precluding conditions.

NJ DEP (2018) indicate the following conditions trigger a VI investigation:

- Groundwater contamination in excess of the NJ DEP Ground Water Screening Levels (GWSL) and within 30 ft (9.1 m) of a building for PHC or 100 ft (30 m) for non-PHC compounds.

- Free and residual product within 30 ft (9.1 m) of a building for PHC compounds or 100 ft (30 m) for non-PHC compounds.

2.1.6 Preferential Pathways

Preferential pathways may consist of natural (e.g., shallow fractured bedrock or vertically fractured soil) or anthropogenic (e.g., buried utilities) features and can be important pathways that affect VI (e.g., NJ DEP 2018; WA Ecology 2018). Anthropogenic pathways include subsurface utilities such as sewers, utility backfill, drains, sumps and elevator shafts. Several guidance documents (CCME 2016; SABCS 2011) indicate preferential pathways are potentially significant when they connect subsurface contamination (i.e., intersect the contamination) and the building. Because there are numerous subsurface utilities in built-up areas, judgment is needed to determine when utilities may be a significant preferential pathway to VI. Because of the emerging importance of sewers as preferential pathways for VI and the relatively limited information in guidance, review of select recent literature is presented in Appendix B.

2.1.7 Other Considerations in Guidance

CCME (2016) note that soil vapour migration is affected by sorption and/or biodegradation or partitioning into soil moisture. The time for soil vapour concentrations to reach near steady-state conditions may have implications for design of soil vapour sampling programs.

US EPA (2012a) present a comprehensive review of CSMs and potential effect on subsurface vapour migration and vapour attenuation factors through numerical computer simulations of vapour intrusion into a building. The vapour concentration attenuation between a source and building is related to site conditions, building properties and chemical properties. The factors addressed include vapour source characteristics (e.g., concentration, size, location, depth), subsurface conditions (e.g., soil layers, moisture conditions, O_2 levels for biodegradation) and building and environmental conditions (e.g., foundation type and condition, pressurization, air exchange rates, and wind) and ground cover beside buildings.

2.2 Vapour Sampling Locations

Review of the guidance documents (Appendix A) commonly indicate that vapour sampling locations depend on site-specific CSM, investigation stage and data objectives. A common theme amongst the reviewed guidance is the determination of the vapour investigation zone in three dimensions, also described as lateral and vertical investigation zones. The general approach begins with an evaluation of the lateral extent of vapour investigation relative to the vapour source and vertical screening where applicable, prior to selection of the vapour sampling locations. Overall, the sampling locations are categorized into soil vapour (deep and near source and shallow), indoor air, outdoor air, and sub-slab. In broad terms, vapour sampling is recommended to begin in locations nearest to the vapour source, which is commonly the deeper and near source soil vapour. The conventional approaches and the site conditions that would require an alternate sequence in vapour sampling locations are summarized in the following sections.

2.2.1 Lateral Investigation Zone

Lateral vapour screening may be based on evaluation of the impacted soil and groundwater zone in the subsurface such as 30 m from detectable concentrations in soil and groundwater (e.g., SABCS 2011; Health

Canada 2010; 100 ft (30 m) separation in CA DTSC 2011a). Other guidance specifically for petroleum vapour intrusion (PVI) for aerobically biodegradable constituents recommend a lateral screening zone or a lateral inclusion zone overlying the contamination source (US EPA 2015b; ITRC 2014). The type of contamination source (LNAPL or dissolved phase) and threshold concentrations in groundwater are used in defining the contamination source zone. There are exceptions noted for specific site conditions, where the application of the lateral screening or inclusion zone for vapour investigation does not apply. These conditions are related to the presence of preferential pathways, soil gas under pressure, and extent of impermeable surface covers.

An alternate approach is provided in CA DTSC (2015), which recommends an initial grid base sample spacing for soil vapour investigation based on historical site use and potential contaminant release points of 50 ft x 50 ft. (15 m by 15 m). If no historical information is available, an initial grid spacing of 100 ft x 100 ft (30 m by 30 m) is recommended. Where the source is laterally removed from a building, some guidance documents recommend a minimum of three samples as part of a transect consisting of i) edge of contamination source nearest to the building; ii) mid-point between source and building; and iii) near the edge of the building (CCME 2016; SABCS 2011).

While the above guidance provides useful strategies for systematic sampling approaches, in the BC regulatory context, BC ENV TG 4 describes general requirements for vapour source characterization and delineation based on the relationship between sources of volatiles in soil, sediment and water to the generation of vapours. In addition, TG 4 includes a lateral screening distance of 30 m, except for select petroleum hydrocarbon compounds, for which the screening distance is 10 m.

2.2.2 Vertical Investigation Zone

Most guidance documents recommend a bottom-up approach, where deep and near source soil vapour samples are prioritized in a staged vapour assessment approach. At sites where the vapour source is at the water table, it is recommended to obtain soil vapour samples immediately above the capillary fringe to avoid high moisture conditions that would impede the flow of soil gas. Certain site conditions such as shallow water table, low permeability soils or where soil vapour sampling results indicate potential risk of vapour intrusion, sub-slab, indoor and outdoor air sampling may be required. Shallow contamination below or near a building such as dry cleaners, or when initial site screening using soil and/or groundwater data indicates the potential for significant risk associated with vapour intrusion may require a different approach with more emphasis on sub-slab and indoor air and preferential pathways instead of a bottom-up approach (SABCS 2011; CCME 2016).

There are PVI specific guidance for vertical screening distance defined as a vertical separation distance between the vapour source and the lowest point of an overlying receptor (e.g., building basement floor, foundation, or crawl space surface) (US EPA 2015b; ITRC 2014) beyond which vapour assessment may be unnecessary. The separation distance applies to clean and biologically active soil with specific criteria and precluding conditions. In these guidance documents, paired deep and shallow soil vapour sampling, and/or paired indoor air and sub-slab sampling are recommended for PVI sites that do not meet the vertical screening distance. For PVI sites, there is a greater emphasis on evaluating factors that can affect aerobic biodegradation and notably O_2 availability in the subsurface.

Regardless of the approach in identifying the lateral and vertical investigation zone, some of the guidance reviewed specifically note that transient factors should be accounted for in the sampling design. Modelling tools and references are provided for estimating the time for the vapour sources to reach steady-state condition, or equilibration time following remediation (e.g., Johnson et al. 1999; CA DTSC 2011a). There may also be changes in site conditions, for example, change in the groundwater flow direction or water levels that can impact the vapour source zone and therefore the lateral and vertical investigation zones.

2.2.3 Indoor Air Sampling Locations

Specific guidance on number and location of indoor air samples accounts for factors affecting building operations. For a small to moderate size house that is well ventilated one sample per floor is recommended in most guidance documents reviewed and with priority given to the lower floors closer to the contamination source such as basements or crawlspaces. More than one sample per floor is recommended for larger buildings, commercial buildings and schools. The specific number and locations depend on variability in building ventilation and use. NJ DEP (2018) provides minimum numbers based on building footprint area for eight scenarios ranging from < 1,500 square feet (139 m^2) to > 1,000,000 square feet (93,000 m^2). US EPA (2015a) notes a minimum of one sampling location for buildings < 1,500 square feet (139 m^2) in the lowest level (basement or first floor) and one sample from the second floor.

NJ DEP (2018) recommends that the height of the sample above floor is to correspond to the breathing zone (1.0 – 1.5 m) and located centrally in the room being investigated with consideration to the breathing zone of the most sensitive receptor. In CCME (2016), this is defined as an “exposure point” sample, whereas “pathway point” samples would be collected at openings and cracks in the foundation, depending on the data objectives for the vapour investigation. If a preferential pathway from utilities is a concern, vapour samples from kitchen and bathroom locations may be needed, otherwise the primary living/use area would be targeted (CA DTSC 2011a). Appendix E presents considerations relating to breathing height.

2.2.4 Outdoor Air Sampling Locations

Outdoor air samples are typically obtained for two types of data objectives: to assess outdoor air exposure; and/or to assess ambient background sources for the interpretation of indoor air data. For evaluating background sources, a sampling location upwind of the contamination source is recommended. CA DTSC (2011a) recommends collecting samples at 6 ft (1.8 m) above the ground and at least 10 ft (3.0 m) beyond a tree’s drip line and at a lateral distance twice the height of the building in the upwind direction. While collection of several samples is noted in most guidance documents, exact numbers and locations are site specific. Emission sources to identify include gasoline stations, major highways, paving operations and remediation systems. NJ DEP (2018) recommends a minimum of one outdoor air sample and US EPA (2015a) recommends one or two samples near a building with additional samples if multiple buildings or wide site (“wide” site is not defined). For the assessment of background sources, US EPA (2015a) recommends obtaining a sample near the HVAC intake, where applicable.

2.2.5 Soil Vapour Sampling Locations

Once the lateral and vertical extent of the vapour investigation area has been identified, the number and locations of external soil vapour samples depend on site-specific conditions identified in the CSM. The locations depend on whether the investigation is for VI in an existing or future building and/or outdoor exposure. SABCS (2011) recommends samples be obtained close to existing buildings with a minimum of 1 m distance from the building foundation and maximum of 10 m. Two samples are recommended from at least two sides of the building with one sample collected from location of highest expected concentrations based on soil and groundwater data. NJ DEP (2018) does not recommend external soil vapour sampling for decision making for existing buildings except when it is not possible to obtain sub-slab samples (due to high water table) or when there is lateral vapour migration through the basement walls.

CCME (2016) recommends a minimum of two soil vapour sampling locations per source area (e.g., Area of Potential Environmental Concern (APEC)), where there is no building. CA DTSC (2015) specifically recommends close interval grid or radial, or a step-out sampling pattern such as 10- to 20-foot (3- to 6-m) grid pattern and an initial multi-level sampling at 5-, 10- and 15-ft depth (1.5-, 3.0-, 4.6-m depth).

Vertical profiles are recommended in CCME (2016) where assessing for biodegradation, vapour source in residual NAPL in the unsaturated zone, or future building scenario. A minimum of three sampling depths are advised: at a depth nearest to the source but above the capillary fringe; the mid-point between the source and ground surface or base of the building foundation; and shallow soil vapour (see below) typically > 5 ft (1.5 m) below the ground surface. CA DTSC (2015) notes that ideally numerous vertical profiles may be needed for characterization of soil vapour at a site; however, once the depths of contamination have been determined, soil vapour collection may be targeted at these depths site wide.

Commonly referenced factors in guidance affecting sampling locations and numbers include soil heterogeneity, particularly related to soil physical properties such as soil-air permeability and moisture content, in addition to zones of high organic vapour readings noted in the headspace of soil samples during site investigation, or installation of soil vapour probes. Most guidance documents recommend review of lithologic information on boring logs.

The factors described in US EPA (2015b) are building dimension, source type and whether the source is in direct contact with the building in order to determine sampling approach for a soil vapour or indoor air assessment. CA DTSC (2011a) specifically addresses soil vapour sampling post remediation for excavation and disposal and SVE systems.

In the BC regulatory context, BC ENV TG4 describes fundamental requirements for implementing vapour investigations that begin with characterization of the vapour source and delineation that is based on the relationship between volatiles in soil, sediment and water to the generation of vapours.

2.2.6 Sub-slab Vapour Sampling Locations

There can be significant spatial and temporal variability in sub-slab vapour that may be due to heterogeneities in the subsurface as well as weather conditions and building type and operation. Most guidance documents recommend at least two sub-slab sampling locations immediately or few inches or centimeters below the slab at each residential building, where one probe is installed near the centre of the foundation. In some of the guidance documents reviewed, due to potential effect of dilution through “short-circuiting”, sampling locations near the edges of the foundation are not recommended due to potential wind effect on the representativeness of the vapour sample. The sub-slab vapour sampling locations may also depend on the distribution of the source below the building.

More than two samples are considered required to delineate areas with elevated sub-slab vapour for larger buildings (SABCS 2011). NJ DEP (2018) provides recommended minimum number of sub-slab vapour samples based on building footprint area for eight scenarios ranging from < 1,500 square feet (139 m^2) to > 1,000,000 square feet (93,000 m^2). Paired sub-slab vapour and indoor air sampling may be used to determine the impact of background sources, or to estimate building-specific attenuation factors. Pressurized building conditions may lead to the transport of interior vapour sources to the sub-slab region. This condition can be evaluated by concurrent monitoring of pressure differentials between the sub-slab vapour probe and the indoor air (SABCS 2011).

2.2.7 Shallow Soil Vapour Sampling Locations

Soil vapour samples collected at shallow depths are more influenced by ground surface cover, changes in temperature, barometric pressure and there is greater potential for breakthrough of atmospheric air during sampling. Based on these factors, most guidance documents reviewed recommend a minimum sampling depth of 5 ft or 1.5 m (US guidance) or 1.0 m (Canadian guidance). Health Canada (2010) and CCME (2016) state the minimum depth as 1 m below the foundation slab (rather than ground surface).

At site conditions with shallow water table, where the minimum depth requirements cannot be met, the following recommendations are made:

- SABCS (2011) recommends that probes be carefully sealed and the integrity of the seal confirmed by leak tracer testing for samples collected from less than 1 m depth. A modelling assessment of sample depth, flow rate, purge volume, surface cover and leakage is provided in Appendix B of SABCS (2011).
- In CCME (2016), valid samples may be collected at depths as shallow as 0.5 m with precautions such as plastic ground sheet and careful sealing of the probe verified by a leak test. However, it is noted that at sites where there is an O_2 shadow (and potentially drier soils) below the building, shallow external soil vapour samples may be non-representative of conditions below the building.
- CA DTSC (2011a) recommends that groundwater grab samples should be obtained where groundwater is shallow and soil contamination is close to the water table.
- Health Canada (2010) recommends collection of both soil and groundwater data for vapour assessment.
- NJ DEP (2018) recommends collection of soil vapour samples from below existing large impervious surfaces as an alternative approach.

2.2.8 Spatial Variability

The reviewed guidance documents note spatial variability in vapour data due to heterogeneity in subsurface soil and vapour source. In addition, weather conditions, distance from building walls, pressure differentials, and foundation properties are also noted to impact indoor air and sub-slab vapour concentrations. CA DTSC (2011a) suggests soil vapour collection close to the source zone and around the perimeter of the building and as close as possible to the foundation.

The Canadian guidance reviewed suggest vertical profiles and lateral transects to characterize spatial variability with consideration given to changes in lithology in selecting the number and locations of soil vapour samples. In broad terms, CCME (2016) states that spatial variability generally increases with increasing distance from the contamination source with greater variability in shallow external soil vapour data than deep vapour data due to effects of near-surface changes such as temperature and barometric pressure. Similar or greater spatial variability is noted for sub-slab data relative to data from shallow external soil vapour. To address spatial variability in sub-slab samples, many of the guidance suggest the high purge volume (HPV) method (McAlary et al. 2010) for obtaining representative sub-slab vapour concentrations.[2]

The effects of spatial variability on the availability of O_2 are also noted to have greater impact on soil vapour distribution of aerobically-biodegradable PCOCs. These factors include soil physical properties such as moisture content and porosity or impermeable surface cover (e.g., concrete, asphalt, ice, very large buildings) as noted in the PVI guidance (ITRC 2014; US EPA 2015b) as well as in other guidance.

2.2.9 Other Vapour Sampling Locations

Other vapour sampling locations noted in the reviewed guidance document are samples collected from vent risers of vapour mitigation system for performance assessment; or vapour samples collected from utility corridors in the assessment of preferential pathways. CA DTSC (2011a) provides guidance and a decision tree for evaluating potential vapour intrusion from utility corridors.

2.3 Vapour Sampling Frequency

Similar to the design of vapour sampling locations, review of the guidance documents (Appendix A) commonly indicate that vapour sampling frequency also depends on site-specific CSM, investigation stage and data objectives. There are also considerations of when to collect vapour samples, or to initiate vapour assessment based on a timeline for the occurrence of the vapour source and processes affecting vapour migration and time to reach approximate steady-state conditions. Direct and indirect transient effects due to seasonal, weather related and building operations from review of the guidance documents listed in Appendix A are summarized in sections below in terms of the suggested vapour sampling times and frequency.

2.3.1 Seasonal

Most guidance documents reviewed suggest a minimum of two sampling events to capture seasonal and temporal variations, whereas CA DTSC (2011a) recommends quarterly sampling of soil vapour in the first year of investigation and based on site-specific considerations thereafter. On the other hand, three of the guidance documents note that a single monitoring event may be sufficient under specific conditions:

- NJ DEP (2018) state that one round of indoor/ambient air samples may be sufficient, assuming there are no other contradictory lines of evidence, and that the indoor air sampling event takes place between November 1 and March 31 (heating season) as generally “worst case” conditions for vapour intrusion.
- Two other guidance documents also note that one sampling event may be justified if estimated vapour concentrations are more than one order of magnitude below criteria and it is unlikely for vapour concentrations to increase over time (SABCS 2011), or estimated vapour concentrations are more than one to two orders of magnitude below criteria (CCME 2016).

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[2] The HPV method involves purging a relatively large volume of soil gas prior to collection of soil gas samples for analysis, which is representative of a larger areal extent and soil volume below the building foundation.

- WA Ecology (2018) note that in general, a lower number of sampling events are needed to determine further VI investigation than to screen out the VI pathway.

In broad terms, two monitoring events over contrasting seasonal conditions in terms of temperature (heating and cooling seasons), or precipitation (dry and wet seasons) are noted in the reviewed guidance. Examples of recommended seasonal monitoring are:

- January/February and June/July as representing “worst case” months and recommended for performance monitoring of a vapour mitigation system (CA DTSC 2011b).
- For indoor air sampling, CA DTSC (2011a) recommends late summer/early autumn and late winter/early spring.
- SABCS (2011) recommends at least two events based on water level fluctuations and moisture (wet and dry seasons).
- CCME (2016) recommends sampling events to coincide with conditions most affecting temporal variability. For example, it is noted that during winter, many buildings in Canada are depressurized, which would generally be the most influential factor for vapour intrusion, although other factors such as soil moisture, temperature and water table elevation may also be important, and which may be more favourable to higher vapour intrusion during summer.

Another common approach noted in the reviewed guidance is to conduct at least one vapour monitoring event during “worst case” conditions, which in most cases is considered to correspond to the heating season due to stack effect for indoor air and sub-slab vapour samples. US EPA (2015a) recommend samples be obtained in the heating season or when building ventilation is off. Other seasonal factors that are noted for consideration are the following (SABCS 2011; US EPA 2015b; and CCME 2016):

- Increase in temperature can result in increased volatilization due to effect of temperature on Henry’s constant.
- The amplitude in seasonal temperature variation decreases with increasing depth below ground surface, and at many sites, temperature effects will be insignificant.
- Seasonal changes due to HVAC operation of a building or natural ventilation through open doors and windows can impact ventilation rates and/or building depressurization.
- Transport of petroleum vapours is affected by temperature trends and fluctuations, precipitation, barometric pressure changes, and wind.
- While conservative vapour assessment is preferred, ITRC (2014) recommends that indoor air sampling during unusual weather conditions should generally be avoided (e.g., unusually windy conditions or during extreme storm events).

There are indirect seasonal effects noted in the guidance documents as well. These are related to seasonal effects on biodegradation (e.g., effect of temperature on microbial activity; effect of soil moisture content on transport of O_2). Seasonal effects may also influence the formation and migration of dissolved plumes and LNAPL, which in turn may affect the lateral inclusion zone for vapour assessment.

2.3.2 Rainfall or Soil Moisture Conditions

Rainfall or soil moisture conditions are noted to have direct and indirect influences on soil vapour (SABCS 2011, CCME 2016, ITRC 2014 and US EPA 2015b):

- Higher moisture in near surface soils beside the building and drier soils beneath the building can enhance soil vapour transport below the building.
- Intensive snowmelt or rain and wetting fronts impact mass transfer and equilibrium condition between contaminant in water and gas phases.
- Frost and snowmelt can potentially affect hydrocarbon flux to the surface and reduce O_2 flux to the subsurface. However, one cold climate study (Hers et al. 2014) showed little effect of frost and snowmelt and thus repeat vapour sampling with and without frost or snow cover is recommended.
- Higher moisture in surface soils can impact O_2 availability for biodegradation, while a certain minimum amount of soil moisture is necessary for microorganisms to live.

For the above reasons, vapour sampling after a heavy rainfall event or prolonged periods of continuous rain are not recommended. There are various rain conditions and waiting periods recommended:

- Significant rainfall is defined as greater than 0.5 in (1.3 cm) in one day in CA DTSC (2015) guidance, in which a waiting period based on soil type is recommended. This guidance provides reference for drainage curves for different soil types (Appendix G of CA DTSC 2015).
- A heavy rainfall event is defined as 1 cm in SABCS (2011) and 0.5 cm in CCME (2016) guidance documents with the recommendation to avoid sampling during or at least 1 day after for coarse-grained soils, and several days for fine-grained soils.
- A significant rain event is defined as greater than 1 in (2.6 cm) in ITRC (2014) guidance, which states that measurements made during or immediately after significant rain event may not be representative of long-term average conditions, but that the effect will depend on climatic conditions.

Other guidance documents do not provide specific guidelines on rainfall events and waiting periods but indicate potential effect and suggest noting rainfall in the last 12 hours prior to or during vapour sampling (NJ DEP 2018), or obtaining weather data and recording whether significant recent precipitation occurred (US EPA 2015a).

2.3.3 Groundwater Fluctuations

The reviewed guidance documents recognize the impact of groundwater fluctuations on the deep (near source) soil vapour concentrations, where there is a LNAPL smear zone as well as in the creation of a smear zone (Appendix A). The strength of the vapour source located in the smear zone can thus depend on water levels such that during high water table elevation, there is a dissolved phase source, while residual LNAPL in soil is exposed during low water table elevation resulting in higher vapour concentrations. US EPA (2015a) thus recommends deep (near) source soil vapour sampling in different seasons that coincide with groundwater fluctuations; and the PVI guidance documents recommend consideration of seasonal groundwater fluctuations when assessing the vertical separation distance.

Other potential impacts that are noted in the guidance are related to consideration of high water level on design of vapour mitigation system (CA DTSC 2011b), and the potential impact of locally increased groundwater levels in the vicinity of a UST (within the tank pit) potentially resulting in a groundwater recharge mound, changes in the local flow field, and migration of contaminants from the tank excavation (US EPA 2015b).

2.3.4 Barometric Pressure Changes

Sampling of soil vapour during a period of increasing barometric pressure can result in dilution of soil vapour by atmospheric air. This effect is noted to be significant for higher permeability soils and thicker unsaturated soil zones with greater effect on shallower sampling depths. This is because there will be greater opportunity for pumping of atmospheric air into soil than soil gas out of soil due to gas compression. In one guidance (SABCS 2011), deep groundwater is defined as greater than 10 m depth. Other considerations in the guidance documents reviewed are the combined effect of barometric pressure changes and presence of surface covers (pavement, building slab) that can impede pressure propagation and equalization in the subsurface (SABCS 2011).

Monitoring of barometric pressure on site, or otherwise obtaining data from a local weather station for a period before and after vapour sampling is therefore noted in many of the guidance documents. This data can be used to support the interpretation and comparison of soil vapour data obtained under varying weather conditions. Where practical, CCME (2016) recommends sampling during a decreasing period of barometric pressure as a conservative approach.

The US EPA (2015b) also considers the potential direct impact of wind and barometric pressure changes on vapour intrusion, where pressure gradients inside buildings may result in enhanced intrusion of petroleum hydrocarbon vapours, whereas positive pressure inside buildings can both prevent intrusion of petroleum hydrocarbon vapours into buildings and facilitate O_2 transport through cracks in the foundation into the subsurface.

Although not addressed in guidance reviewed, a possible mechanism for false positives in soil vapour could be intrusion of air into soil that is impacted by ambient air contamination sources such as industrial emissions or drill rig exhaust when installing soil vapour probes caused by an increase in barometric pressure. When suspected, review of vapour analytical chromatograms can be considered, in addition to resampling after a period of equilibration with soil vapour.

2.3.5 Temporal Variability

In addition to the temporal variability induced by seasonal and weather-related conditions (see sections above), the reviewed guidance documents also note the potential impact of diurnal temperature fluctuations and building operations. The suggested methods for assessing temporal variability include longer-term monitoring, increased frequency, selection of sampling locations and methods, and time-integrated sampling using passive samplers.

Indoor air and sub-slab samples may be more affected by temporal variability due to variations in building ventilation and use, in addition to seasonal and weather-related factors.

SABCS (2011) provides summaries of long-term vapour monitoring that indicate temporal variability can be significant and very site-specific. Other tools noted are the use of modelling to provide insight on temporal variability and longer time-integrated sampling with analogy to guidance on radon. US EPA (2015b) states that analysis and comparison of temporal changes in weather data such as temperature, barometric pressure, wind speed and direction, relative humidity, and precipitation can aid in correctly identifying trends and results in a more accurate CSM. Indoor air sampling is generally conducted over the duration of expected exposure time, typically 8-hour for a commercial building and 24-hour sampling interval for a residential building. Many of the guidance documents reviewed suggest passive sampling of indoor air for site conditions that require longer-term averaging of temporal variations (e.g., 8-hour to several week period noted in US EPA 2015a).

There may also be long-term transient effects, where the source concentration may be changing over time (e.g., mobile groundwater plume), or may be important if there is depletion of the contamination source through volatilization, leaching and/or biodegradation (CCME 2016). US EPA (2015b) recommends periodic monitoring of groundwater flow directions and plume migration, possibly over more than one annual cycle. In addition, CA DTSC (2011a) note long-term effects at sites, where soil matrix data indicates a large mass of volatile contaminants in the subsurface. This guidance also suggests long-term monitoring of soil vapour at sites where groundwater is influenced by tides.

2.3.6 Other Factors

Several guidance documents note that transient source and vapour migration and other processes such as sorption and biodegradation can influence development of steady-state vapour concentrations (e.g., Health Canada 2010). Multiple monitoring events may be required to assess steady-state conditions of the vapour source and plume, or equilibration time after disturbance to the subsurface such as probe installations or remedial activities. Steady-state or equilibration conditions can be assessed, where a trend in long-term monitoring data is available, or the timeframe can be estimated using an analytical model and approach in Johnson et al. (1999) (e.g., referenced in CA DTSC 2011a and SABCS 2011). Section 4.2 and Appendix D provide additional information on soil vapour plume transport and stability.

Guidance is also available on vapour sampling times and frequency for sites with a vapour mitigation system. CA DTSC (2011b) recommends performance monitoring for sub-slab venting system on a seasonal basis (twice a year) for the first three years or consistent verification that the mitigation system is meeting performance goals. It is noted that sub-slab depressurization systems require less frequent monitoring, since system performance can be assessed through monitoring of pressure differentials. At sites where vapour mitigation through sub-slab depressurization is occurring, NJ DEP (2018) recommends the system be turned off and to cap vents, and to wait a minimum of 48 hours before collecting a sub-slab soil vapour sample.

2.4 Sampling and Analysis Methods

Key components of a sampling and analysis plan include data quality objectives, target compounds, detection limits, sample containers, sample transport, analytical methods, quality assurance/quality control (QA/QC), holding times, duplicates and blanks, and leak testing.

CA DTSC 2015 provides a detailed protocol for sampling that specifies:

- Probe equilibration consisting of a minimum of two hours for probes installed by direct push methods and sub-slab probes and 48 hours for probes installed with hollow stem or hand auger drilling methods; for soil vapour probes installed with the rotosonic or air rotary method, do not conduct purging, leak testing, and soil vapour sampling until it can be empirically demonstrated that the subsurface equilibrium time is sufficient to collect representative samples (time for equilibrium can vary from a few days to a few weeks).
- Shut-in tests prior to purging or sampling (minimum measured vacuum of 100 in (39.7 cm) water column with sampling canister attached, i.e., valve closed).
- Leak tests at every soil vapour well each time a soil vapour sample is collected (using a liquid tracer, e.g., difluoroethane or n-propanol or gaseous compounds, e.g., helium or sulphur hexafluoride).
- Sampling and purging flow rates of 100 to 200 mL/min.
- If the purge volume is excessive (e.g., deep probe and large diameter tubing), flow rate may be greater than 200 mL/min but vacuum must be maintained less than 100 in (39.7 cm) water column.
- Removal of three borehole volumes through a purging step. Previously purge volume tests were required to determine the “optimal” volume but there was sufficient evidence from sites in California to conclude that three purge volumes were appropriate.
- Vacuum in sample train less than 100 in (39.7 cm) water column.

CCME (2016) describes similar requirements as CA DTSC (2015) with minor differences in equilibration times including: driven probes or where samples are obtained from direct push drive rods that remain in the ground (20 minutes), probes installed in small diameter direct push holes (one day), probes installed in auger holes or rotosonic holes where no air or water is used for drilling (two days). CCME (2016) recommends that air rotary boreholes or hydrovac holes should be developed by removing air introduced into the formation followed by minimum equilibration time of one week. In addition, sequential purging and testing of soil vapour should be conducted to confirm stable concentrations.

Acceptable methods for sampling and analysis of soil vapour and air include canisters (e.g., US EPA Methods TO-14 and TO-15) and active sorbent samplers (e.g., US EPA Method TO-17) (US EPA 2015a). Individual certification of canisters is generally desirable where data are to be used to directly measure exposure concentrations in ambient air because of the low analytical reporting limits required. The flow rate and duration should be determined for active sorbent samples and care must be taken to avoid breakthrough. US EPA SW-846 Method 8260B is the most common method utilized for field screening of soil vapour samples in New Jersey (NJ DEP 2018). Where active soil vapour sampling is not possible, passive soil vapour samples should be considered, along with sampling of the soil matrix for chemical impacts using US EPA Method 5035 (US EPA 2015a).

Passive samplers enable characterization of time-integrated samples, which can be beneficial because VI can be temporally variable within a day and between days (US EPA 2015a). Passive diffusive samplers are commonly used for indoor air quality studies and with thermal desorption methods may be able to quantify concentrations to low levels needed for indoor air quality studies. A potential advantage is that one- to two-week samples can be obtained using passive samplers.

For soil vapour, passive diffusive samplers that quantify concentrations based on the rate of chemical permeation through a membrane with a low uptake rate are capable of quantifying soil vapour concentrations. Certain samplers have indicated reasonable comparisons in soil vapour (within a factor of two) to active canister (TO-15) results for select compounds excluding subsurface conditions when the starvation effect is significant, which may be the case in clays or wet soils (McAlary et al. 2014; CCME 2016). The more conventional use of passive soil vapour samplers is to provide the mass of absorbed chemicals as a relative screening tool, which is useful for identifying chemically impacted areas and mapping plumes and preferential migration pathways (e.g., utilities).

The value of continuous real-time field instruments such as field gas chromatography (GC) include multiple, less expensive data that can be used to better characterize spatial and temporal variability and locate vapour migration routes into structures and VOC sources inside the structures. Examples of the use of field GC include HAPSITE gas chromatograph/mass spectrometer (Gorder and Dettenmaier 2011) or the US EPA Environmental Response Team's Trace Atmospheric Gas Analyzer (TAGA) Mobile Laboratory (EPA-ERT 2012). In California and other parts of the US it is common practice to retain a mobile laboratory and analyze samples in real time. Samples are collected into a syringe and directly injected in the GC. Samples are analyzed according to Modified US EPA Method 8260 or Method TO-15 and typical reporting limits are sufficiently low for assessing whether soil vapour concentrations meet screening levels.

Hartman and Kram (2019) describe readily available methods for obtaining concurrent real-time concentrations, pressure differential and weather data (barometric pressure, temperature, wind speed). An on-site GC with photoionization detector (PID)/electron capture detector (ECD) meeting the requirements of US EPA Method TO-14 enable low-level analyses to be completed. The value of continuous monitoring is demonstrated through case examples where both indoor and subsurface vapour sources are identified from concentration and weather data patterns, which enable improved remedies to be designed (Hartman and Kram 2019). Depending on the example site, HVAC systems and weather (primarily barometric pressure and wind) are shown to affect vapour intrusion. The key factors affecting vapour intrusion are indicated to be people (i.e., their occupancy patterns), HVAC system operation, sub foundation pressure and climatic variables.

In the BC regulatory context, sampling and analysis must meet the BC Field Sampling Manual (Standard Operating Procedure for Soil Vapour / Gas Sampling SOP-D1-11), BC Environmental Laboratory Manual, the ENV protocols and guidance documents, the EDQRA from the BC government (i.e., the CSR standards with methods acceptable to the Director). Special preapproved permission from BC ENV to conduct non-standard sampling and analyses is required.

2.5 Multiple Lines of Evidence

It is generally recognized in the review of the guidance documents listed in Appendix A that there are various degrees of uncertainty associated with soil vapour assessment at many sites. As such, alternative and complementary methods are recommended in support of vapour assessment depending on specific site conditions and the CSM. Additional lines of evidence may include sampling of multiple media; pressure monitoring; indicators, tracers and surrogates; and building pressure control tests, as described in the sections below.

2.5.1 Multiple Media

At many sites, vapour assessment typically begins with delineation of contaminant vapours in the subsurface through review of soil and groundwater data. Estimates of soil vapour concentrations from groundwater or soil data using equilibrium partitioning calculations for vapour assessment may be recommended, where collection of soil vapour samples is not practical (e.g., tight clays or high moisture conditions), or for a screening level assessment (CA DTSC 2011b; CA DTSC 2015; NJ DEP 2018).

Typically, most guidance recommend a bottom-up approach with collection of deep (near source) soil vapour samples, but specific situations may warrant collecting indoor air samples before collecting subsurface data because of an immediate need due to for example, shallow spill event, when field screening indicates concern, odours with unknown source, contaminated groundwater or LNAPL is in contact with or directly below building (ITRC 2014). Other lines of evidence for assessing vapour pathway include comparison of contaminant vapour concentrations in indoor air, outdoor air, sub-slab, soil vapour and estimates derived from concentrations in soil and groundwater (SABCS 2011; CA DTSC 2011a; CCME 2016). A table of evaluation methods and issues related to data from each media is provided in one of the guidance documents reviewed (Table 3.1 in SABCS 2011).

In broad terms, US EPA (2015a) suggests assessing the vapour intrusion pathway by collecting, weighing, and evaluating multiple lines of evidence in support of assessment and risk management decisions. Concurrent indoor air and sub-slab samples are recommended for determining site-specific attenuation factors and assessing the impact of background sources. Additional lines of evidence for pathway assessment can be gathered from comparisons of concurrent indoor, outdoor, groundwater, and soil vapour constituent ratios for identifying background sources and use of tri-linear plots (SABCS 2011; CCME 2016; CA DTSC 2011a).

In the assessment of petroleum hydrocarbon vapours, guidance on PVI (including SABCS 2011 and CCME 2016) suggest monitoring of carbon dioxide (CO_2), methane (CH_4) and O_2 in soil vapour at multiple depths from shallow and deep (near source) locations to assess aerobic biodegradation of petroleum hydrocarbons. Thresholds of benzene concentrations in groundwater and soil, as well as hydrocarbon ranges (e.g., gasoline range organics or total petroleum hydrocarbon (TPH)) are adopted to identify dissolved phase versus LNAPL sources of petroleum hydrocarbons, where screening distance criteria are used in PVI (US EPA 2015b; ITRC 2014). Using this approach, it is also recommended that groundwater samples be analyzed for PHCs and non-PHC fuel additives (e.g., alcohols, ethers, organic lead, lead scavengers) typically found in petroleum-based fuels, when appropriate.

2.5.2 Pressure Monitoring

Review of guidance documents indicates recommendations for pressure monitoring in various forms and for various purposes. For example, barometric pressure monitoring is recommended to guide sampling time and interpretation of data (SABCS 2011; CCME 2016), which also support collection of other meteorological data such as wind and temperature. Differential pressure monitoring, however, are more commonly recommended due to their direct effect on vapour migration. Measurement of pressure differentials between indoor and outdoor air, or between indoor air and sub-slab soil vapour are recommended (CA DTSC 2011a; SABCS 2011; CCME 2016; US EPA 2015a).

Vapour migration can be affected by low pressure differentials on the order of one Pascal (Pa), thus, pressure monitoring can also serve as an indirect measure of temporal variability, where sensitive measurement devices with accuracy to 1 Pa are suggested (ITRC 2014).

Sub-slab depressurization systems for vapour mitigation require the monitoring of spatial extent of vacuum below the building (e.g., CA DTSC 2011b; ITRC 2014).

2.5.3 Indicators, Tracers and Surrogates

Many of the guidance documents reviewed note the use of compound specific isotope analysis (CSIA), naturally occurring radon, or other surrogate chemicals and tracers to distinguish sources and pathways. Identifying vapour sources, SABCS (2011) mentions carbon isotopes and CA DTSC (2011) suggests analysis of ^{36}Cl or ^{13}C to distinguish between different chlorinated solvent sources. The use of radon data for pathway assessment and sub-slab to indoor air attenuation is recommended by CA DTSC (2011a), SABCS (2011), US EPA (2015a), ITRC (2014) and CCME (2016).

SABCS (2011) and CCME (2016) note that building ventilation tracer tests can be accomplished using inert gases such as CO_2 or SF_6. These guidance documents also note the use of tracers to evaluate preferential pathways such as sewers; or use of larger-scale tracer and pneumatic testing to estimate soil-air permeability and evaluate soil vapour migration pathways. Another line of evidence suggested by these guidance documents is pathway assessment using “marker chemicals”, which are chemicals generally not found in background air sources but are associated with subsurface contamination (e.g. 1,1-dichloroethylene or cis-1,2-dichloroethylene) (also noted in US EPA 2015a and ITRC 2014).

PVI guidance documents (ITRC 2014; US EPA 2015b), depending on site conditions, recommend obtaining vertical sampling profile of O_2, CO_2, and CH_4, and nitrogen (N_2) as a quality control check and indicator of soil gas advection. The guidance documents state that depleted O_2 and elevated CO_2 levels are indicators of aerobic biodegradation of hydrocarbons. Elevated CH_4 concentrations are an indicator of anaerobic biodegradation. Additionally, analysis of hydrocarbon compounds that are less soluble and potentially less biodegradable than the BTEX compounds (e.g., cyclohexane, 2,2,4-trimethylpentane), or conservative tracers that may serve as useful tracers for hydrocarbon vapour transport is recommended.

Indicators, tracers and surrogates (ITS) as a formal concept to guide optimization of vapour intrusion investigations is relatively new (Schuver et al. 2018) and was not addressed in detail in guidance reviewed. Schuver et al. (2018) define ITS as follows:

1) Indicators are metrics that can be used to identify an elevated potential for exposure through vapour intrusion, and consequently the best times and locations to sample. Pressure and temperature are identified to be useful indicators.

2) Tracers are readily measurable substances that migrate in a similar way to the volatile chemical of interest. Radon is indicated to be a useful natural tracer.

3) Surrogates are metrics with a quantitative relationship to the chemical of interest that is sufficiently accurate to be a substitute for decision-making.

2.5.4 Building Control Tests

Building pressure can have a significant effect on the degree of vapour intrusion and may be caused by building use and operation, as well as weather related effects. When building pressure is controlled through HVAC or use of a blower door, controlled pressure conditions can be created to assess the impact of background sources or to create worst case conditions, for example, by building depressurization (Lutes et al. 2019). In the reviewed guidance, SABCS (2011) and CCME (2016) mention the potential application of building pressure control tests for pathway assessment and to determine whether volatiles measured in indoor air are from subsurface or background sources.

ITRC (2014) notes that on-site GC/MS analysis can be used to determine the pattern of changes in VOC concentrations in indoor air under different pressure conditions. This approach can aid in pathway assessment and addressing temporal variability.

2.5.5 Other Factors

Other lines of evidence include alternative sampling methods such as active and passive sampling, specifically mentioned for investigation of naphthalene (CA DTSC 2015). Collection of soil samples for determining soil physical properties and other geological and hydrological factors that can affect vapour migration including soil-air permeability, tortuosity and attenuation through biodegradation for petroleum hydrocarbons. The site-specific data on subsurface properties is suggested for use in models of vapour transport, for example to estimate site-specific attenuation factors (CA DTSC 2011a; SABCS 2011; CCME 2016; Health Canada 2010).

Data on building operation such as ventilation is noted for interpretation of data and determining site-specific attenuation factors (NJ DEP 2018; CCME 2016). CCME 2016 states that it is possible to estimate the ventilation rate from HVAC system design for commercial building, where the air exchange rate is calculated from the make-up volume, and not the total air handling volume.

In performance assessment of mitigation systems, monitoring of flow rates, smoke testing or liner installation, where applicable are recommended (CA DTSC 2011b).

Tree coring is suggested as a screening tool in SABCS (2011) and CCME (2016), where tree core concentrations of chlorinated solvents may be related to soil and groundwater concentrations

On a broader scale, SABCS (2011) suggests assessment of spatial trends at various locations within one building or multiple buildings and comparison to the CSM for expected vapour sources. Another recommended line of evidence is the comparison of site-specific attenuation factors derived from measurements to the literature reported empirical or modelled values.

For estimating emissions to outdoor air or above a crack on a concrete floor, or sumps, ITRC (2014) and CCME (2016) suggest the use of flux chamber tests (static or dynamic) (Hartman 2003). US EPA (2015b) further recommends field instrument screening at utility access point(s) as an initial step to determine if the utility is acting as a conduit for vapours. If the transport of vapours from the source area to the building could occur along utility conduits, then US EPA (2015b) states that vapour sampling inside the utility conduits, manholes, or sumps should be considered in addition to vadose zone and sub-slab soil vapour sampling.

US EPA (2015b) notes that the following conditions provide additional line of evidence that the site may be more affected by seasonal and weather effects:

- Poor drainage around the building indicated by flooded soils,
- Area subject to permafrost/long lasting snow cover (based on altitude or latitude), and

- Shallow and highly variable water table.

2.6 Ambient Air

2.6.1 Indoor Air

CA DTSC (2011a) indicate that indoor air monitoring is conducted at later stages of an investigation (bottom-up approach). Several guidance documents recommend concurrent or near concurrent indoor air, outdoor air and soil vapour testing be conducted as part of an MLE approach (e.g., SABCS 2011; NJ DEP 2018). Indoor air testing may either be performed sequentially after sub-slab testing has been performed to determine if there is a vapour concern or concurrently with sub-slab testing (NJ DEP 2018). If concurrent, a minimum wait time of 24 hours is noted after sub-slab probe installation/sampling to avoid cross-contamination of indoor air. WA Ecology (2018) recommends that installation be delayed shortly after the indoor air samples are collected or to install the probes prior to indoor air sampling (which allows for concurrent sampling) as long as equilibration time is taken into account following installation.

Key planning aspects in the reviewed guidance are to conduct a building survey and communication with the owners and occupants. Preliminary screening with portable air monitoring instruments such as PID/FID may be used for identifying indoor VOC sources or targeting sampling locations at some sites; they may not be used to rule out the presence of background contaminants in indoor air and the sensitivity of instruments and detection levels should be considered. Compared to soil vapour, generally lower detection limits, larger sample volumes and longer sampling durations are required for indoor air testing.

2.6.2 Outdoor Air

Outdoor air characterization may be warranted to assess outdoor exposure to contaminant vapours; or for identifying background sources for an indoor air assessment (CCME 2016). NJ DEP (2018) recommends that samples be located upwind of buildings and away from VOC sources.

2.6.3 Building Conditions

Indoor air samples should be obtained under normal building conditions when the objective is to assess human health risk (ITRC 2014). A worst-case scenario for indoor air sampling for vapour intrusion is indicated by ITRC (2014) to be when the HVAC system is turned off and after the building has equilibrated for a few hours. The rationale for this conceptual model is not described. We note the combined effect of HVAC operation, ventilation, and environmental factors (e.g., temperature) is complex and therefore it may not be possible to predict worst-case conditions.

To create conservative conditions during indoor air sampling, ingress and egress activities should be minimized (SABCS 2011). HVAC operation should be normal for the season and time of day; during colder months when the heating system is used, the HVAC system should be on for at least one day prior to scheduled sampling to maintain an indoor air temperature greater than 18 ^{o}C before and during sampling.

During sampling it is recommended that the building occupancy; indoor and outdoor temperatures; HVAC system operation; building ventilation and pressures; presence of chimneys, flues and exhaust vents; wet basements, foundation properties and potential vapour entry points be noted (NJ DEP 2018). Review HVAC design and operation and obtain HVAC test-and-balance data if available. Pressure data may be used to help evaluate whether there is a complete vapour intrusion pathway.

The presence of an elevator shaft may be important because drains in a shaft pit may be an entry point for vapours and because the shaft may be a conduit for vapour migration between floors, may cause pressure differentials or may promote a stack effect because air may move upward in the shaft (SABCS 2011).

2.6.4 Background Sources

Potential sources of VOCs include household products; off-gassing from building products (i.e., carpeting, shower curtains, building insulation, pressed wood products and fabrics); home heating (i.e., heating oil storage and combustion emissions), wood stove or candles, tobacco smoke, attached garages (i.e., vehicle emissions and stored products). Volatilization of trihalomethanes occurs from tap water (particularly when heated) as well as through activities in the home or workplace (SABCS 2011). Even after soil vapour intrusion is mitigated, chemicals of concern may be detected in indoor air as a result of desorption from building materials (SABCS 2011).

Best practices for addressing background sources of VOCs in indoor air include the following (NJ DEP 2018; SABCS 2011; CCME 2016):

1) Conduct building walkthrough using questionnaire.
2) Be aware of potential indoor VOCs based on available databases of chemicals in household products (e.g., Schmidt & Clark 2013; eHow 2013).
3) Remove background sources of VOCS at least 24 hours prior to sampling (this guidance recommends 72 hours if possible).
4) Obtain indoor air, outdoor air and soil vapour samples to add in interpretation (e.g., MLE approach).
5) Evaluate ratios of chemical concentrations for single point or single-chemical concentrations for multiple points as part of forensic type analysis.
6) Conduct indoor air sampling under controlled building pressure conditions (positive and negative pressures).
7) Evaluate natural tracers such as radon or conduct testing where a conservative tracer is injected below building.
8) Conduct environmental forensic type analyses; strategies include using (ITRC 2014; CCME 2016):
    a) Compound ratios (such as benzene/TPHv) in soil vapour and indoor air results.
    b) Chemical fingerprinting (including chromatogram traces) to distinguish between different types of PHCs (such as diesel, gasoline, and jet fuels).
    c) Stable carbon isotope ratios such as carbon, hydrogen, and O_2 in the source determination of methane and other light hydrocarbon gases or isotopes such as carbon, hydrogen and chlorine in the source determination of petroleum and chlorinated hydrocarbons.

Not all lines of evidence are required and building control tests and/or forensic analyses are typically only conducted at select sites where warranted.

2.7 Vapour Intrusion Mitigation

Approaches to risk management of soil vapour intrusion include: 1) prompt response measures (over-pressurization, increased ventilation and sealing of utilities); 2) mitigation (active sub-slab depressurization); and 3) Institutional controls (receptor relocation or restrictions) (US EPA 2015a).

Two main mitigation approaches described in the CA DTSC (2011b) guidance are: 1) sub-slab depressurization (SSD); and 2) sub-slab venting (SSV). While there is a continuum between the two approaches, SSD reduces vapour intrusion by creating a slight depressurization below a building slab while SSV dilutes vapour concentrations below the building by drawing in outdoor air (while often also creating a negative pressure below the building). One common approach is to construct a passive system that can be converted to an active system if warranted.

SSD mitigation is commonly implemented through an active venting system (fan or blower) and may be constructed at existing or new buildings. SSV mitigation may be effective at existing buildings when soils are sufficiently permeable to enable efficient venting or when there are open sub-floor building elements (e.g., crawlspace). More commonly, SSV systems are implemented for new building construction where sub-floor materials can be engineered to meet performance objectives (e.g., aerated sub-floors or coarse-gravel layers) and may be either active or passive systems. Commonly used mitigation systems for new buildings include gas barriers (e.g., a sprayed-applied or sheet geomembrane). Aerated sub-floors because of their very high permeability are effectively ventilated using passive or low-powered fans and can be a sustainable approach to mitigation (Hers and Hood 2012). Additional elements of vapour mitigation systems include monitoring systems and alarms when warranted.

Building controls such as over-pressurization and/or increased ventilation may be an option at some sites and have been demonstrated to reduce indoor vapour concentrations, but their effectiveness is highly dependent on the concentration reduction required and building conditions. The extent to which building HVAC conditions required to mitigate vapour intrusion can be controlled may be limited or may be costly to achieve because of the cost to retrofit and operate systems and heat air used for ventilation.

2.8 Attenuation Factors

As noted in the above sections, vapour assessment may be conducted through measurements in multiple media and at various locations with respect to the receptor or point of exposure. While attenuation factors used to estimate vapour concentrations at point of exposure are not the focus of the reviewed guidance documents, five of the documents reviewed (CA DTSC 2011a; NJ DEP 2018; Health Canada 2010; WA Ecology 2018; US EPA 2015a) provide generic (or default) attenuation factors, and/or guidance on estimating building-specific estimates through modelling or direct measurements. The sections below summarize the review on attenuation factors in terms of media in which the measurement is made, applicable land use, and derivation basis for the recommended attenuation factors.

2.8.1 Media

The reviewed attenuation factors apply to estimation of indoor air concentrations based on soil vapour measurements (sub-slab and open-field or exterior soil vapour concentrations), as well as soil vapour concentrations estimated from measured groundwater concentrations. Soil data may be used to estimate soil vapour concentrations (e.g., CA DTSC 2011a), but not as a sole line of evidence (i.e., must be considered in conjunction with groundwater or soil vapour data).

The generic attenuation factors are intended to be conservative and generally recommended for screening assessment of soil vapour intrusion (e.g., CA DTSC 2011a). US EPA (2015b) references the US EPA (2015a) generic values; however, the recommendation for UST sites is to use attenuation factors based on source strength and separation distance (Figures 9 and 10 of US EPA 2015b), where site conditions correspond to those used in the model simulations to derive them (Abreu et al. 2009), which were:

- Building has a basement that is surrounded by homogeneous, uniform sandy soil that is directly exposed to the atmosphere.
- Preferential pathways for vapour migration into the building or through the vadose zone are not present.
- Vapour source is not in direct contact with the foundation.
- A square building of 10 m x 10 m dimensions

In the BC regulatory context, BC ENV TG 4 indicates that the estimation of substance concentrations in subsurface vapour from measured substance concentrations in soil is not recommended as a sole characterization approach for substances with a liquid specific gravity greater than one (e.g., trichloroethylene) because these substances can be present in the form of DNAPLs, which are often difficult to identify and delineate.

2.8.2 Land Use

The generic attenuation factors or approaches for modelling generally consider residential land use, while some also consider commercial (Health Canada 2010; CA DTSC 2011a) or non-residential land use (NJ DEP 2018). CA DTSC (2011a) further classifies the generic attenuation factors for preliminary screening purposes, based on existing or future buildings. The values provided for future buildings are lower by a factor of two based on consideration of a layer of engineered fill in the Johnson and Ettinger (J&E) model calculations (Appendix B of CA OEHHA 2004).

In the BC regulatory context, BC ENV prescribes four land uses in the CSR for vapour standards, consisting of: 1) Agricultural, Urban park and Residential Use; 2) Commercial Use; 3) Industrial Use; and 4) Parkade Use.

2.8.3 Derivation Basis

Attenuation factors applicable to vapour concentrations in a crawlspace of a building or a sub-slab vapour sample are generally empirically derived based on database studies (CA DTSC 2011a). Likewise, Health Canada (2010) specify an empirically-based attenuation factor for sample locations less than 1 m depth below ground surface or foundation base. US EPA (2015a) recommended values for groundwater and soil vapour at any depth are also empirically based on a database of vapour intrusion, while NJ DEP (2018) assumes empirically-based attenuation factors in the derivation of soil vapour screening levels, and the J&E model in the derivation of groundwater screening levels.

Depending on site conditions and for aerobically biodegradable PCOCs such as petroleum hydrocarbons, the use of the J&E model is considered overly conservative and thus a biodegradation adjustment factor is recommended or used in the derivation of attenuation factors (e.g., NJ DEP 2018; Health Canada 2010). Health Canada (2010) considers other adjustment factors for an earthen foundation or for mass depletion. Site-specific model predictions using the J&E model may be used for the derivation of site-specific attenuation factors based on assessment of soil physical properties, building properties, and chemical-specific biodegradation rates, if applicable. The PVI guidance documents reviewed in Appendix A provide options to evaluate site-specific attenuation factors using computer modelling of PVI such as BioVapor and PVIscreen[3] (US EPA 2015b; ITRC 2014).

CCME (2016) provides a review of empirical attenuation factors that can be compared to the site-specific attenuation factor as one line of evidence to evaluate the potential influence of background sources on indoor air concentrations. The method is based on comparison of empirical data for the land use and building type category that corresponds to the site-specific attenuation factor of interest.

Empirical studies have focussed on assessing soil vapour intrusion for residential buildings (US EPA 2012b; CCME 2014) and there are fewer data for non-residential buildings. Hers (2018) compiled data from multiple studies of vapour intrusion in non-residential buildings and described the conceptual model and building-related factors (HVAC systems, ventilation rates and pressures) that affect vapour intrusion in non-residential buildings. Ettinger et al. (2018) describe a database that is being developed of sub-slab and soil vapour to indoor air attenuation factors that include a significant number of non-residential buildings in California. A gap in the research and literature are vapour attenuation factors for buildings with basement structures that are in contact with groundwater (e.g., tanked foundations) or near to groundwater that may have foundation design measures to mitigate water ingress and thus may also reduce vapour intrusion.

In the BC regulatory context, BC ENV P 22 provides vertical attenuation factors (VAFs) for indoor air and outdoor air exposures, for varying distances between the building or outdoor air and vapour measurement or estimation location, and three land uses subject to the precluding conditions identified. The derivation of VAFs other than those provided in BC ENV P 22 must be conducted by a qualified professional under detailed risk assessment.

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[3] https://www.epa.gov/land-research/pviscreen

3.0 CONCEPTUAL SITE MODEL DEVELOPMENT

The purpose of this section of the report is to provide a summary of the CSM. Key factors for the CSM with respect to vapour source, vadose zone geology, vadose zone hydrogeology, vadose zone bio-chemistry, building foundation, building operation and utilities are summarized in Figure 1.

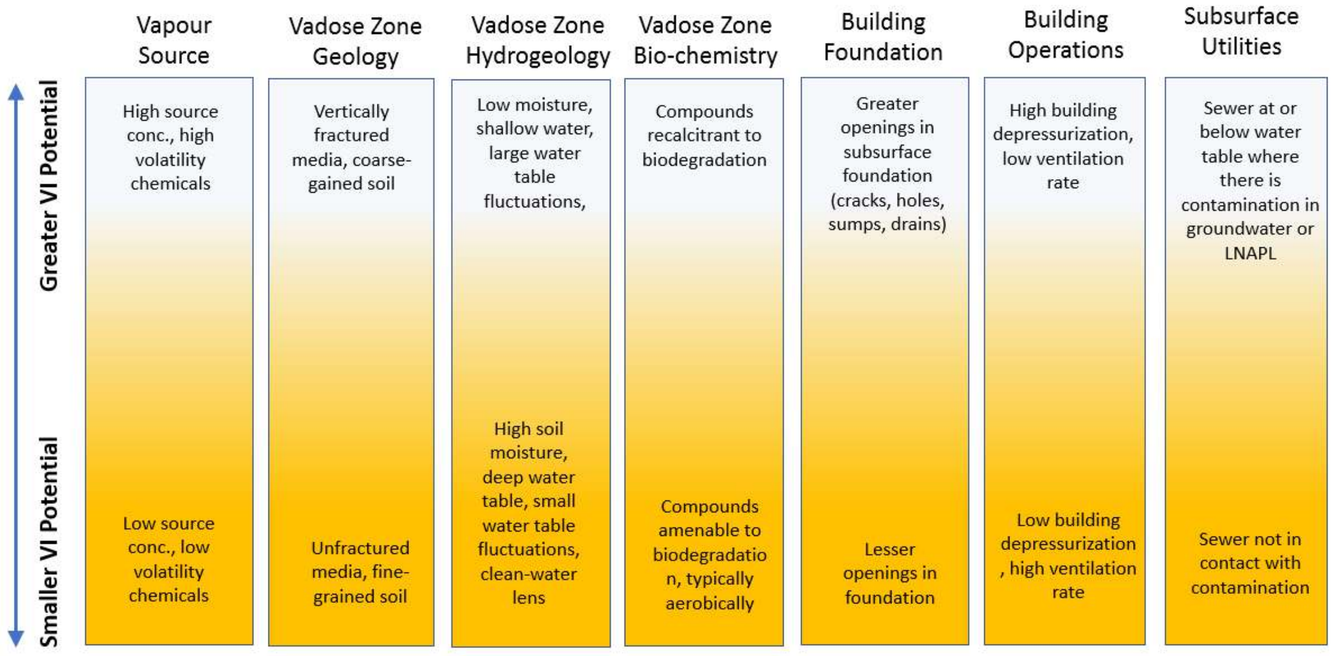

Figure 1: Select factors that affect vapour intrusion (adapted from US EPA 2015a).

3.1 Vapour PCOCs

Vapour PCOCs potentially include chlorinated or halogenated hydrocarbons, petroleum hydrocarbons, volatile components of coal tar and creosote (hydrocarbons, phenolics, heterocycles), lighter chlorophenols, ketones and ethers (e.g., MTBE) and volatile pesticides, fixed or biogenic gases (methane, carbon dioxide and hydrogen sulphide) and radon.

The BC CSR based the identification of regulated substances with vapour standards on a review conducted by the BC Environmental Laboratory Quality Assurance Advisory Committee (BCELQAAC) 2008). The main findings of this review were as follows:

- The criteria for definition of volatile substances is a chemical with both a Henry's Law constant greater than 1×10^{-5} atm-m^3/mol and vapour pressure greater than 0.05 Torr (0.05 mm).
- A threshold based on Henry's Law constant alone is considered impractical. For example, most n-alkanes have low vapour pressures, but Henry's Law constants that exceed 1×10^{-5} atm-m^3/mol because they have very low solubilities. The vapour pressure is considered a more effective measure of total volatility for screening purposes.

Functionally, the above criteria screens in naphthalene, 1-methylnaphthalene and 2-methylnaphthalene as volatile substances, but not PAHs with higher molecular weights. With respect to n-alkane compounds, tridecane (n-C13) is identified as being a volatile chemical, but heavier molecular weight n-alkane compounds are not. The review of soil vapour data for semi-volatile analyses performed by BCELQAAC indicated that at sites where PAHs heavier than methyl-naphthalenes were identified (acenaphthylene, acenaphthene and fluorene), they were usually found at concentrations that were below 2.5% of the naphthalene concentrations. With respect to n-alkane fractions, concentrations in soil vapour drop off significantly for alkanes heavier than n-C13. On average, the review of soil vapour data revealed that the n-c13 to n-C16 fraction was 2-4% of the total volatile organic fraction, and never above 25%.

In the BC regulatory context, the substances regulated as vapours in the CSR (Schedule 3.3), and potentially non-prescribed substances if deemed a vapour concern, should be considered as warranted based on the site CSM. The CSAP Practice Guideline (2009) provides useful PCOC lists for gasoline, diesel, waste oil and dry cleaners. No further refinement of vapour PCOCs is considered warranted for these types of industrial land uses.

In a detailed review and guidance on PFAS, SLR (2019) concluded that of the regulated PFAS substances, the PFOA, which are more volatile in acid form, are expected to represent a small fraction even at low environmental pH (e.g., 4.5-5.0), and that they are more likely to be present in air-borne particulates than in the vapour phase.

A comprehensive analysis of PCOCs was completed by PGL Environmental Consultants Ltd. (PGL 2018). Numerous land uses are identified where volatile PCOCs are used, including, but not limited to engine repair, metal plating, salvage and welding, paint shops and coal gasification. While PGL (2018) does not specifically identify volatile PCOCs for the purpose of vapour investigations, it is recommended that practitioners consult this guidance for identification of potential vapour PCOCs.

3.2 Vapour Sources

Soil vapour sources consist of NAPL zones, and soil and groundwater impacted by volatile or semi-volatile chemicals. Soil vapour sources include contaminated building air and materials, for example, that could be associated with a dry cleaner and vapour leaks from tanks and pipelines (e.g., vapour phase source or “vapour cloud”). The potential for a building to impact subsurface vapour increases when the building has a higher pressure than the subsurface soil. While in the BC regulatory context, vapour sources are associated with a gaseous emission from soil, sediment or water, it is important to recognize building air or material sources because of their potential confounding influence on shallow soil vapour.

3.3 Building and Environmental Factors

Processes within buildings and the interaction of the building and subsurface environment are important considerations in developing a CSM for vapour intrusion. Key factors include the building use, foundation type and construction, the surface cover beside buildings, the depth of the foundation (e.g., presence of basements), building size and height, HVAC system, potential for stack effect arising from indoor and outdoor temperature differences, effect of wind and barometric pressure, building pressures and ventilation and potential vapour entry points in the subsurface building envelope.

Because HVAC systems affect building pressures and ventilation rates, available information on the type of system should be gathered and where available, test-and-balance data on building air supply and exhaust should be obtained. The potential for negative pressures in buildings varies depending on whether there are exhaust-only systems (e.g., which may be present in kitchens and laboratories), which may create negative pressures, or where there is fresh air supply from a central air handling unit via ducts or plenums and an exhaust system, which are typically intended to be balanced and approximately neutral-pressure systems.

A key aspect of the CSM is that building pressures and the potential for vapour intrusion varies temporally at different timescales based on operable processes. Diurnal temperature differences may result in daily fluctuations in pressures due to the stack effect, which may increase during night-time hours as the differences between indoor and outdoor temperatures increase. The potential for stack effect often increases with increasing building height but will also depend on cross-floor air leakage.

Daily HVAC system operation may also be variable although the interaction between different factors such as HVAC operation and stack effect (and other factors) is complex. The processes are dynamic and influence on peri-foundational zone variable as buildings may be negatively or positively pressurized at different times of the day. The dynamic effect on sub-slab concentrations was shown through the results of tracer experiments where a chemical released in indoor air was detected at varying concentrations in sub-slab and deeper soil vapour (Holton 2015). Consequently, there are implications for sub-slab soil vapour sampling because of the interaction between indoor air and shallow soil vapour.

The effect of barometric pressure and wind may also affect vapour intrusion on the time scales of days. Hartman and Kram (2019) present continuous indoor concentration and weather data where indoor PCE concentrations increased when the barometric pressure decreased.

Seasonal processes include increased potential for stack effect in buildings during the heating season. There may also be differences in HVAC operation based on seasonal weather conditions that affect building pressures and ventilation rates. Commercial building ventilation measured with a perfluorocarbon tracer indicated that air change rates were lowest during cold and hot periods for buildings with ventilation economizers (Figure 2). Although somewhat dated, these data suggest that seasonal sampling is warranted for commercial buildings.

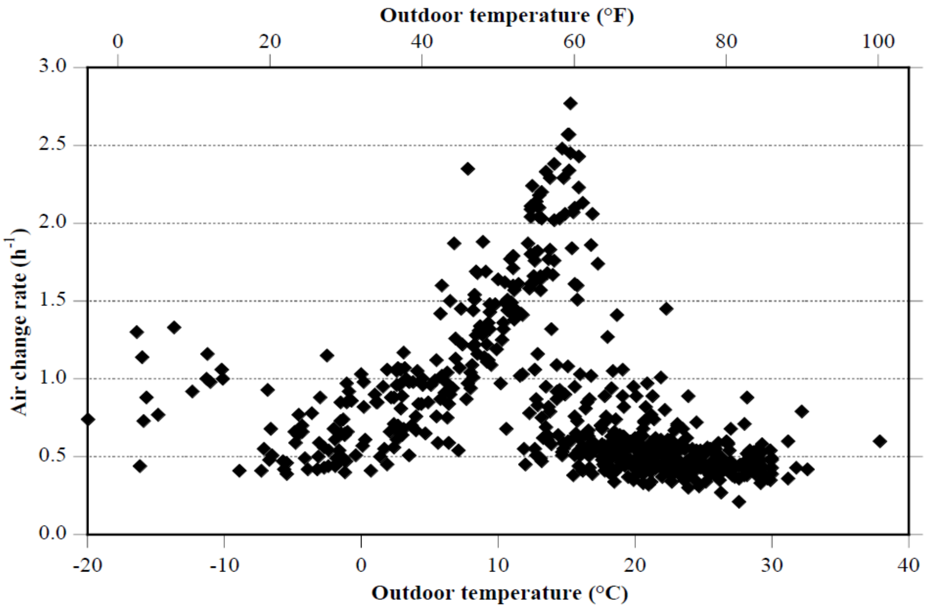

Figure 2: Measured Building Ventilation Rates as Function of Outdoor Temperature (from Persily 1989).

Recent building innovations that are being implemented to improve energy efficiency include natural ventilation, breathable buildings and solar chimneys.[4] The implications for vapour intrusion from these factors are not well understood.

For aerobically-degrading chemicals (e.g., petroleum hydrocarbons), there are factors that could affect O_2 migration or “recharge” to below buildings including the building size; the properties of the foundation slab and surface cover beside buildings; and soil properties.

3.4 Subsurface Factors

The key fate and transport mechanisms that control the migration of vapours to indoor air or outdoor air include the partitioning of vapours from contaminated soil, groundwater, or NAPL into soil vapour; diffusion of vapours in vapour- and liquid-phases; biodegradation of aerobically-degrading chemicals; soil gas advection and diffusion through the building foundation; and mixing of vapour in building indoor air. The unsaturated soil zone properties that may be considered in the CSM include soil type or texture, soil heterogeneity, soil moisture, porosity, organic carbon content and soil-air permeability. Site-specific factors that should be considered are summarized in Table 1.

NJ DEP (2018) highlight the importance of evaluating the potential for VOC mass storage in soil within the vadose zone when conducting VI investigation because slow desorption of VOCs from fine-grained and/or organic rich soil zones can result in long-term impacts to shallow soil vapour and potentially cause vapour intrusion.

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[4] An example is the Pittsburgh PNC Plaza 33 story building designed to operate 42% of time under passive ventilation. https://www.archdaily.com.br/br/789428/torre-na-pnc-plaza/56706a58e58ece8c550001c7-the-tower-at-pnc-plaza-gensler-diagram

Table 1: Site-specific CSM Factors

Factor	Effect on Vapour Intrusion
Soil type or texture	Finer-grained soils will typically have lower effective diffusivity and lower soil-air permeability, which will reduce the potential for VI.
Clean water lens or "submerged" contamination below the water table	Will reduce the potential for volatilization of dissolved chemicals and VI.
Interface plume	Volatile chemicals may partition in and out of capillary fringe water from soil vapour and thus migrate laterally.
Depth to saturated zone	For a dissolved groundwater source increasing depth decreases VI potential.
Fluctuations in depth to saturated zone	Decline in the water table could result in an increase in volatilization and VI.
Infiltration fronts and wetter soils outside building and drier soils below the building	May influence soil vapour transport because of reduced diffusion of chemicals to atmosphere beside building and increased flux in drier soils below the building.
Soil temperature	An increase in temperature will result in increased volatilization rates through higher Henry's law constants, higher vapour pressures and higher diffusion coefficients. For chemicals that biodegrade, an increase in temperature will tend to result in higher biodegradation rates.
Snow and frost	Snow and frost may have negligible effect on vapour migration (Hers et al. 2014); an exception may be when there is significant snow melt, although this effect will be a short-term effect.
Proximity of contamination to preferential pathways	May increase the potential for VI.
Potential for contaminant degradation	Generally, decreases the potential for VI (although for chlorinated hydrocarbons daughter products should be considered).
Tides	When tides affect groundwater levels soil gas pumping could occur, which may affect soil vapour concentrations and VI.
Biogenic gases (e.g., methane and carbon dioxide)	Methane may represent an explosion hazard, and methane and carbon dioxide may represent an asphyxiation hazard. Generation of biogenic gases can occur through anaerobic biodegradation of organic contamination and naturally-occurring organic matter. Possible gas pressures that result can cause soil gas advection. Methane will consume O_2 through oxidation reactions and consequently there may be implications for fate and transport of volatile contaminants and increased potential for VI in some cases[1].

Note: 1) The assessment of biogenic gases such as methane, carbon dioxide and/or hydrogen sulphide is beyond the scope of this guidance.

3.5 Preferential Pathways

Preferential pathways may consist of natural features such as shallow fractured bedrock or soil or anthropogenic features such as sewers, utility backfill, drains, sumps and elevator shafts. Recent research indicates that sewers and drains are potential pathways for migration of contaminants in sewer water and air (Appendix B) and are particularly important when:

- Sewers intersect contaminated groundwater plumes
- Where sewer discharges contain contaminants
- Where sewers connect to buildings

There are data that indicate significant impacts over relatively large distances beyond the zone of groundwater contamination (i.e., through sewer water and air migration). Monitoring data shows that common plumbing features such as sinks, toilets and drains can be vapour intrusion pathways. The regulatory implications of recent science and understanding of preferential pathways is summarized in Appendix B.

3.6 Spatial and Temporal Variability

Subsurface spatial variability in soil vapour concentrations typically increases with increasing distance from source due to factors including variability in the source, geologic heterogeneity, variable soil conditions (e.g., soil moisture), variable weather conditions (barometric pressure, temperature, precipitation), variable ground surface conditions and chemical transformations through biodegradation or abiotic reactions. The available research data indicates sub-slab concentrations below a building can be highly variable and span several orders of magnitude. Spatial variability of indoor air concentrations within a well-mixed building airspace is relatively small, although with greater variability between rooms and floors of a building. A generalized conceptual model for spatial variability is shown in Figure 3.

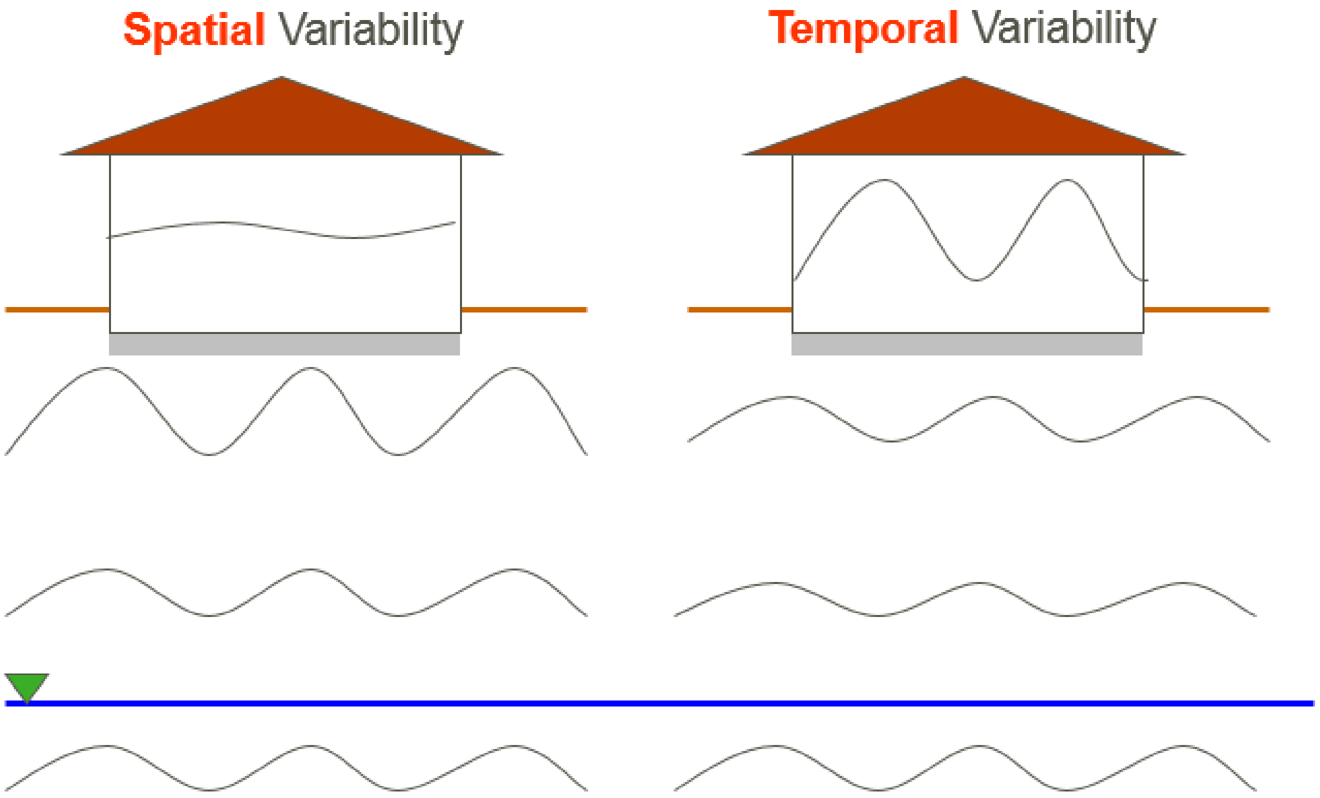

Figure 3: Conceptual Model of Spatial and Temporal Variability Where Waveform Height Denotes Variability (adapted from Folkes 2006).

Comparison of external soil vapour concentrations obtained at the same elevation or depth relative to ground surface as sub-slab vapour concentrations indicate that external concentrations underpredict sub-slab concentrations (US EPA 2012b). This has led to the recommendation for deeper, near source soil vapour sampling.

Temporal variability in soil vapour concentrations is also expected to increase in soil vapour with increasing distance from a source. As described above, sub-slab vapour concentrations may be influenced by interactions with the building and vary at different time scales from days to months (seasonal). The temporal variability may be greater near cracks or openings in the building envelope. A generalized conceptual model for temporal variability is shown in Figure 3.

Temporal variability in indoor vapour concentrations may be high and depends on several factors including building type and size and construction, foundation properties, building HVAC system, building operations, weather conditions and preferential pathways. Developing an improved understanding of variability in indoor air concentrations is an ongoing and important area of research. The research findings from two intensively monitored research houses, the Sun Devil Manor in Utah (Holton et al. 2013) and Indianapolis house (US EPA

2015c; Schumacher et al. 2015), include extensive data on temporal and spatial variability. An example of sub-slab vapour variability measured at the Sun Devil Manor is shown in Figure 4.

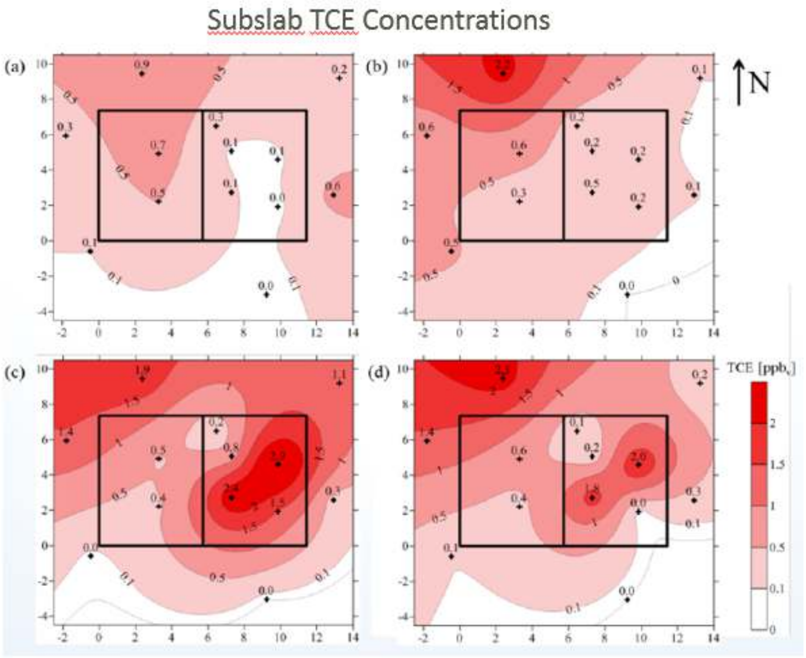

Figure 4: Variability in Sub-slab TCE Concentrations from (a) September 2011, (b) November 2011, (c) December 2011, and (d) January 2012. (DOD SERDP 2016[5]). The x and y axes are distances in metres.

There was up to three orders of magnitude variability observed in seasonal indoor trichloroethylene concentrations at the Sun Devil Manor (Holton et al. 2013; DOD SERDP 2016) as shown in Figure 5. The high degree of variability was, in part, caused by a preferential pathway (sewer). In addition, air samples were generally collected over short durations (4-hours) and are therefore expected to reflect diurnal as well as seasonal variability. Higher indoor air concentrations were generally measured in the winter compared to summer season, inferred to be a result of winter-time heating of the house and the stack effect. The indoor air monitoring data also indicated episodic higher concentration periods that were often short lived (a few hours or days). This suggests that at some sites, there may be a decrease in the likelihood that a small number of indoor air samples would yield representative data for risk assessment purposes.

Statistical evaluations have been performed from this data set to evaluate different sampling strategies. Using a synthetic data set where the data in Figure 5 was converted to 24-hour daily average concentrations, a sampling strategy based on two winter heating season samples was shown to be more reliable than four quarterly monitoring events, as indicated by a higher probability for at least one of the two samples to exceed the true annual mean concentration (average annual concentration over 2 years) for winter time sampling (66%) compared to quarterly sampling (60%). To achieve an approximate 90% probability that at least one of two winter-

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[5] Provision of data by Dr. Chase Holton, Geosyntec gratefully acknowledged.

time samples exceeds the true annual mean requires a five-times safety factor. The Sun Devil Manor dataset is valuable in illustrating potential variability in indoor air concentrations but because of the factors described above (short-term 4-hour samples and preferential pathway), the range of indoor TCE concentrations measured may not be representative of residential houses in general. In addition, use of MLEs, for example, pressure monitoring data can increase confidence in concentration data, leading to a decrease in sampling frequency or the safety factor. Consequently, caution should be exercised when using these data to inform the CSM and to develop guidance. We note that there are limited available long-term indoor air datasets of this type.

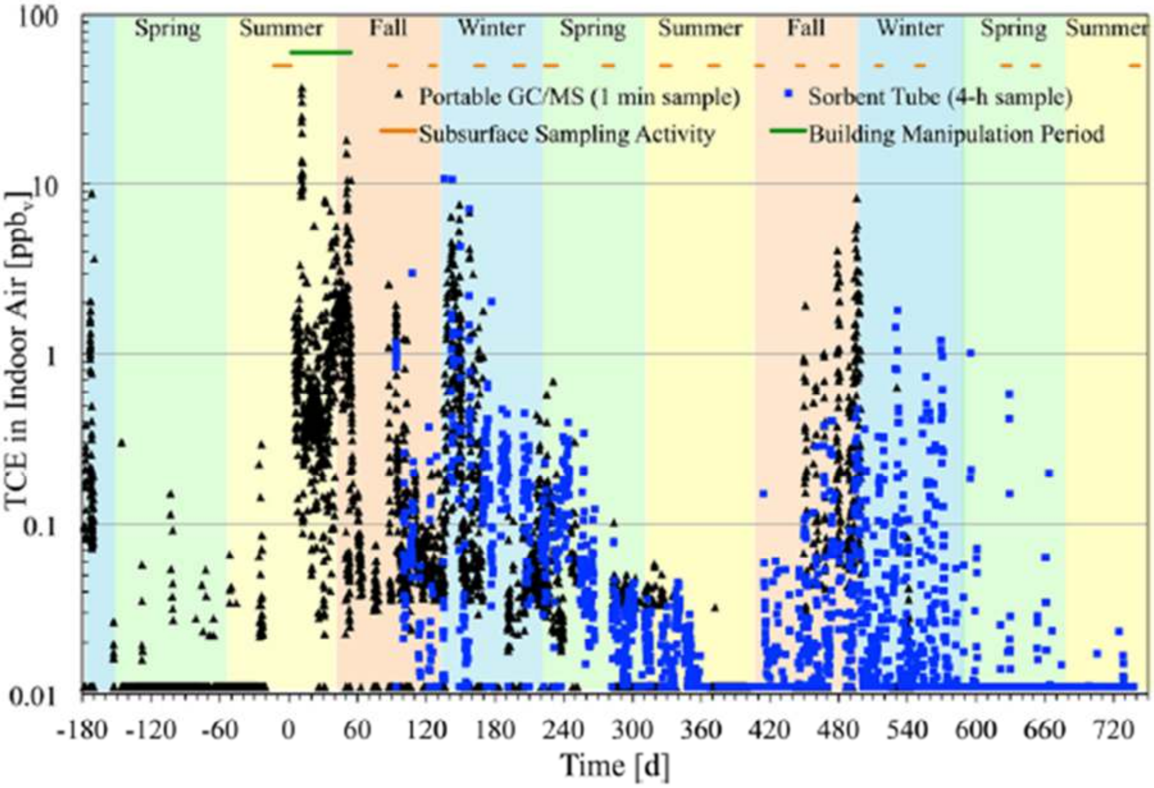

Figure 5: Indoor Air TCE Concentrations Measured by Portable GC/MS and Sorbent Tubes from February 2010 to August 2012 (from Holton et al. 2013).

There was less variability observed in indoor air concentrations of chlorinated solvents at the Indianapolis house (approximately one to two orders of magnitude). There was a moderate correlation that was statistically significant between indoor-outdoor temperature difference and indoor chlorinated solvent concentrations with higher concentrations measured in the winter months during the heating season (US EPA 2015c). The data suggested a stronger correlation with decreasing temperatures and increase in the differential temperature (change in gradient) than with absolute value of the differential temperature (Lutes 2018). There was also evidence of a possible capping effect from snow that may have resulted in higher indoor vapour concentrations (US EPA 2015c). A sewer or drain may also have contributed to the variability in indoor air concentrations observed, but likely to a lesser degree than the Sun Devil Manor site.

3.7 Current or Future Development and Land Use

The current and future development and land use including building type and foundation should be defined when possible because of the potential implications for the soil vapour investigation approach and design. When there are existing buildings, the focus of the conceptual model may be processes that occur in the immediate area of the building. When future buildings and development (e.g., surface paving) is planned, the potential for these changes to impact the soil vapour regime should be considered including effect on biodegradation rates and infiltration rates. When there are buildings with basements, the CSM should consider whether the building will be in contact with the seasonally high-water table, and deeper subsurface processes that may be relevant. If there are remediation systems that include groundwater pumping systems, the groundwater drawdown should be considered.

The significance of future changes to site conditions (e.g., future site capping) should be understood in context of chemical-specific properties and potential impact of changes in biogeochemical conditions (e.g. O_2 concentration and soil moisture) because of the implications for soil vapour concentrations as well as the source zone processes. For examples, capping can create anaerobic conditions that may result in fermentation and methane generation, or the anaerobic biodegradation of chlorinated solvents and formation of daughter products.

3.8 Summary

The significance of factors should be considered on a site-specific basis as their combined effect may not be obvious with respect to the relative importance of seasonal factors. For example, while the ASU Sun Devil Manor (Holton et al. 2013) and US EPA Indianapolis (US EPA 2015c; Schumacher et al. 2015) monitored research houses indicated indoor vapour concentrations that were, in part, correlated with indoor-outdoor temperatures, with higher indoor vapour concentrations during the winter months, there are recent published data (Barnes et al. 2017) and unpublished data for buildings in colder climate areas suggesting higher indoor vapour concentrations were not positively correlated with indoor-outdoor air temperature difference, or stack effect, at these sites but instead concentrations were higher in summer months. Barnes et al. (2017) showed soil temperature (on seasonal time scales) and barometric pressure (on shorter time scales) had the greatest influence on indoor vapour concentrations for a passively heated house in Fairbanks, Alaska.

The key factors for the CSM summarized in Figure 1 and Table 1 should be integrated as to their overall potential impact on vapour intrusion. This understanding of the CSM including current and future development and land use, as informed by the factors described and data presented above, highlights the importance of site-specific factors and is incorporated in the framework for vapour intrusion assessment in Section 4. An example of developing a CSM and vapour sampling program is provided in a case study in Appendix C.

4.0 INVESTIGATION OF VAPOUR PATHWAYS

This section of the report builds on the CSM and review of guidance to provide the recommended assessment approach, assessment of vapour plume stability, vapour sampling locations and frequency, shallow soil vapour sampling for future building, methods for indoor air assessment, and methods for outdoor air assessment. The approach described includes recommendations on vapour sampling to enable characterization of near worst-case conditions.

Although beyond the scope of this guidance, it is noted that before conducting a vapour investigation, it is recommended to review the available information on potential explosion hazard, odours, physiological effects and/or wet basements. The purpose of this preliminary step is to determine whether there are high-risk[6] conditions and whether an expeditated response may be required to address potential acute exposure conditions (Health Canada 2010; US EPA 2015a).

4.1 Assessment Approach

Two broad approaches for conducting detailed vapour investigations should be considered (Figure 6):

1) A bottom-up approach where the initial phase of the investigation consists of the characterization of the nature and extent of soil and groundwater contamination combined with testing of external soil vapour concentrations typically obtained relatively near to the source where feasible.

2) A top-down approach where the initial phase of the vapour investigation includes characterization of indoor air quality and sub-slab or shallow soil vapour concentrations.

For a bottom-up approach, depending on the results of an initial phase of testing and comparison to numerical or risk-based standards, the next phase consists of characterization of sub-slab soil vapour and indoor air concentrations. Either staged collection and analyses of sub-slab vapour samples, followed by indoor air samples if warranted, or testing of concurrent sub-slab and indoor air samples are considered acceptable approaches. If a staged approach is followed, the subsequent monitoring event should typically include both indoor air and sub-slab vapour sampling. Given the intrusive nature of indoor air monitoring and cost of remobilization, initial concurrent collection and analyses of indoor air and sub-slab samples may be warranted.

A top-down approach is warranted when there is contamination in contact with or in close proximity to a building; or when there are elevated indoor air concentrations that could represent a higher risk condition where it is important to test indoor air on an expedited basis (e.g., highly volatile chemicals, contamination in contact with or inside the building based on observations or odours). While the focus of a top-down approach is characterization of indoor air quality, subsurface data should also be obtained to determine the extent of soil, groundwater and soil vapour contamination. When the source of the vapour contamination is uncertain, an assessment of the vapour migration pathway between possible source(s) and the building is recommended.

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[6] "High-risk" in this context is generically defined and is not a regulatory definition (e.g., BC ENV Protocol 12)

In either assessment approach, multiple lines of evidence (MLE) should be considered in the implementation of a VI investigation (Section 2.5). The goal of the MLE investigation is to improve the reliability of assessments through collecting and weighing different types of data. While not all data types will necessarily be required, the data for primary lines of evidence consist of concentrations in soil, groundwater, soil vapour (external to building), sub-slab vapour, indoor air and outdoor air. Partitioning calculations from groundwater or soil to soil vapour can be performed in accordance with BC ENV TG 4 and referenced guidance (e.g., Health Canada 2010). The advantages and disadvantages of each media for investigation of vapour intrusion are described in Table 2.

Table 2: Comparison of Different Media for Vapour Intrusion Investigations

Media Investigated	Indoor Air Evaluation Method	Principal Issues
Soil	Partitioning model combined with generic attenuation factor or vapour transport model	Partitioning model highly uncertain, possible negative bias due to losses during sampling, contaminants with specific gravity greater than water (e.g., DNAPLs) can be difficult to identify and delineate and may be highly variable in the subsurface.
Groundwater	Partitioning model combined with generic attenuation factor or vapour transport model	Partitioning model uncertain because of capillary fringe, imprecision of soil vapour transport model requires conservative attenuation factors, moderate to high spatial variability, moderate to low temporal variability, not representative of contamination in vadose zone.
Soil vapour beside building (external)	Generic attenuation factor or vapour transport model	More direct indication of potential exposure, but high spatial variability (generally more so than groundwater), shallow soil vapour may be non-representative of deeper sources, moderate temporal variability.
Soil vapour below building (at depth below foundation soils)	Generic attenuation factor or vapour transport model	More direct indication of potential exposure but intrusive, high spatial variability, moderate temporal variability.
Sub-slab vapour[1]	Generic attenuation factor or vapour transport model	Closest representation of potential vapours migrating into building, but intrusive, high spatial and moderate to high temporal variability, infiltrating air may confound results if building is positively pressurized.
Indoor air	Indoor air concentrations directly measured	Direct measurement, but intrusive, background sources may confound data interpretation; temporal variability likely high.

[1] For a building with crawlspace, it is not possible to obtain a sub-slab vapour sample unless the crawlspace has a concrete floor. A sample from the crawlspace may be obtained but depending on crawlspace ventilation and connection to house, there may be little attenuation between the crawlspace and house.

[2] Definition of soil vapour locations: External soil vapour refers to soil vapour samples collected beside the building. Sub-slab soil vapour refers to samples collected within the peri-foundational area, typically within a few centimetres of the foundation slab within sub-foundation fill material. Soil vapour below building (at depth below foundation soils) refers to deeper samples that are beyond sub-foundation fill materials.

The secondary lines of evidence for assessing the VI pathway include:

- *Site hydrogeology*: A fresh-water lens is associated with lower potential for soil vapour intrusion when there is a dissolved groundwater source.
- *Soil properties*: Fine-grained soil with high soil moisture content is associated with lower soil vapour migration and vapour intrusion potential.
- *Building pressures*: A positively pressurized building is associated with lower potential for soil vapour intrusion.
- *Building background VOCs*: Indoor sources of VOCs such as building materials or consumer products can indicate the potential for background VOC sources that may confound interpretation of vapour intrusion potential.
- *Constituent ratios*: Similar ratios of individual VOCs in indoor air and deeper soil vapour are associated with higher confidence in vapour intrusion (i.e. lesser potential for background sources) after accounting for differences in fate and transport properties of individual chemicals.
- *Preferential pathways*: Sewers, tunnels, or utility lines that connect contamination to indoor air are associated with higher potential for soil vapour intrusion.
- *Vertical profiles of light gas data*: O_2, CO_2 and CH_4 data that indicate biodegradation is occurring, are associated with lower vapour intrusion potential.

Collecting multiple lines of evidence can be particularly helpful at complex sites with variable vapour migration pathways. Moreover, because many VOCs are ubiquitous in indoor air from background sources, obtaining multiple types of data is useful for interpretation of indoor air quality data.

Overarching guiding concepts for data interpretation and decision-making are:

- Predictions from measured soil vapour data (external or sub-slab) generally take precedence over predictions from soil and/or groundwater data consistent with BC ENV TG 4.
- Where measured indoor air or outdoor air data and subsurface vapour data have been collected, the former generally take precedence except for a future scenario; however, an MLE approach should be followed where the subsurface concentration data, building condition, consistency of data and predictions, and other relevant factors are considered in context of the CSM before drawing conclusions.
- If the predicted vapour concentration from different media are significantly different, it is important to consider the potential factors for this difference, and additional data may be warranted.
- The appropriate decision may depend on how close the predicted and/or measured concentrations are to the standard or threshold being evaluated and data trends. Regardless of the approach, multiple rounds of measurements are typically required for data interpretation and decision making, which are further discussed in the remainder of this Section.

Example decision matrices are provided in NJ DEP (2018) and Health Canada (2010).

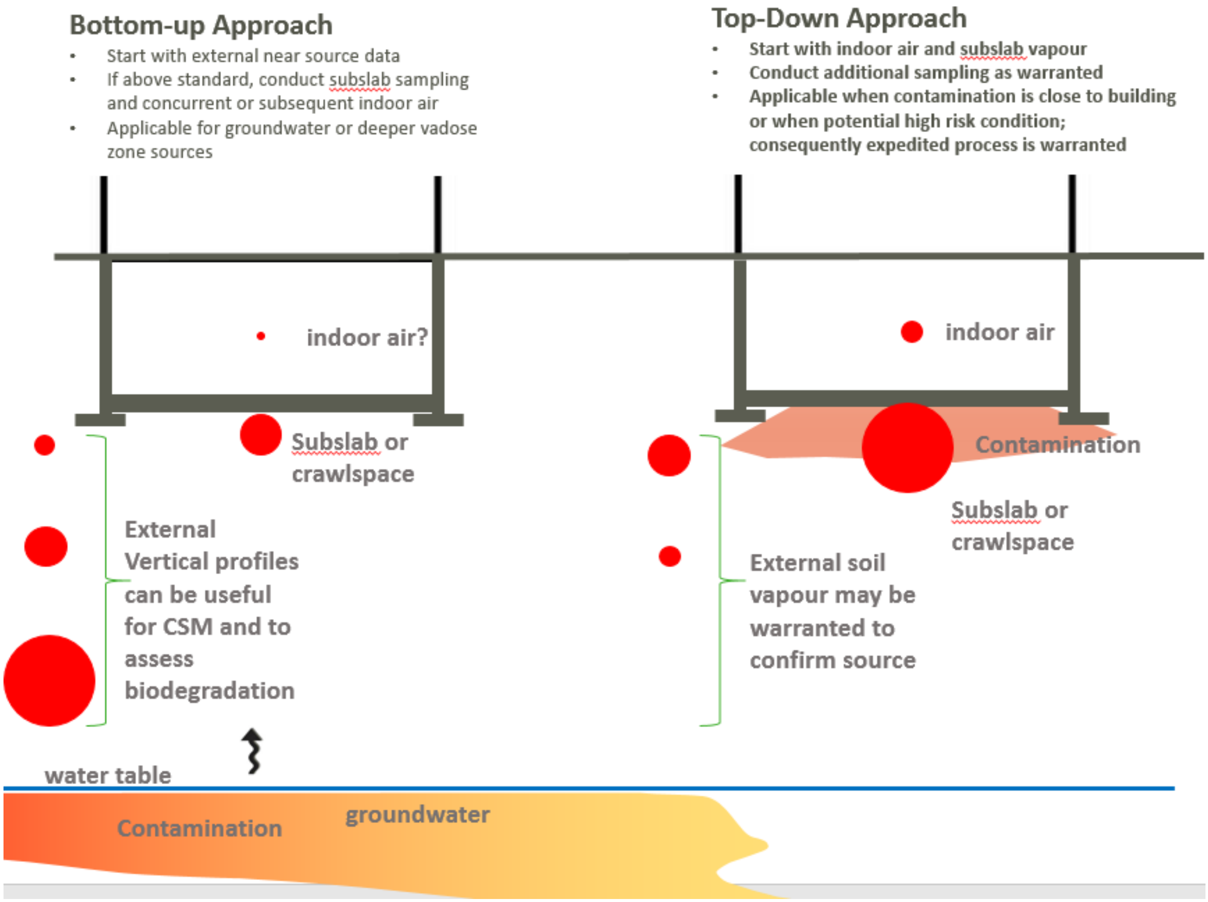

Figure 6: Conceptual illustration of bottom-up and top-down approaches. Red circles denote magnitude of soil vapour concentrations.

Vapour investigations should incorporate potential future changes to site contamination and site conditions, including building construction, surface cover and subsurface utilities. The stability of source zones and associated groundwater and vapour plumes should be well understood (Section 4.2). If there is the potential for source zones and/or plumes to expand in size, appropriate measures should be taken in the vapour assessment including monitoring of sufficient intensity and frequency to characterize transient conditions. Regardless of the approach, the vapour assessment must result in vertical and lateral delineation of the vapour plume. The potential for changes in soil vapour fate and transport as a result of future site capping by buildings and/or pavement should be considered. Often this change can be addressed through characterization of source concentrations, which are less likely to undergo significant future changes compared to concentrations in non-source locations. The future building design, including the presence of basements or underground parking structures, should be considered when determining the soil vapour measurement depths.

4.2 Vapour Plume Stability

A requirement of BC ENV TG 4 is that “qualified professionals need to indicate, with supporting documentation, whether or not a substance concentration in vapour is at steady-state or decreasing at the location where the vapour sample was taken.” In addition, a precluding condition in P 22 indicates that “to support legal instrument applications under the Regulation, vapour contamination must be stable or shrinking." TG 4 provides reference to Johnson et al. (1999) with respect to assessing steady-state concentrations.

This guidance provides two key considerations to address the above requirements in the planning of the vapour investigation:

1. Demonstrating the stability of the vapour contamination source; and
2. Demonstrating that vapour migration has reached the point of measurement (assessment of near steady-state conditions for soil vapour concentrations).

The first key consideration requires that the vapour contamination source in soil, groundwater, sediment and NAPL is stable or shrinking. For purposes of the framework described in Section 4.3, it is assumed that the vapour source is stable. If the source is not stable, there may be additional sampling requirements beyond those described in this guidance (e.g., soil and groundwater sampling) to complete the site investigation. Following the release of the source and steps taken to establish the vapour source is stable or shrinking, the second key consideration is the time for vapour migration from the source zone to the sampling locations (or time to reach near steady-state soil vapour concentrations).

It is important to emphasize that the vapour sampling location and frequency described in Section 4.3 assumes that the vapour investigation is proceeding following the assessment for the stability considerations noted above. At the vapour investigation stage, Section 4.3 considers diurnal, seasonal variations, changes in the building operations, and other site-specific conditions in identifying vapour sampling times and frequency and near worst-case conditions. The intent of this section is to provide guidance on vapour migration from the source to the sampling point to demonstrate near steady state soil vapour concentrations.

Following the stability of the vapour source, the time for vapour concentrations to reach approximate steady-state concentrations can be estimated through use of models and/or repeated measurements of vapour concentrations. The approach depends on the CSM and knowledge of the release history, where available, and assessment of stability of the vapour source. Site factors affecting the time to reach steady-state vapour concentrations include the vapour source location, partitioning and sorption, soil properties, chemical-specific properties, pressure gradients causing advective flow of soil gas, and conditions that affect biodegradation or biotransformation reactions. It is assumed that the maximum vapour transport distance of concern is 30 m from the vapour source consistent with TG 4. Some tools and methods are suggested below to aid the practitioners for adopting model predictions and/or monitoring of concentrations.

4.2.1 Approach Based on Modelling

There are analytical or numerical models that can be used for simulating vapour migration processes at varying levels of complexity. One model for the estimation of the time to reach an approximate steady-state vapour concentration is based on an analytical solution to one-dimensional diffusion and linear three-phase partitioning as described by Johnson et al. (1999), which is the model recommended in TG 4. A mathematical model was developed for simulating vapour migration and evaluating time to reach steady state. The model is based on a conceptual model that includes boundary conditions for vapour migration and is described in Appendix D. This appendix also provides practical guidance on selection of input parameters and example calculations. The approach illustrated in Appendix D highlights the importance of considering the conceptual model and defining applicable boundary conditions relevant to vapour assessment.

In addition to diffusion and sorption, processes such as biodegradation and soil gas advection can also affect vapour plume stability. Typically, there is significant uncertainty associated with use of models given geologic complexity and often limited data.

4.2.2 Approach Based on Concentration Trend Analysis

When using a measurement approach, the distance from the vapour source and diurnal and seasonal variability should be accounted for when interpreting concentration data (e.g., data should be obtained from the same season). Consideration should be given to use of statistical tools (e.g., non-parametric methods such as Mann-Kendall or regression methods) where feasible, and uncertainty related to the effects of short-term variabilities, as well as practical limitations related to number of sampling events and time needed.

Practically, an approach to address potential questions on vapour plume stability is to obtain deeper, near or within source vapour samples. Additionally, to optimize sampling programs and reduce costs, it may be possible to use field measurements (e.g., PIDs and fixed gas detectors) to supplement laboratory analytical data.

4.3 Vapour Sampling Locations and Frequency

The recommended approach in line with BC ENV TG 4 and the reviewed guidance is the delineation of the vapour source in three dimensions and identification of the lateral and vertical zones of investigation. The lateral investigation zone is 30 m for most vapour contaminants and 10 m for aerobically biodegradable petroleum hydrocarbons from the edge of contamination based on soil and groundwater analytical data and in accordance with BC ENV TG 4 and most guidance reviewed. Conditions that would require an extension to the lateral investigation zone are related to the presence of preferential pathways (Appendix B), soil gas under pressure, and extent of impermeable surface covers (Section 2.2.1). Vertical screening distances have been identified for petroleum hydrocarbons as described in the PVI guidance documents (Appendix A; Tables A-5 and A-8) and adopted by other guidance, for example, WA Ecology (2018), which replaces the use of the 10x reduction in attenuation factor for biodegradable petroleum hydrocarbons (Section 2.2.2).

Generally, the approach for most sites is to stage the investigation starting with soil vapour sampling at deep/near source locations (bottom-up approach) following the recommendations and exceptions summarized in Table 3. The overall concept is to advance to the next stage of investigation when potential for vapour intrusion risk is identified and to proceed with vapour mitigation measures when warranted.

Vapour samples collected in various locations and media (i.e., soil vapour, sub-slab soil vapour, indoor air, or outdoor air) are susceptible to temporal variations in contaminant concentrations due to natural seasonal and weather-related factors, as well as building operations and use. Review of guidance on vapour sampling frequency (summarized in Section 2.3 and Figure 3) indicate seasonal factors are key in temporal variations observed in soil vapour (deep and near source, shallow or sub-slab), indoor air and outdoor air. Conceptually, at most sites, the degree of variation is expected to increase with increasing distance from the vapour source, particularly when the source is located in deeper vadose zone and in proximity of the water table. It is therefore also important to consider the temporal variability in identifying the lateral and vertical zones of investigation (i.e., in the delineation of the soil vapour plume).

For practical considerations, continuous monitoring of vapour concentrations on seasonal timescales is not feasible at most sites. On this basis, most guidance recommend at least two monitoring events corresponding to presumed worst-case conditions related to seasonal changes in water levels (wet or dry seasons), or ambient temperature (warm or cold; summer or winter seasons). With respect to changes in the temperature, it is often the indirect effect of heating of the building that creates temperature difference leading to stack effect (heating season). As described below, we recommend the following framework in consideration of the key questions and the approach in Table 4.

The detailed review of the guidance on subsurface, seasonal or weather related, and building factors are key in selection of timing and frequency of vapour sampling in addition to the data objective and reliance on the data for vapour assessment. For the purposes of long-term exposure assessment, factors that result in sustained periods of change in vapour concentrations, such as seasonal or heating of indoor air space require more careful consideration. In line with other guidance reviewed here, sampling during short-term unusual conditions such as an extreme weather event (e.g., a winter storm) should generally be avoided, since short-term transient conditions may not provide a representative exposure concentration. At the same time, due to the level of uncertainty associated with both spatial and temporal variabilities, a conservative approach requires the selection of worst-case conditions. To address both the data objective in collecting representative long-term exposure sample and a conservative approach based on high temporal and spatial variabilities, it is suggested to define and consider worst-case conditions in terms of seasonal factors and potential impact on vapour source and migration in the selection of sampling events (Table 4).

Table 3: General Sequence of Investigation Stages, Sampling Media, and Locations

General sequence of investigation stage	Recommendations	Exceptions
1. Soil vapour sampling	• Immediately above the capillary fringe to avoid high moisture conditions that would impede the flow of soil gas, where the vapour source is at the water table. • Vertical soil vapour profiles for delineation or as a line of evidence for biodegradation • Shallow soil vapour for VI assessment of future building (Section 4.4)	• Soil vapour sampling may not be feasible, for example, when there is shallow water table or low permeability soils • Significant risk identified during the screening based on soil and groundwater data (e.g., shallow contamination below or near a building such as dry cleaners)
2. Sub-slab sampling	• Consideration of significant spatial variability due to heterogeneities in the subsurface and building type and foundation (Section 2.2.8 and Section 5) • At least two sub-slab sampling locations immediately or few centimeters below the slab at each residential building, where one probe is installed near the centre of the foundation; more samples may be required depending on building size and spatial variability (Appendix A; Table A-10) • Nearest to cracks and openings and away from the edges of the foundation to avoid potential wind effects • Concurrent measurement of pressure differentials to assess potential impact of indoor air on sub-slab sample; or for assessing temporal variability (Section 5)	• Future building scenario • Sub-slab sampling may be conducted concurrently with indoor air sampling as an additional line of evidence (Section 2.5.1) for determining background sources; or for estimating a building specific attenuation factor as part of a detailed risk assessment
3. Indoor and outdoor air sampling	Sections 4.5 and 4.6	• Future building scenario • Limited access to building interior • Installation of vapour mitigation system is necessary and is at a higher priority than further investigation. It is noted that indoor air sampling may still be required for the design of the system and performance monitoring (Section 2.7).

A clear and consistent result from the review of guidance documents and other literature for this report is that there are many site-specific and regional climate specific conditions that need to be considered in the design of the vapour sampling program. Table 4 is intended to capture many of the key factors in temporal variability and their potential impact, in order to guide the selection of factors that apply to the site and selection of the time in the year based on climate data or other site-specific factors. Taking this approach, it is expected that two to four sampling events can be used in vapour assessment in consideration of worst-case conditions for long-term exposure.

A thorough understanding of the CSM and factors affecting vapour source and migration is required and other factors may need to be added, such as frost and snow cover. This is an example of adding additional rows to the table for consideration. There may be factors other than strictly seasonal, yet causing temporal variability on a seasonal or monthly timescale such as operation of a remediation system, and it is recommended to take the same approach and add to Table 4, where potential impact on source and migration are identified along with corresponding sampling times. The following questions can support the approach in Table 4 to identify worst-case conditions for vapour sampling, and are based on data objectives, as well as building and subsurface factors described in the CSM Section 3.0:

1) Do changes in the water level affect vapour source concentrations? Is there likely an interface plume and increased volatilization from dropping water levels?
2) Is there a fresh-water lens present between the vapour source and vapour sampling location? And is this likely to be a seasonally varying condition?
3) Are site conditions that would be sensitive to barometric pumping effects?
4) Are durations of events such as barometric pumping, snowmelt, snow or frost cover, temperature in air or soil, spring freshet, or wind effects at the site and their effects on vapour concentrations significant for long-term vapour assessment?
5) Are there potential for aerobic or anaerobic biodegradation and the potential for pressure-driven flow from methane generation (e.g. at landfills)?
6) Are there other factors affecting groundwater elevation and flow direction including tidal influences? (Section 2.3.3).
7) Do changes in water levels or groundwater flow directions affect the extent of the investigation zone?
8) Are preferential pathways a concern, or would become a concern during elevated water levels?
9) Are there effects of remediation system in operation at the site that can lead to longer-term temporal variations?
10) How do the building operations, and importantly HVAC, affect the building ventilation and pressures? Could there be future significant changes to the building foundation?
11) How does the potential for changes in future land use factor into the assessment (i.e., are land use and potential future changes clearly defined in the vapour investigation area on-site and off-site)?

Table 4: Seasonal Factors and Considerations in Selection of Sampling Events

Seasonal factors	Site-specific consideration	Potential impact on vapour source and/or migration	Likelihood of worst-case or applicability to site-specific conditions Example Scenario (see text for more details)	
High water level / wet season	Free product / LNAPL present above the water table	Stronger vapour flux due to decreased distance to vapour source	e.g. ☑ April	Greater VI potential in April
	Submerged conditions of LANPL smear zone	Lower vapour source due to lower diffusion of vapours through water	e.g. ☒ not applicable	
Low water level / dry season	Exposed LNAPL smear zone	Stronger vapour source due to exposure of previously submerged LNAPL	e.g. ☑ August	Greater VI potential in August
Relatively higher temperatures in air or soil	Increase in Henry's constant and effective diffusion	Increased source from greater partitioning into vapour phase and transport rate in the subsurface	e.g. ☒ not significant	Lower VI potential in August
	Increase in building pressurization due to air conditioning operation	Lower vapour migration from sub-slab to indoor air; greater transport of O_2 to the subsurface	e.g. ☑ August	
Relatively lower temperatures corresponding to heating of indoor air	Increase in building depressurization due to higher indoor air temperature relative to outdoor air (stack effect)	Greater vapour intrusion from subsurface to indoor air	e.g. ☑ January (sub-slab or indoor air) Not applicable to soil vapour or outdoor air	Greater VI potential in January
Other site-specific or regional climate considerations e.g. frost and snow cover and melt	e.g. Greater build-up and transport of vapours below the building where soil is drier during snowmelt e.g. Decrease in O_2 transport to subsurface for aerobic biodegradation	e.g. Greater vapour intrusion from subsurface to indoor air e.g. Decrease in vapour transport from subsurface to outdoor air	e.g. ☑ January/February (sub-slab or indoor air) ☒ Not Applicable (outdoor air or soil vapour)	Greater VI potential in January/February
Seasonal changes in building HVAC conditions	e.g., Industrial building where HVAC is turned off during summer season	e.g. lower pressure differentials and greater ventilation with outdoor air	e.g. ☑ July/August (sub-slab or indoor air) ☒ Not Applicable (outdoor air or soil vapour)	Lower VI potential in July/August

Depending on the investigation stage and completeness of the CSM, the above questions can be addressed with supporting data such as:

- Soil lithology and stratigraphy
- Water level monitoring data and LNAPL monitoring, where applicable
- Meteorological and climate data
- Delineation of the source zone
- Long-term differential pressure monitoring and/or data on HVAC operation, where applicable

An example scenario of these considerations is provided in the right most column of Table 4. In this example scenario, free product is present at the water table at a site where an industrial building is being assessed for potential vapour intrusion at the investigation stage, where indoor air characterization is planned. The near worst-case times (e.g., times for greater VI potential) for this example scenario and based on the defined conditions are identified as follows:

- During high water levels, where the contamination source is considered closer to potential receptors, which is determined to occur in the month of April.
- During low water levels, where residual contamination is exposed that was previously submerged, which is determined to occur in the month of August.
- During relatively colder winter temperatures in the months of January/February, where heating of indoor air can result in stack effect and greater vapour migration into indoor air.

As noted in Table 4 there were other factors that identified lower VI potential during the summer season (July and August), however, because of uncertainty in the relative significance of these factors and as a conservative measure, three sampling events would be recommended for this hypothetical scenario. At sites where multiple lines of evidence are available to increase the level of certainty in these factors, different outcomes may be decided. A more detailed example of developing a CSM and vapour sampling program is provided in a case study in Appendix C.

It is generally expected that in following this approach, fewer sampling events would be selected for soil vapour assessment than for example, indoor air or sub-slab. This is consistent with the conceptual understanding of temporal variability with increasing distance from the vapour source (Figure 3). The approach in this Section supports the requirements in TG 4 for determining the number of vapour sampling events.

A single monitoring event may be sufficient if the criteria in TG 4 are met, for example in terms of scientific rationale. In addition, it is recommended that the sampling event be conducted during one of the worst-case conditions identified in the Table 4 approach. The measured vapour concentrations (or predicted values using the measurements) should be at least two orders of magnitude below the applicable numerical or risk-based standard, and there should be no contradictory lines of evidence. For example, it is noted that for very coarse-grained and high permeability soils, the variability may be greater than two orders of magnitude. This is in line with other guidance (see review in Section 2.3; CCME 2016; SABCS 2011 and NJ DEP 2018), and review of studies on two intensively monitored research houses (see Section 3.6), where temporal variability remains below two orders of magnitude.

If the results of one round of sampling indicate potential risk that would require advancing the investigation stage and taking further action, then additional rounds of sampling may not be needed at that stage. For example, as in the following scenarios (Table 3):

- Soil vapour sampling stage to sub-slab sampling stage
- Sub-slab sampling stage to indoor air sampling stage
- Indoor air sampling stage to vapour mitigation measures or risk management

An alternative approach, where practical, is to collect sufficient samples in one year to conduct a statistical analysis on the data for estimating a representative vapour concentration for comparison to numerical standards or to use in risk assessment. It is suggested to adopt a similar approach to BC CSR Technical Guidance 2 (TG 2) with the following conditions:

> “The data is demonstrably representative of one population; and, for that data set, the upper 90th percentile of the sample concentrations is less than the criterion concentration; the upper 95% confidence limit of the average concentration of the samples is less than the criterion concentration; and no sample within the data set has a concentration exceeding two times the criterion concentration.”

Based on the approach proposed in the CA DTSC (2011a)[7], it is further recommended that at least eight samples (spatial and temporal and pertaining to one building) be collected within the building’s footprint, and that sampling events are spread out in one year and include the worst-case conditions (Table 4). The validity of the CA DTSC approach will depend on the building size and conditions.

At some sites, the use of passive methods for time-integrated vapour samples may be considered. Passive sampling may not be a quantitative approach for estimating soil vapour concentrations and comparison to applicable standards but can provide for a lower cost method for greater spatial coverage and relative concentrations. However, it may be accepted as a quantitative measure for indoor air sampling where there are consistent flow conditions and not affected by the “starvation effect” (Section 2.4). The value of time-integrated methods is the averaging of short-term temporal variability (i.e., up to several weeks). Further assessment of the approach and available tools and methods is recommended (Section 5).

4.4 Shallow Soil Vapour for Future Building

There are various scenarios and data objectives for soil vapour samples collected at a shallow depth. Collection of a shallow soil vapour could be part of a vertical sampling profile to delineate the vertical zone of investigation for vapour assessment, and/or for evaluating biodegradation (e.g., concentration profiles of VOCs, O_2, CO_2, and CH_4). Shallow soil vapour sampling, however, becomes a more necessary step when evaluating the site for a future building scenario and the source is at shallow depth.

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[7] CA DTSC (2011a) recommendation is for large commercial buildings.

The vapour source, for example, could be shallow groundwater. Therefore, in developing the CSM and soil vapour sampling depth, it is necessary to consider groundwater fluctuations and thickness of the capillary fringe. In the Canadian guidance reviewed (Appendix A), the minimum recommended depth for soil vapour sampling is 1 m, while the US guidance consider 5 ft (1.5 m) as the recommended threshold.

Shallow vapour samples are more influenced by ground surface cover, changes in temperature, barometric pressure and there is greater potential for breakthrough of atmospheric air during sampling. At site conditions with shallow water table, where the minimum depth requirements cannot be met, the following recommendations are made:

- For existing buildings, sub-slab and/or indoor air assessment.
- For future building scenario, samples may be collected at depths as shallow as 0.45 m (consistent with CSAP 2009) with precautions such as plastic ground sheet and careful sealing of the probe verified by a leak test with the following conditions:
  - Collection of soil vapour samples from below existing large impervious surfaces as an alternative, where this option is available (adopted from recommendation in NJ DEP 2018).
  - Collection of depth discrete sample as close to the source (immediately above capillary fringe, where applicable) using a short screen interval; and use of modelling to support representativeness of the sample for a future building scenario.
  - Creation of large impervious surface, for example, by placement of a surface seal with dimensions representative of a future building scenario, and equilibration time of six to eight months prior to shallow soil vapour sampling (consistent with CSAP 2009).
- Where the above conditions cannot be met for site-specific or practical considerations (i.e., equilibration time of six to eight months), the following tools may be used:
  - Estimating time to reach steady state or equilibrium conditions following the placement of a surface seal:
    - Evaluation of trends in concentrations of hydrocarbons using field detectors (e.g., PID) and light gases such as O_2, CO_2 and CH_4.
    - Modelling assessment based on diffusive transport, sorption and biodegradation (if applicable) that incorporates site-specific parameters and assumed foundation depth and footprint of the future building scenario. An example of a modelling assessment of sample depth, flow rate, purge volume, surface cover and leakage is provided in Appendix B of SABCS (2011) using the VapourT model (Version 2.16 developed by Dr. Carl Mendoza). VapourT is a finite-element model for flow and transport of vapours in the unsaturated zone and is based on the models presented in Mendoza and Frind (1990) and Mendoza and McAlary (1990). A similar approach using the VapourT or similar model can be used.
  - Collection of both soil and groundwater data for vapour assessment (consistent with Health Canada 2010 and Approach C in BC ENV TG 4).

The vapour assessment and the CSM must consider the potential that a future building foundation may come in direct contact with contaminated groundwater or NAPL, for example, during elevated water levels. This would have implications for the selection and application of an attenuation factor in predicting indoor air concentrations for a future building scenario. It is generally helpful if information on type of foundation, depth below ground surface, building footprint area and land use are available. Another key consideration in vapour assessment for a future building scenario is the changes in O_2 availability and transport in the subsurface as a result of the building, or other ground surface cover.

4.5 Methods for Indoor Air Assessment

Indoor air monitoring is generally the last step in a bottom-up approach for characterization of the vapour intrusion pathway when subsurface media concentrations exceed standards and there is the potential for a complete vapour intrusion pathway. When compared to the other investigative tools available, indoor air characterization represents the most direct measure of exposure to human receptors, however, there may be background VOC sources in indoor air that confound data interpretation, as well as high temporal variability in indoor air concentrations.

To address potential background VOC sources, a MLE approach should be followed where indoor air, outdoor air and sub-slab vapour samples are analyzed, and where the data analysis follows a lines of evidence approach where constituent ratios, literature background VOC concentrations and other forensic tools are considered (Section 2.5 and Section 2.6.4). To address temporal variability in indoor air concentrations, where sampling is usually conducted in discreet or short-term sampling events (e.g., 8 or 24 hours), many guidance documents recommend sampling during periods of “worst-case” conditions, or as noted in the WA Ecology (2018), creating such conditions through building pressure control (BPC) (Section 4.5.4, Section 5, and Appendix A; Table A-11). Vapour sampling locations and frequency in terms of collecting representative samples for exposure assessment are discussed in Section 4.3, while the remainder of this Section provides further details on location and frequency for indoor air sampling and methods for addressing background sources and temporal variability.

The specific characteristics of the site, land use and receptors should be clearly documented in the air quality assessment report to ensure that the indoor air sampling program was designed and implemented to assess the actual current and/or reasonable future site use and receptors.

4.5.1 Indoor Air Sampling Locations and Frequency

Table 5 provides location and frequency recommendations for indoor air sampling based on review of available guidance in Section 2 and framework developed in this guidance. The number of indoor air sampling locations will depend on building use (e.g., residential, commercial, industrial), building size and number of storeys. It is recommended that the number of samples for different building sizes in NJ DEP (2018; Appendix A; Table A-10) be adopted, which ranges from one to two samples for a building with up to 1,500 ft^2 (140 m^2) footprint area (e.g., house) to greater than nine samples for a building with greater than 1,000,000 ft^2 (93,000 m^2) area. For a house, it is recommended that samples from the basement or ground floor level (if slab at grade) and from ground or second floor be obtained. Samples from multiple levels may also be warranted for commercial, industrial or other types of buildings.

The indoor air monitoring frequency should follow the approach described in Section 4.3. Based on site-specific considerations, if the stack effect in the heating season is determined to be significant and the main driver of VI, then two (or more) events in the heating season may be warranted. We note that MLE such as pressure monitoring can increase confidence in the indoor air concentration data and lead to a decrease in frequency of sampling events. For non-residential buildings there may be additional considerations related to HVAC operation that could affect timing of sampling.

Table 5: Summary of Indoor Air Monitoring Recommendations

Factors	Indoor Air Assessment
Building conditions	Conduct survey to assess chemical storage and use, occupant uses, HVAC operation, building foundations and utilities (see SABCS 2011 and NJ DEP 2018 for example surveys). Generally, it is recommended that samples be obtained under normal building occupancy and HVAC conditions representative of the exposure.
Sources of Background VOCs	Where warranted, remove products that are VOC sources a minimum of one day prior to sampling and if possible three days prior; collection of IA samples in a building (or portion of a building) where operations use, handle or store the same investigative COC (e.g., dry cleaners, active gas service stations, maintenance facilities, various industrial operations) is generally not recommended. Because outdoor air quality can affect indoor air quality, obtain data on types of industries and potential background sources including remediation systems, equipment exhaust (e.g., drill rigs and vehicles) and if available, air monitoring data from nearby stations.
Location	Exposure samples: Near middle of room; at height representative of most sensitive receptor (Appendix E) Pathway samples: From sumps, drains or other openings.
Number of locations	Guidance in NJ DEP (2018; Appendix A; Table A-10) is recommended; obtain samples from multiple levels in residential houses; requirements for non-residential buildings will depend on site-specific conditions.
Timing	Determine following approach in Section 4.3; if stack effect is determined to be significant and the main VI driver, two events in the heating season may be warranted; for non-residential buildings there may be additional considerations related to HVAC operation.
Frequency	Determine following approach in Section 4.3*; typically, 2 – 4 events
Duration	Based on receptor exposure assessment and building conditions; typically obtain 24-hour samples for residential buildings and 8-hour samples for commercial or industrial buildings.

*A single sampling event may be sufficient if measured concentration is two orders of magnitude below applicable risk-based or numerical standards, or where a single event indicates that risk management or mitigation measures are required (see Section 4.3).

As noted in Section 4.3, indoor air sampling should generally be avoided during extreme wind conditions. When there are very deep vadose zones (depending on soil type), barometric pressure effects on soil vapour migration can potentially be significant, and consideration should be given to sampling under falling barometric pressure conditions. However, in most cases, the effect of barometric pressure is insignificant. It is also typically not practical to obtain routine samples during falling barometric pressure conditions. It is therefore recommended to carefully document building and weather conditions several days prior, during, and after the sampling program.

A toolbox of methods that may be used to improve indoor air assessments are described below, with additional recommendations for guidance development provided in Section 5.0.

4.5.2 Continuous (Real-Time) VOC Concentration Monitoring

Continuous (real-time) monitoring of indoor air and vapour concentrations using field GCs has been demonstrated as an effective method of characterizing temporal trends in indoor air concentrations, identifying vapour intrusion pathways and distinguishing between background and vapour sources (Section 2.4 and Appendix A). Because processes for VI are complex and variable, high frequency data from multiple locations can be an effective tool for reducing uncertainty and providing a basis for assessing worst case conditions. These tools are becoming more readily available and should be more routinely considered (Section 5).

4.5.3 Monitoring of Pressure, Temperature and Other Indicators of Vapour Intrusion Potential

Monitoring of pressure difference between the indoors and the subsurface is recommended during indoor air monitoring programs. Differential pressure data should be obtained continuously during indoor air monitoring but should also be conducted before sampling starts and after sampling ends (at least one day on either side) to enable short-term pressure and weather trends to be evaluated.

Differences in driving forces (direction or magnitude) that occur during different indoor air monitoring events is expected to help to explain significant differences in observed indoor air concentrations over time (US EPA 2015a). Consequently, concurrent indoor air concentration and pressure data are expected to help assess whether samples are obtained under near worst-case conditions.

Greater indoor-outdoor temperature differences may also be a useful indicator of increased vapour intrusion potential and temperature data can be readily obtained. Other indicators are described in Schuver et al. (2018) and Section 2.5.3.

Development of a protocol and guidance on available tools and methods is recommended (Section 5).

4.5.4 Building Pressure Control Tests

An emerging approach is the use of building pressure control (BPC) tests to create worst-case conditions for vapour intrusion (Appendix A; Table A-11). Holton et al. (2017) identified approximately 20 studies in the literature where the test had been performed. The BPC test involves temporary pressurization and/or depressurization (typically in multiple pressure steps) to building air spaces often coupled with real-time field GC for monitoring indoor air concentrations. The test involves using a blower door or fan with sealing materials to depressurize the building. The differential pressures between indoor air and sub-slab soil gas, and indoor air and outdoor air should be continuously measured using pressure transducers. The test can be used to estimate near-worst indoor air concentrations from vapour intrusion and mass flux into a structure, and can be used to distinguish between indoor, outdoor and sub-slab sources. There remain questions associated with this test in terms of protocol needed to achieve near-worst case conditions given the range of building types and conditions (e.g., leaky to tight, small to large, etc.) and also depending on whether the pressure conditions created could exceed worst-case under natural conditions (i.e., would not be representative of receptor conditions).

Lutes et al. (2019) conclude that while application of BPC is increasing and is currently the best tool available for determining mass discharge, there is no consensus on procedures (in part due to differences in buildings, project objectives, and available resources) and further research and analysis of case studies are needed to refine the BPC method to site-specific conditions (Section 5).

4.5.5 Tracers

Tracers are readily measurable substances that migrate in a similar way to the volatile chemical of interest (Section 2.5.3 and Appendix A). Tracers may be used to indirectly assess chemical vapour migration and to help distinguish background indoor air sources from subsurface vapour sources. Radon, which is a naturally occurring gas derived from the breakdown of uranium and radium, has been shown to be an effective natural tracer (Schuver et al. 2018) and measurement protocols have been developed (McHugh et al. 2017). Radon is most effective as a tracer for evaluation of chemical vapour attenuation when there are sufficiently elevated radon concentrations in soil vapour, the distribution of the radon and chemical source is approximately similar and radon soil vapour concentrations are well characterized. There are also injected tracers, such as sulphur hexafluoride that may be considered.

4.6 Methods for Outdoor Air Assessment

As for indoor air monitoring, outdoor air monitoring is generally the last step in bottom-up approach for vapour assessment when subsurface media concentrations exceed standards and there is the potential for outdoor air exposure or a complete vapour intrusion pathway to indoor air. The data objectives for outdoor air monitoring are typically the following:

- Assess the outdoor air exposure
- Assess outdoor air as a potential background source to indoor air

Table 6 provides location and frequency recommendations for outdoor air sampling based on review of available guidance in Section 2. Potential emission sources to identify include gasoline stations, major highways, paving operations, remediation systems, and potentially landfills unless it is considered a vapour source as part of the assessment. For sites near landfills, a lateral transect of outdoor air sampling may be conducted as a line of evidence regarding the vapour source. Landfills may be an outdoor emission source of vapours, or subsurface contamination through groundwater migration downgradient of the landfill. Measurements of CH_4 and CO_2 concentrations in outdoor air along with concentrations of the vapour PCOCs concentrations should also be considered.

As with indoor air monitoring, the sampling duration of outdoor air should correspond to the receptor exposure. For longer-term monitoring and averaging of temporal variability, passive sampling methods may be used (Section 2.4 and Section 4.3).

An alternate approach to the collection of outdoor air samples for estimating exposure concentrations is the use of flux chambers (SABCS 2011; CCME 2016; CA DTSC 2011a). CA DTSC (2011a) provides summaries of static and dynamic flux chamber methods in their Appendix A. Box models based on mass balance, taking into account the wind speed and flux from the ground surface can be used to estimate outdoor air concentrations (e.g. Health Canada 2010; Spence and Walden 2010). Another approach is the use of an air dispersion model for estimating outdoor air concentrations from flux data. Further research and guidance on use of tools such as flux chambers and models are recommended (Section 5).

Table 6: Summary of Outdoor Air Monitoring Recommendations

Data Objective	Outdoor Air Exposure Assessment	Background Source to Indoor Air
Location	Potential receptor location nearest to the contamination source At height representative of most sensitive receptor Away from outdoor emission sources	Near the HVAC intake where applicable Upwind of contamination Upwind of building at distance twice the height of building, where applicable At 1.8 m (6 ft) height 3.0 m (10 ft) beyond a tree's drip line, where applicable Away from outdoor emission sources
Number of locations	At least 2	At least 2
Timing	See vapour frequency section	Concurrent with indoor air sampling
Duration	Based on receptor exposure assessment	Same as the concurrent indoor air sample
Frequency	Determine following approach in vapour frequency section*; typically, 2 – 4 events	2 – 4 events; concurrent with indoor air sampling

*A single sampling event may be sufficient if measured concentration is two orders of magnitude below applicable risk-based or numerical standards, or where a single event indicates that risk management or mitigation measures are required (see Section 4.3).

5.0 OVERVIEW OF OTHER POTENTIAL VAPOUR INTRUSION ISSUES FOR FUTURE CONSIDERATION

The science and technology surrounding vapour assessment is evolving as practitioners encounter challenging site conditions related to preferential pathways, spatial and temporal variability, along with new potential vapour contaminants and exposure pathways identified by regulators and others practicing in this field. There is also a greater awareness of available resources and sustainability considerations in management of sites requiring vapour assessment and mitigation.

With respect to regulations and guidance, more research and development on the role of emerging contaminants is needed and a protocol should be developed for investigation of vapour transport and potential exposure through preferential pathways, particularly sewers, which previously have not been well understood but are now known to be potentially significant. Vapour assessment related to soil relocation is also a new potential exposure route that requires further development and guidance as for example identified by the BC ENV in the updated soil relocation requirements in the BC CSR and the BC ENV Final Policy Document (BC ENV 2019). There may be benefits from refinement of vapour PCOCs for sites impacted by dry-cleaning activities that would warrant further research and consideration.

The review conducted in this guidance has identified the need for further development of approaches and suggested operating procedures (SOPs) on methods that can be practically implemented for vapour assessment in site investigation, remediation and mitigation measures, including:

- **Sustainable Vapour Mitigation**: A protocol for practical and sustainable measures for vapour mitigation systems and performance monitoring. For example, guidelines for where a passive method such as a wind turbine can be used instead, or small fans and sensors powered by alternative energy sources, with remote monitoring and alarms for mitigation systems.
- **Preferential Pathways:** Methods for vapour sampling and monitoring of potential preferential flow and migration pathways through sewer lines and guidance for vapour sampling (e.g., sampling from manholes) and estimation of attenuation factors.
- **Pressure Monitoring and BPC Method**: Practical guidance on continuous pressure monitoring and novel methods for addressing temporal variability and assessing near worst-case conditions such as the BPC method (Lutes et al. 2019).
- **Continuous Monitoring of Indicator Parameters**: Continuous monitoring of indicator parameters for vapour intrusion, which can often be readily measured where applicable. Key indicators may include pressure (barometric, building differential), temperature (indoor air, outdoor air, soil), soil moisture and light gases consisting of CO_2, O_2 and CH_4. Guidance is needed on how and where to conduct such measurements and practical considerations for power supply and use of telemetry for remote data access as a potentially more sustainable approach.
- **Passive Samplers:** Methods and review of available technology for passive samplers that may be used for locating contamination hot-spots and to obtain longer term time-averaged vapour data. Data interpretation and estimates of concentrations from passive samplers requires careful consideration. Passive sampling may also have potential applications in providing a more practical approach on spatial coverage of vapour impacts.

- **High Purge Volume and Building Foundation Assessment:** Methods for evaluating spatial variability such as the high purge volume sampling method (McAlary et al. 2010) and/or estimating air permeability and leakage of building foundation slabs (McAlary et al. 2018).
- **Mass Flux and Discharge**: Methods for contaminant mass discharge and/or flux to aid in the interpretation of vapour intrusion (Dawson et al. 2017).
- **Building Basements in Contact with Groundwater:** Methods for vapour assessment for high density residential buildings or commercial buildings with an underground basement (typically parkade) that is in contact with groundwater. When it is infeasible to obtain soil vapour data, an assessment that relies on estimation of partitioning from soil and/or groundwater is required.
- **Sampling and Analysis Methods**: More detailed guidance on sampling and analysis methods including considerations related to probe design, potential false positives from ambient sources, equilibration, leak testing, purging and sampling (including flow rates to limit bias from non-equilibrium conditions) and methods for collection and analysis of canisters, active sorbent tubes and passive diffusive samplers.
- **Background Sources of VOCs in Indoor Air**: Identification of common sources of background contamination, and approaches and methods for distinguishing background from subsurface vapour sources.

In summary, there are many areas where further research and development can provide for more efficient and sustainable vapour assessment and increase the level of confidence in decision making for site management. One recommendation is to consider the creation of a future wiki page for an updated listing and description of tools or products related to vapour assessment (examples include: portable instruments for vapour monitoring; pressure monitoring; building pressure control tests; flow rate measurements; types and installations of vapour barriers; temporary and permanent vapour sampling ports, etc.). The overall goal would be to help practitioners access latest available technology and allow for up-to-date information from vendors and service providers.

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APPENDIX A

Review of Guidance

This appendix provides excerpts or short summaries of key aspects of guidance reviewed. Readers should consult original source documents for guidance.

Table A-1
Health Canada Federal Contaminated Risk Assessment in Canada: Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites, Health Canada (2010).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors — Table A-1: Health Canada (2010)
CSM	Type of contamination	Broad range including petroleum and chlorinated hydrocarbons
	Vapour source	NAPL; groundwater; soil Transient soil vapour concentrations identified as a consideration
	Building factors	Obtain information on buildings, including • location, • building size and height, • foundation type (e.g. crawlspace, basement), • foundation characteristics (e.g. construction, utility penetrations, sumps). Note if there are basements with earthen or wooden floors.
	Subsurface factors	• Contaminant source depth • Contaminant source distribution • Hydrogeology • Geology • Vadose zone soil properties (moisture, porosity, organic carbon content, soil-air permeability) • Water table fluctuations identified as mechanism for increased short-term transfer of chemicals from groundwater to soil vapour • Soil gas advection in media with very high permeability identified as a factor that could result in enhanced transport
	Proximity to source	The following conditions trigger a VI investigation: Are there current or potential future inhabited buildings within a 30 m distance of subsurface contamination? (excluding conditions include low permeability surface cover, significant preferential pathways or gas migration under pressure)
	Preferential pathways	Potentially significant preferential pathways are fractured bedrock, karst, vertical fissuring, or other media with unusually high gas permeability or where utility conduits directly connect the contamination source to the enclosed space of the building. Sewers are not specifically referenced.

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-1: Health Canada (2010)**
	Other factors considered in the guidance	Spatial and temporal variability discussed in broad terms for different media
Vapour sampling locations	Indoor air	Not addressed
	Outdoor air	Not addressed
	Soil vapour	Bottom-up approach recommended starting with groundwater and near source soil vapour, followed by shallow soil vapour, sub-slab vapour and indoor air as warranted. Recommendations for soil vapour samples: • Minimum depth equal to 1 m below foundation base or half the distance between the foundation and vapour contamination source (whichever is greater), • Maximum lateral distance of 10 m from building (if present), • Samples on both sides of building,
	Sub-slab	Not addressed
	Shallow soil vapour	Collection of shallow soil vapour < 1 m distance below foundation slab is prohibited
	Spatial variability	Vertical profiles and lateral transects to evaluate concentration attenuation
	Other factors considered in the guidance	Not addressed
Vapour sampling frequency	Seasonal	Minimum of two sampling events .
	Rainfall or soil moisture conditions	Not addressed
	Groundwater fluctuations	Not addressed
	Barometric pressure changes	Not addressed
	Building operations	Not addressed
	Temporal variability	Not addressed
	Other factors considered in the guidance	Transient source and vapour migration; sorption and biodegradation can delay the development of steady-state vapour concentration profiles

Topic if applicable	**Sub-topic if applicable**	**Listing of applicable factors Table A-1: Health Canada (2010)**
Sampling and Analysis Methods	Laboratory	Not addressed
	Field GC	Not addressed
Multiple lines of evidence	Multiple media	Estimation of soil vapour concentrations from soil and groundwater data
	Pressure monitoring	Not addressed
	Indicators, surrogates, and tracers	Not addressed
	Building pressure control test	Not addressed
	Other factors considered in the guidance	Non-chemistry factors (geology, hydrogeology)
Ambient air assessment	Indoor air sampling	Not addressed
	Outdoor air sampling	Not addressed
	Building operation	Not addressed
	Other factors considered in the guidance	Not addressed
	Background Sources	Limited information, out-of-date, guidance includes background indoor air check where predicted indoor air concentrations are compared to literature background concentrations
Mitigation methods		Not addressed
Attenuation factors (AFs)	Media	Groundwater, soil vapour
	Land use	Residential, commercial
	Derivation basis and AFs	Empirical AF of 0.02 for distance between building and source < 1 m Model-predicted AF (Johnson and Ettinger) for distance between building and source > = 1 m 10X biodegradation reduction factor

Topic if applicable	Sub-topic if applicable	Listing of applicable factors	Table A-1: Health Canada (2010)
		Mass depletion adjustment factor Earthen foundation adjustment factor	

Table A-2
California Department of Toxic Substances Control (CA DTSC) Vapor Mitigation Advisory, October, CA DTSC (2011b).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-2: CA DTSC (2011b)
CSM		Not addressed
Vapour sampling locations	Indoor air	Vapour sampling for performance monitoring of vapour mitigation system
	Outdoor air	Not addressed
	Soil vapour	Not addressed
	Sub-slab	Not addressed
	Shallow soil vapour	Not addressed
	Spatial variability	Location with respect to building walls and foundation
	Other factors considered in the guidance	Monitoring of flow rates and vapour concentrations from vent risers of vapour mitigation system
Vapour sampling frequency	Seasonal	Performance monitoring of a vapour mitigation system (minimum of two events per year) “worst case” months considered January/February and June/July for most locations in California
	Rainfall or soil moisture conditions	Not addressed
	Groundwater fluctuations	Consideration of the potential impact of high water level on the vapour mitigation system
	Barometric pressure changes	Potential effect on the vapour mitigation system and vapour sampling for performance monitoring
	Temporal variability	Not addressed
	Other factors considered in the guidance	Performance monitoring of the vapour mitigation system e.g., for sub-slab venting system, vapour sampling seasonally (twice a year) for the first 3 years or consistent verification that the mitigation system is meeting performance goals
Sampling and analysis methods	Laboratory	Not addressed
	Field GC	Not addressed
Multiple lines of evidence	Multiple media	Not addressed
	Pressure monitoring	Monitoring spatial extent of vacuum below the building for a sub-slab depressurization system
	Indicators, surrogates, and tracers	Not addressed
	Building pressure control test	Not addressed
	Other factors considered	Monitoring flow rate where applicable for the vapour mitigation system

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-2: CA DTSC (2011b)
	in the guidance	Smoke testing of a liner installation
Ambient air assessment	Indoor air sampling	Performance monitoring of the vapour mitigation system
	Outdoor air sampling	Assessment of background sources
	Building operations	Impact of HVAC operation on the indoor air sampling for performance monitoring
	Other factors considered in the guidance	Consideration of air emissions for the vapour mitigation system
	Background sources	New buildings and off-gassing of building materials Off-site and potentially regional sources
Mitigation methods		Main focus on sub-slab depressurization systems (SSDs) and Sub-slab venting system (SSV) Design and construction for new or existing buildings Operation and Maintenance Performance monitoring Other vapour mitigation systems noted: • Submembrane depressurization • Sub-slab pressurization • Building pressurization • Indoor air treatment
Attenuation factors		Not addressed

Table A-3

Science Advisory Board for Contaminated Sites (SABCS) in BC Guidance on Site Characterization for Evaluation of Soil Vapour Intrusion into Buildings, May, SABCS (2011).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors	Table A-3: SABCS (2011)
CSM	Type of contamination	Volatile and semi-volatile chemical contaminants evaluated for chronic exposure; including petroleum hydrocarbons from fuel products, coal-tar or creosote, and chlorinated solvents; Common sources and volatility of vapour PCOCs and including breakdown products	
	Vapour source	NAPL (primary source) Dissolved phase plume (secondary source) Soil contamination in the unsaturated zone Distribution of NAPL relative to the water table has large influence on potential for vapour intrusion Current and future distribution of the source Buildings (pressurized building with vapour contamination source; a dry cleaner is possible example) can result in subsurface vapour plume Tanks (e.g. leaking underground storage tanks) can result in subsurface vapour plume	
	Building factors	Foundation type HVAC system Effect of “oxygen shadow” on aerobic biodegradation; Stack and wind effects	
	Subsurface factors	Soil type Soil air permeability; Soil heterogeneity Fresh-water lens Groundwater fluctuation; Formation of interface plume Falling water table leading to increase in mass transfer rate and thus the need for seasonal evaluation High organic carbon content of soil and effect on O_2 availability	

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-3: SABCS (2011)
		Vadose zone fate and transport processes including vapourization and volatilization (thorough discussion on diffusion, advection, partitioning, sorption, biodegradation)
	Proximity to source	Reference to Health Canada guidance for vapour intrusion screening for buildings within 30 m lateral distance of the contamination
	Preferential pathways	Utility conduits with granular backfill Contaminated groundwater in contact with sumps or drain tiles Elevator shafts
	Other factors considered in the guidance	Near-building processes are described: soil gas advection, diffusion Receptors (current and future land use) Transient soil vapour migration due to sorption and/or biodegradation, or partitioning into soil moisture Time for soil gas profile to reach steady-state may have implications for design of soil gas sampling program The effect of barometric pumping on soil gas sampling and on O_2 availability below slabs is discussed
Vapour sampling locations	Indoor air	Two types of samples defined: • “exposure point” samples obtained to reflect exposure conditions (i.e., breathing height, near middle or room) typically collected at 1 to 1.5 m above floor • “pathway samples” obtained to evaluate potential entry points for soil gas into a building (i.e., from cracks or utilities) Number of samples depends on study objectives, investigation phase, building type and operation For example, for a small to moderate size house, one sampling location may be sufficient; for a larger house, commercial building or school, multiple samples are required to capture the spatial variability For a residence with multiple floors, at least one sample per floor is recommended with priority given to the lowest level of the building (e.g. basement) Sample collected from an attached garage can be used in identifying potential background sources
	Outdoor air	Number and locations is site-specific and dependent on study objectives Several samples obtained from multiple locations may be needed Important to identify emission sources such as gasoline stations, major highways, paving operations and remediation systems

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-3: SABCS (2011)**
		May be needed to assess outdoor exposure to contaminant vapours; or for identifying background sources for indoor air assessment
	Soil vapour	Bottom-up approach is recommended starting with deep near source sampling where contamination in NAPL or dissolved phase above the water table Deep/near source vapour samples most stable (least affected by building and weather conditions) and most representative for evaluating potential vapour intrusion for a future building Vertical profiles and lateral transects to evaluate biodegradation Soil vapour samples at various points along the migration pathway to evaluate models Lateral sampling locations: • Collected from at least two sides of the building • One sample from location of highest expected concentrations based on soil and groundwater data • Within few metres of the building (where practical) but at least 1 m away from building foundation. Vertical sampling locations: • As close to the source and above the water table as practical • Above the capillary transition zone (references provided to estimate the transition height based on soil type) • Minimum depth of half the distance between the building foundation and the contamination source • Maximum depth of 10 m based on practical considerations • Minimum of 1 m below the elevation of the foundation slab base and 1 m below ground surface (when no buildings are present)
	Sub-slab	Generally sampled when deeper soil vapour data indicate potential risk or where there is shallow source of contamination Interpretation of data may be confounded by downward migration of vapours from indoor air (vapour extrusion) of VOCs in a pressurized building (e.g. VOCs at a dry cleaner site). Monitoring pressure differential across the slab Significant spatial and temporal variability require multiple sampling locations and sampling events Recommended sampling locations: • Immediately below foundation slab. • Generally, central location away from the foundation footings preferred • Minimum of 2-3 for screening purposes for small to moderate size houses • For larger buildings, may need to install sufficient probes to delineate areas with elevated sub-slab vapour concentrations.

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-3: SABCS (2011)
	Shallow soil vapour	Can be affected by changes in barometric pressure, temperature, heterogeneity in subsurface soils, surface covers (e.g. paved surfaces) and building conditions such as depressurization and utilities Sampling location close to the building, but outside peri-foundational area. Samples from depths that are less than 1 m can be obtained provided the probe is carefully sealed and the integrity of the seal is confirmed by leak tracer testing. A modelling assessment of sample depth, flow rate, purge volume, surface cover and leakage is provided in Appendix B.
	Spatial variability	Vertical profiles and lateral transects to characterize spatial variability Lateral transects specially used when source zone laterally removed from building location: Minimum of 3 locations: • Edge of contamination source nearest to building • Mid-point between source and building • Near the edge of building Vertical profiles where source zone is below the building Minimum of 3 locations: • Just above the contamination source • Mid-point between upper and lower sampling point • Sampling point located near the building and/or a sub-slab sample. Contamination source must be at least 1.5 m below the building foundation (and preferably greater than 3 m) for vertical profiles to be effective in resolving vertical concentration trends. Additional probes are recommended where there are changes in lithology. High purge volume sampling method is discussed to address spatial variability particularly for sub-slab sampling to obtain volume-integrated concentrations
	Other factors considered in the guidance	Shallow contamination below or near a building such as dry cleaners may require a different approach with more emphasis on sub-slab and indoor air and preferential pathways instead of a bottom-up approach
Vapour sampling	Seasonal	Increased vapour intrusion during heating season due to stack effect

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-3: SABCS (2011)
frequency		Increase in temperature can result in increased volatilization due to effect of temperature on Henry's constant The amplitude in seasonal temperature variation decreases with increasing depth below ground surface, and at many sites, temperature effects will be insignificant. Seasonal changes due to HVAC operation of a building or natural ventilation through open doors and windows can impact ventilation rates and/or building depressurization At least two events based on water level fluctuations and moisture (wet and dry seasons) One event may be justified if estimated vapour concentrations more than an order of magnitude below criteria and unlikely for vapour concentrations to increase over time.
	Rainfall or soil moisture conditions	Higher moisture in near surface soils beside the building and drier soils beneath the building can enhance soil vapour transport below the building Intensive snowmelt or rain and wetting fronts impact mass transfer and equilibrium condition between contaminant in water and gas phases Higher moisture in surface soils can impact O_2 availability for biodegradation; it is hypothesized that frost may have a similar effect Sampling should be avoided during and after heavy rainfall events or after several days of continuous rain It is recommended to wait at least 1 day after a heavy rainfall event (defined here as 1 cm) for coarse-grained soils (sand or gravel), and several days for fine-grained soils.
	Groundwater fluctuations	Can result in variability in deep (i.e. near source) soil vapour concentrations, where there is a LNAPL smear zone
	Barometric pressure changes	May affect shallower samples obtained at sites with deep water tables (i.e., greater than approximately 10 m); or where there is a surface barrier (building slab, clay) that delays propagation of pressure changes and equalization when there are rapid changes in barometric pressure. May be helpful to obtain weather data from a nearby weather station
	Temporal variability	Diurnal temperature fluctuations, occupant use (e.g., opening windows and doors), wind, and barometric pressure variations Can be very site-specific; provides summaries of studies with long-term vapour monitoring (Exhibit 4.1) Modelling can be used to provide insight on temporal variability
	Other factors considered in the	It is suggested that in Canada, soil vapour intrusion would tend to be greatest during winter months based on climatic conditions.

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-3: SABCS (2011)
	guidance	Consideration should be given to repeat sampling for frost and non-frost cover conditions.
Sampling and analysis methods	Laboratory	Guidance on active soil gas probe installation including multi-level probes Guidance provided on soil gas equilibration, flow and vacuum testing, sampling containers, decontamination, methods to detect leaks and short- circuiting, and purging and sampling, and quality control procedures Generally lower detection limits, larger sample volumes and longer sampling durations required for indoor air testing than soil vapour Passive diffusive sampling can be an acceptable method for indoor air testing (details provided in appendix K) Guidance on soil and groundwater sampling intended for estimating soil vapour concentrations Use of passive soil vapour samplers, which do not provide a quantitative measure of soil vapour concentrations but provide mass of vapours adsorbed to the sampling media. Method can provide for time-integrated sample which can be used in mapping location of plumes and/or identifying pathways Passive diffusive samplers for indoor air better suited for longer sampling periods
	Field GC	Mobile laboratory can be advantageous for larger sampling programs in providing near real-time data and assessing sampling, spatial and temporal variability May need to analyze sub-set of samples using fixed laboratory methods Some contractors can provide field mass spectrometers for analysing the field GC data for greater accuracy Can be used in combination with driven probes for multiple soil gas samples from a single probe installed to varying depths enabling near real-time evaluation of vertical vapour profiles. Field portable GC/MS (HAPSITE) with detection limit of approximately 1 $\mu g/m^3$ for TCE has been demonstrated
Multiple lines of evidence	Multiple media	Soil, groundwater, external soil vapour, sub-slab, indoor and outdoor air Table 3.1 provides evaluation method and issues related to data from each media Comparison of indoor and outdoor air concentrations Comparisons of concurrent indoor, outdoor, groundwater, and soil vapour constituent ratios for identifying background sources and use of tri-linear plots
	Pressure monitoring	Barometric pressure monitoring and other meteorological data that can be obtained from nearby weather station or portable

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-3: SABCS (2011)
		stations at the site to guide sampling time and interpretation of data Pressure differential data between indoor/outdoor air or between indoor air /sub-slab vapour for assessing vapour intrusion potential Measurement of differential pressure to quantity pressure gradients due to: • Building operation • Barometric pressure • Wind forces Pressure differential data may be used to evaluate the potential for a complete vapour intrusion pathway
	Indicators, surrogates, and tracers	Larger-scale tracer and pneumatic testing to estimate soil-air permeability and evaluate soil gas migration pathways. Inert tracers such as CO_2 or SF_6 to estimate building ventilation (ASTM E741-00) Radon tracer test for estimating building-specific attenuation factor or
	Building pressure control test	May use HVAC to create conditions of positive and negative building pressure to confirm whether volatiles measured in indoor air are from subsurface or background sources. One way to control building conditions is to either extract or blow in air using a blower or fan (blower door test).
	Other factors considered in the guidance	Geological, chemical, and biological factors Bioattenuation assessment: • Continuous or near continuous soil cores • Headspace vapour testing (using a photoionization detector) • Soil property data (e.g., moisture content and grain size) • High moisture content layers act as diffusive barriers, which may give the appearance of bioattenuation. Measurements of soil gas flow rates, pressures and vapour concentrations may be used for evaluating contamination source zones and for remediation design. Tree coring as a screening tool, where tree core concentrations of chlorinated solvents related to soil and groundwater concentrations Assessment of “marker chemicals”: chemicals generally not found in background air sources and which are associated with subsurface contamination (e.g. 1,1-dichloroethylene) Spatial trends at various locations within one building or multiple buildings and comparison to the conceptual site model for

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-3: SABCS (2011)
		expected vapour sources CSIA to identify vapour sources; carbon isotope and radon examples provided Comparison of site-specific attenuation factors derived from measurements to empirical or modelled (e.g. J&E model)
Ambient air assessment	Indoor air sampling	Significant variability due to building and weather related factors Concurrent testing of outdoor air; sub-slab; and soil vapour Portable PID (ppb range) may be useful to identify background sources or vapour intrusion entry points through cracks
	Outdoor air sampling	May be for assessment of outdoor air exposure or conducted concurrently with indoor air sampling to determine influence on indoor air quality Flux chamber tests may be useful for assessing emissions to outdoor air
	Building operations	Review of HVAC design and operation Other factors affecting building pressures include temperature differences between indoor and outdoor air, the number of storeys, degree of air leakage between floors, HVAC system operation, and presence of chimneys, flues, exhaust fans and vents Potential for building depressurization during heating season due to stack effect Presence of elevator: • sump and drain pipe in elevator pit can be a subsurface vapour pathway • elevator shaft can be a conduit for vapour migration between floors, cause pressure differentials, or have significant stack effect
	Background sources	Household products; Off-gassing from building products (i.e., carpeting, shower curtains, building insulation, pressed wood products, fabrics); Home heating (i.e., heating oil storage, combustion emissions), wood stove or candles, tobacco smoke, attached garages (i.e., vehicle emissions, stored products); Volatilization of trihalomethanes from tap water (particularly when heated) as well as through activities occurring in the home or workplace (Table 4.1) Generally higher contaminant sources in indoor air than outdoor air Outdoor sources may be vehicle or industrial air emissions Even after soil vapour intrusion is mitigated, chemical of concern may be detected in indoor air as a result of desorption from building materials Concurrent sampling of indoor air and sub-slab as a line of evidence for identifying background sources
	Other factors	Foundation construction: type; cracks or openings;

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-3: SABCS (2011)**
	considered in the guidance	Utility penetrations acting as preferential pathways Air mixing between building floors depends on HVAC system and air leakage between floors Pre-sampling building survey and questionnaire (Appendix J)
Mitigation methods		Not addressed
Attenuation factors	Media	Not addressed
	Land use	Not addressed
	Derivation basis	Not addressed

Table A-4
CA DTSC Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air, October, CA DTSC (2011a).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors	Table A-4: CA DTSC (2011a)
CSM	Type of contamination	Volatile chemicals Methane not specifically addressed (other references provided) List of volatile and toxic chemicals provided (Table 1)	
	Vapour source	NAPL; groundwater; soil (surface and subsurface) Adjacent properties and off-site migration Primary source and release mechanism Secondary sources Contaminated building materials	
	Building factors	Foundation type and condition; building use (if commercial indicating office use or not) HVAC	
	Subsurface factors	Contaminant transport mechanism (e.g. advection and diffusion through the vadose zone)	
	Proximity to source	Screening of VI pathway based on 100-foot lateral distance from subsurface contamination	
	Preferential pathways	piping and utility corridors, voids, sumps and floor drains, foundation construction joints, seams or cracks; elevator shafts geological discontinuities (e.g., fault zones, sand channels)	
	Other factors considered in the guidance	Potential receptors Importance of and recommendations for public participation activities	
Vapour sampling	Indoor air	All occupied areas including basement; different floors where there is potential for vapour intrusion; based on site-specific conditions	

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-4: CA DTSC (2011a)**
locations		Samples collected in centre of the room and away from doors; Approximately 3 to 5 feet off the ground for adults and at lower sampling heights if the receptors of concern are children as in a daycare or school; Locations of primary living areas and likely locations for vapour sources (kitchen and bathroom) In office space, sample locations should be from primary work area and near sources such as sumps, elevator shaft or floor drains
	Outdoor air	Collected 6 ft above the ground Away from gasoline stations, automobiles, gasoline- powered engines, fuel and oil storage tanks, chemical storage areas, and dry cleaners At least 10 feet beyond a tree's drip line On the upwind side of a building at a distance equal to twice the height of the building Upwind of the subsurface contamination, where data used to interpret indoor air concentrations Note distance to discharges from environmental treatment systems, which should ideally be shut-down during indoor and outdoor air sampling Minimum of 3 samples concurrent with each indoor air sampling event
	Soil vapour	Lateral and vertical delineation Lateral delineation extended by a 100-foot buffer zone beyond the extent of the soil gas plume Collected near contaminant source Sufficient density for delineation and extrapolation to areas of interest Guidance on confirmation sampling of soil gas post-remediation: • For excavation and off-site disposal: Collected from around the perimeter of the excavation, and within and/or below the excavation footprint, to evaluate the effectiveness of the remedy on eliminating the possibility of vapour intrusion. Samples

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-4: CA DTSC (2011a)**
		should be collected at least five feet from exposed soil surfaces to minimize the effects of atmospheric influences on sample representativeness. • Where excavations are above contaminated groundwater or adjacent to residual volatile chemical contamination, soil gas monitoring in the backfilled material may be necessary to determine if the remedial objectives have been achieved. Duration of the post-excavation monitoring within the backfilled material should be based upon the time needed to re-establish subsurface equilibrium. • SVE system: Soil gas samples should be collected from vapour monitoring wells during the operation and rebound testing of SVE systems. For rebound testing, data from soil vapour monitoring wells are preferred over data from extraction wells because of their shorter screen intervals. • Significant concentration rebound during the first few sampling events after system shutdown indicates a need to optimize and restart a SVE system. If no significant rebound occurs, the next step typically is an assessment of whether the system is ready for site closure. • The closure assessment for a SVE system should be based on concentration and trend data obtained from the system's inlet stream, extraction wells, and depth-specific vapour monitoring wells located in the original contaminant plume. • Final confirmation sampling should be conducted only after the subsurface has reached Equilibrium.
	Sub-slab	Sampling recommended where soil gas data indicate potential for unacceptable risk (bottom-up approach) At least two probes at each residential structure (one in the centre of the building's foundation; in inconspicuous areas, such as utility closets or beneath stairs; not near the edges of the foundation due to the effects of wind) For larger buildings, additional sampling locations recommended.
	Shallow soil vapour	Where groundwater shallow and soil contamination in close proximity to water table, groundwater grab samples should be obtained Where no-flow conditions encountered, both soil and groundwater data are required
	Spatial variability	Soil gas collection close to the source zone; and around perimeter of the building and as close as possible to the foundation
	Other factors considered in the	Deep soil gas samples may be collected from groundwater monitoring wells Provides guidance and decision tree for evaluating potential vapour intrusion from utility corridors

Topic if applicable	Sub-topic if applicable	Listing of applicable factors — Table A-4: CA DTSC (2011a)
	guidance	Precluding conditions to 100-foot separation distance: • continuous low permeability surface (such as pavement or surface clay layers) covers the ground between the contamination and the building • vadose zone has very high gas permeability due to fracturing • soil gas is under pressure (typically at landfills where methane is present)
Vapour sampling frequency	Seasonal	Quarterly in the 1st year and based on site-specific conditions thereafter For indoor air, a minimum of sampling over two seasons: late summer/early autumn and late winter/early spring.
	Rainfall or soil moisture conditions	Not addressed
	Groundwater fluctuations	Not addressed
	Barometric pressure changes	Potentially significant where deep groundwater and soil with high air permeability
	Temporal variability	Permanent vadose monitoring points installed to monitor long-term concentrations representative of subsurface conditions; stability and steady-state conditions; seasonal and other temporal variability Soil matrix data indicates large mass of volatile contaminants in the subsurface Groundwater influenced by tides This guidance specifically notes the influence of tides and presence of large contaminant mass in the soil as factors that may result in greater temporal variability in soil gas data and the need for long-term monitoring
	Other factors considered in the guidance	Steady state condition of subsurface contamination In context of confirmation sampling (soil gas), timeframes for equilibration Steady state or equilibration can be determined from long-term monitoring of soil gas concentrations, or can be determined using the approach in Johnson and others (1999) with an example shown in Figure 4

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-4: CA DTSC (2011a)**
		This guidance provides reference and example for determining equilibration or steady state timeframes
Sampling and analysis methods	Laboratory	Important to ensure reporting limits below the risk-based concentrations. Detailed guidance on canister sampling, QA/QC and laboratory analytical methods provided Subsurface: Where low flow conditions exist, such as low permeability clay-rich zones or saturated vadose zone conditions, permanent probes to be installed and sampled using low flow protocols Where active soil gas sampling not possible, passive soil gas samples should be collected, along with soil matrix samples using USEPA Method 5035 Indoor air: Active sampling for the first event of indoor air sampling should be for sampling duration of 24-hour; when vapour intrusion is confirmed subsequent sampling durations should correspond to the anticipated daily exposure for the building occupants; in some cases, 24-hour and 8-hour samples can be collected during the same sampling event. Passive samplers may be used in some cases for longer sampling periods (appendix K)
	Field GC	As part of Indoor air: To identify and seal/remove indoor air sources, portable instruments with ppb detection limits can be used such as portable GC/MS; photo-ionization detector (ppb range); or the US EPA trace atmospheric gas analyzer (TAGA) To identify soil gas sources, monitor: • Foundation-wall joints • Foundation cracks and concrete control joints • Building utility entry ways • Elevator shafts • Floor drains • Fixtures and seams around bathtubs and showers
Multiple lines of evidence	Multiple media	Soil gas (open field; sub-slab) Passive soil gas Groundwater Soil matrix Indoor air (including crawlspace)

Table A-4: CA DTSC (2011a)

Topic if applicable	Sub-topic if applicable	Listing of applicable factors
		Outdoor air
	Pressure monitoring	Differential pressure measurements between different locations within the building; or between indoor and outdoor air
	Indicators, surrogates, and tracers	CSIA using ^{36}Cl or ^{13}C to distinguish between different chlorinated solvent sources Radon data
	Building pressure control test	Not addressed
	Other factors considered in the guidance	Site-specific fate and transport modeling Comparison of constituent ratios in soil gas and indoor air Soil sampling during soil gas sampling to determine physical characteristics of subsurface such as total porosity, soil moisture, and dry bulk density
Ambient air assessment	Indoor air sampling	Conducted at later phase of vapour intrusion investigation (bottom-up approach) Select analytical method and work with the laboratory to obtain sufficiently low reporting limits
	Outdoor air sampling	Conducted at later phase of vapour intrusion investigation in conjunction with indoor air assessment where applicable (bottom-up approach) Outdoor air data for interpretation of indoor air concentrations (but not for adjusting the indoor air data for risk assessment
	Building operations	To create conservative conditions during indoor air sampling: windows generally closed except in summer and when air conditioning is off; Ingress and egress activities minimized; HVAC operation normal for season and time of day; during colder months when heating system is used; it should be on for at least one day prior to scheduled sampling to maintain indoor air temperature >65 °C before and during sampling.
	Background sources	Types of industries and potential background sources (including remediation systems) considered in interpretation of data

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-4: CA DTSC (2011a)**
		Obtain information on air permits issued in the area; and if available, air monitoring data from nearby stations Building survey form (Appendix L)
	Other factors considered in the guidance	Acute hazard evaluation for existing buildings: odours; physiological effects; wet basements; fire and explosive conditions.
Mitigation methods		References the CA DTSC vapour mitigation advisory (2011) Engineered remedies to prevent or reduce vapour intrusion Prohibition against construction Informing utility workers or other contractors conducting construction activities Site-specific worker health and safety plan Five-year reviews to verify results of decisions on remediation, mitigation where residual contamination remaining on-site and restrictions on land use are in place
Attenuation factors	Media	soil, soil vapour, sub-slab, groundwater
	Land use	Default factors for: • Existing or future buildings • Residential slab-on-grade • Residential with crawl space • Commercial Default value of 0.05 for sub-slab; 1.0 for crawlspace
	Derivation basis	Empirical derivation based on database study for sub-slab and crawl space vapour samples (Appendix B) Based on J&E model results for existing or future residential or commercial buildings (Appendix B) Site-specific attenuation factors may be determined based on physical properties of subsurface conditions (recommended

Table A-4: CA DTSC (2011a)

Topic if applicable	Sub-topic if applicable	Listing of applicable factors
		methods provided in appendix H) Method to measure effective diffusion coefficient (Appendix I) In-situ measurement of soil air permeability (Appendix J) J&E model recommended but other equivalent fate and transport models may be accepted Maximum concentrations are to be used in model; however, statistical approximation may be used if >8 data spatially and temporally for a single building are available. Air exchange rate can be determined using tracer test (e.g., conservative tracer or naturally occurring radon) Q_{soil} default of 5L/min and proportionally increased for building areas $>100m^2$

Table A-5

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

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-5: ITRC (2014)
CSM	Type of contamination	Petroleum hydrocarbons
	Vapour source	There are two sources: a LNAPL and dissolved plume
	Building factors	Some factors that may hinder the recharge of O_2 in the vadose zone are soils with high moisture content; soils with high organic content; soils with low permeability; large building foundations
	Subsurface factors	The following fate and transport mechanisms: • partitioning of PHC vapours from contaminated soil, groundwater, or LNAPL into soil gas • diffusion of PHC vapours • biodegradation in an aerobic biodegradation zone • advection into a building • mixing of vapours with building indoor air Detailed review of petroleum hydrocarbon biodegradation
	Proximity to source	A key component of the guidance is a screening approach based on vertical and lateral distances between hydrocarbon source and building; the screening method has been developed for two types of petroleum sites: 1. An underground storage tank (UST) or aboveground storage tank (AST) site, 2. A typically larger petroleum industrial site, such as a terminal, refinery or pipeline site, Identification of buildings to include in VI investigation are within 30 ft lateral distance of subsurface contamination. Recommended vertical screening distances of non-impacted soil between the source and building are: • 5 feet: dissolved-phase sources (for both petroleum UST/AST and industrial sites) • 15 feet: LNAPL sources (petroleum UST/AST sites) • 18 feet: LNAPL sources (petroleum industrial sites) Precluding conditions include: • gasoline containing lead scavengers

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-5: ITRC (2014)
		• gasoline containing greater than 10% vol/vol ethanol • High organic matter content (generally > 4% w/w) • o Excessively dry soils (less than 2% by volume or 1.2% by weight moisture)
	Preferential pathways	Preferential pathways that intercept both the source (either LNAPL or dissolved phase) and building foundations, either artificial or engineered such as utility conduits with improper seals and connections to a building, or natural, such as karst geology or fractured rock.
	Other factors considered in the guidance	Not addressed
Vapour sampling locations	Indoor air	Typical single-family residential dwelling (approximately 1,500 square feet) should have one indoor air sample collected from the first floor and one from the basement or crawl space (if present) Significantly larger buildings may require additional samples, especially if there are separate air spaces or separate air handling units Multiple indoor air sample locations are necessary for multifamily residential units and commercial or retail buildings Collect samples in breathing zone, approximately 3 to 5 feet off the ground, in high-use areas
	Outdoor air	Intake should be ~ 3 to 5 feet off the ground (at the approximate midpoint of the ground story level of the building) and about 5 to15 feet away from the building Begin outdoor air sampling 1-2 hours prior to indoor sampling because most buildings have an air exchange rate in range of 0.25 – 1.0 hr^{-1} and therefore air entering the building in the period before indoor sampling remains in the building for some time
	Soil vapour	Exterior samples are located at some distance (usually 10 linear feet or more) away from building of interest, or, in footprint of future building Factors for sampling depth include (1) fluctuations in water table depth; (2) thickness of capillary fringe; and (3) regulatory preference (some states specify minimum sampling depths). In general, regulatory agencies prefer sub-slab or near-slab soil gas samples over exterior samples.
	Sub-slab	More representative data when surface releases May contain contaminants from interior sources
	Shallow soil	Samples < 5 ft depth may not be representative or conservative for screening purposes

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-5: ITRC (2014)
	vapour	
	Spatial variability	There can be large spatial variability in sub-slab soil gas samples by factors of 100 or more
	Other factors considered in the guidance	Not addressed
Vapour sampling frequency	Seasonal	Temporal variability in indoor air quality shows concentrations with a range of a factor of 2 to 5 for 24-hour samples (Kuehster, Folkes, and Wannamaker 2004; McAlary et al. 2002). Long-term integrated average samples (up to several days) are technically feasible. Indoor air sampling during unusual weather conditions should generally be avoided. An 8-hour indoor air sampling period is often selected for commercial buildings. A 24-hour sampling interval is usually selected for residential structures. Stainless steel canisters are generally used for sampling intervals from 5 minutes to 24 hours. Alternative sampling devices (such as passive samplers) can be deployed for longer periods to reduce the effects of short term variability. However, PHC results for samples collected over longer periods are susceptible to false positives, potential interferences from occupant activities, and background sources, because hydrocarbons are ubiquitous in consumer products and ambient air.
	Rainfall or soil moisture conditions	Infiltration can displace soil gas beside building and lead to a short-term spike in VI. Infiltration tends to have greater effect on shallow soils Increased soil moisture after a rainfall can reduce vapour transport and dissolve VOCs into water Measurements made during or immediately after a significant rain event (greater than an inch) may not be representative of long-term average conditions but effect will depend on climatic conditions
	Groundwater fluctuations	Should be considered when applying the vertical screening distances
	Barometric pressure changes	For most normal climatic conditions, the effect of barometric pressure on soil gas concentrations will be minimal; excluding sites with very deep vadose zone
	Temporal variability	Published information on temporal variability in indoor air quality shows concentrations with a range of a factor of 2 to 5 for 24-hour samples (Kuehster, Folkes, and Wannamaker 2004; McAlary et al. 2002).
	Other factors	An 8-hour indoor air sampling period is often selected for commercial buildings. A 24-hour sampling interval is usually selected for

Topic if applicable	Sub-topic if applicable	Listing of applicable factors — Table A-5: ITRC (2014)
	considered in the guidance	residential structures. Alternative sampling devices (such as passive samplers) can be deployed for longer periods to reduce the effects of short-term variability. High wind speed can create pressure differentials around a structure, causing advective soil gas flow below and into the building, potentially causing VI Sampling should not occur during unusually windy conditions or during extreme storm events.
Sampling and Analysis Methods	Laboratory	Comprehensive compendium of methods for volatiles using canisters (USEPA TO-3, USEPA TO-15), volatiles and semi-volatiles using active tubes (USEPA TO-15 and USEPA TO-17) and fixed gases using canisters or Tedlar bags (ASTM D1945) plus other methods
	Field GC	Value of continuous real-time field instruments such as field GC include multiple, less expensive data that can be used to locate problem structures, vapour migration routes into structures, and VOC sources inside the structures.
Multiple lines of evidence	Multiple media	Concurrent sampling of indoor air, ambient air, and sub-slab soil gas may provide data that allow a more detailed understanding of site conditions. Collecting multiple lines of evidence is particularly helpful at PHC sites because of the complex transport and exposure pathway, and because PHCs are ubiquitous in indoor air from background sources. Typically, bottom-up approach advocated but specific situations may warrant collecting indoor air samples before collecting subsurface data because of an immediate need (e.g., shallow spill event, when field screening indicates concern, if significant odors and the source is unknown, contaminated groundwater has entered building, if LNAPL is directly below building).
	Pressure monitoring	Relatively inexpensive data that can provide useful data on pressure gradients Can be significant temporal variability so may need to repeat test Use manometers with accuracy to 1 Pa
	Indicators, surrogates, and tracers	Measurement of a conservative tracer inside the structure and in sub-slab soil gas can allow a site-specific attenuation factor to be calculated assuming PCOCs have similar transport properties. Naturally occurring radon is the most commonly used tracer. Other potential tracers include breakdown products such as 1,1- dichloroethane or cis-1,2-dichloroethene, which are generally not found in consumer products, building materials, or outdoor air.
	Building pressure	Building pressure control can be used with on-site GC/MS analysis to distinguish between indoor

Topic if applicable	Sub-topic if applicable	Listing of applicable factors — Table A-5: ITRC (2014)
	control test	sources of VOCs and VI (Gorder and Dettenmaier 2011; Beckley et al. 2014) and to address temporal variability (McHugh et al. 2012).
	Other factors considered in the guidance	Not addressed
Ambient air assessment	Indoor air sampling	Document conditions at the time of sampling, including heating, ventilation, and air conditioning (HVAC) system operation.
	Outdoor air sampling	Locate upwind of building and away from VOC sources
	Building Operations	Indoor air samples may be collected with the HVAC system on or off, depending on the sampling objectives. To evaluate whether vapour intrusion is possible, sample with HVAC turned off and after the building has equilibrated for a few hours. This method represents a worst-case building scenario for VI. If assessing human risk exposure, indoor air samples should be collected under normal conditions.
	Background Sources	PHCs are ubiquitous in consumer products and ambient air. Environmental forensics is one approach to assess background; strategies include using: 1. Compound ratios (such as benzene/TPHv) in soil gas and indoor air results 2. Chemical fingerprinting (including chromatogram traces) to distinguish between different types of PHCs (such as diesel, gasoline, and jet fuels) 3. Isotope ratios (such as carbon, hydrogen, and oxygen) in the source determination of methane and other light hydrocarbon gases Database of chemicals in household products (references provided)
	Other factors considered in the guidance	Not addressed
Mitigation methods		Three approaches to manage PVI:

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-5: ITRC (2014)
		• environmental remediation • institutional controls • mitigation Issues potentially unique to mitigation of PVI are: • Where there is PVI there is often direct connection between building and contamination consequently method may be different than for deeper contamination • Mitigation systems (piping, barriers, etc.) should consider compatibility with PHCs • Mitigation methods may consider enhancing migration of to below slab through injection or aerated floors • Sealing of floors may have uncertain results because oxygen migration through slab to subsurface may be reduced • Because of common background sources of PHCs, it may be more difficult to demonstrate mitigation effectiveness using indoor air monitoring than in general
Attenuation factors (AFs)	Media	Not addressed
	Land use	Not addressed
	Derivation basis and AFs	Not addressed

Table A-6

United States Environmental Protection Agency (US EPA) Office of Solid Waste and Emergency Response (OSWER) Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air, US EPA (2015a) including Errata dated 29 January 2018.

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-6: US EPA (2015a)
CSM	Type of contamination	Primarily chlorinated hydrocarbons
	Vapour source	Primary sources are NAPL and soil; secondary sources are groundwater and sewer lines. Sources of vapour contamination include: • spills and leaks, • leaking tanks, • discharges to sewer lines, septic tanks, and floor drains, • landfills and other land disposal management units, • fire-training areas, • discharge areas, and • vapour leaks from pressurized tanks and pipelines.
	Building factors	VI occurs through openings or entry points in foundation Different foundation types with respect to openings are described Utilities including sewers, drains and sumps are potentially important pathways Building pressures have significant control on soil gas advection and VI, and result from: • Indoor-outdoor temperature differences (stack effect) • Mechanical devices (exhaust fans, air conditioners, dryers) that vent to outdoors • Fireplaces that vent combustion gases to the outdoors • Wind load on the building walls
	Subsurface factors	Vapour migration can be impeded by • high soil moisture • low-permeability (generally fine-grained) soil • biodegradation, particularly through aerobic biodegradation of petroleum hydrocarbons and some chlorinated hydrocarbons Soil below buildings will tend to be drier than beside building, which may promote vapour migration Water table fluctuations may affect volatilization for groundwater source with increasing flux when water table falls

Topic if applicable	**Sub-topic if applicable**	**Listing of applicable factors** **Table A-6: US EPA (2015a)**
		Building pressures, barometric (atmospheric) pressures and gas generation affect soil gas advection
	Proximity to source	Identification of buildings to include in VI investigation are within 30 m (vertical or lateral) distance of subsurface contamination (excluding cases when there are significant surface covers or preferential pathways)
	Preferential pathways	Naturally occurring feature (e.g., fracture or macropore) or anthropogenic (human-made) subsurface conduit (e.g., sewers, utility vaults, sumps, drains, elevator shafts, permeable fill, underground mine workings) that is expected to exhibit little resistance to vapour or groundwater flow
	Other factors considered in the guidance	Guidance is in two parts, preliminary analysis and detailed investigation. Under preliminary analysis screening is conducted based on qualitative indicators such as chemical toxicity and volatility, odours, physiological effects and wet basements
Vapour sampling locations	Indoor air	Obtain multiple time-integrated samples Obtain sample in breathing zone of most sensitive exposed receptor For typical residential building or commercial building less than 1,500 ft^2, collect one sample in 1st level (basement or 1st floor) and one sample from 2nd level Additional samples recommended for larger buildings or depending on interior partitions, HVAC system, foundation characteristics
	Outdoor air	One or two samples near building, additional samples if multiple buildings or wide site Avoid outdoor VOC sources When building HVAC system draws in outdoor air, consider obtaining sample near HVAC intake
	Soil vapour	Soil gas samples (and particularly shallow samples) generally do not accurately estimate sub-slab or indoor air concentrations. Deeper, near source soil gas sampling is recommended When the contamination source is laterally removed from building, soil gas sampling in worst-case contamination areas is useful
	Sub-slab	Noted that three sub-slab samples have been collected below typical size residential building or commercial building less than 1,500 square feet in area Consider building size, foundation type, foundation or structural elements that would promote VI and receptor characteristics when determining number of sub-slab samples
	Shallow soil vapour	Recommend that soil vapour samples be collected a minimum of 5 ft below ground
	Spatial variability	Significant spatial variability in sub-slab soil gas noted

Topic if applicable	Sub-topic if applicable	Listing of applicable factors	Table A-6: US EPA (2015a)
	Other factors considered in the guidance	Not addressed	
Vapour sampling frequency	Seasonal	Multiple sampling events generally considered necessary (number not defined) Obtain samples in heating season or when building ventilation is off	
	Rainfall or soil moisture conditions	Frequency not provided, but recommend obtaining weather data and recording whether significant recent precipitation	
	Groundwater fluctuations	“Near source” soil gas sampling in different seasons that coincide with groundwater fluctuations.	
	Barometric pressure changes	Frequency not provided, but recommend obtaining weather data and recording barometric pressure data	
	Temporal variability	Several rounds of sampling generally recommended for sub-slab soil gas concentrations Time-integrated samples are obtained over 8 hour to several week period depending on method to address temporal variability	
	Other factors considered in the guidance	Not addressed	
Sampling and Analysis Methods	Laboratory	Canisters (e.g., TO-14 and TO-15) Individual certification of canisters generally desirable where the data are to be used for exposure/risk assessment purposes Active sorbent samplers (e.g., TO-17) Flow rate and duration is determined for active sorbent samples, care must be taken to avoid breakthrough Passive sorbent (diffusive) samplers Passive samplers enable characterization of time-integrated samples which is potentially beneficial because VI can be temporally variable within a day and between days	
	Field GC	Field-portable gas chromatograph and mass spectrometer to identify specific sources of vapour-forming chemicals and estimate their mass emission rate(s). EPA’s Environmental Response Team has employed the Trace Atmospheric Gas Analyzer (TAGA) mobile laboratory for similar purposes. the PID may not be sensitive enough for very low concentration sources. HAPSITE gas chromatograph/mass spectrometer (Gorder and Dettenmaier 2011) or the TAGA Mobile Laboratory (EPA-ERT 2012)	
Multiple lines of evidence	Multiple media	Assess the VI pathway by collecting, weighing, and evaluating MLE Important to support “no-further-action” decisions	

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-6: US EPA (2015a)
		MLE improves confidence in the assessment and risk management decisions and can be used to distinguish between VI and background sources Five step process: 1. There are vapour forming chemicals. 2. There is route along which to migrate toward the building. 3. Building is susceptible to soil gas entry. 4. One or more subsurface vapour-forming chemicals are present inside building. 5. Building is occupied by receptors.
	Pressure monitoring	Measure pressure difference between the indoors and the subsurface, which provides a complementary line of evidence to support data evaluation and interpretation
	Indicators, surrogates, and tracers	Radon may serve as a tracer to help identify those buildings that are more susceptible to soil gas entry but cannot be used quantitatively as proxy for indoor vapour measurements. cis-1,2-dichloroethylene may be used as tracer because rarely detected in indoor environment
	Building pressure control test	Not addressed
	Other factors considered in the guidance	Not addressed
Ambient air assessment	Indoor air sampling	See above, no additional considerations
	Outdoor air sampling	See above, no additional considerations
	Building Operations	Note building occupancy, HVAC system operation, building pressures, wet basements, foundation properties and potential vapour entry points. Obtain HVAC test-and-balance data if available.
	Background Sources	Use MLE approach to assess background contribution Do not use literature background concentrations because historical concentrations are higher than current concentrations for many chemicals Potential indoor sources generally removed from the building at least 24-72 hours prior to the start of sampling, based on an

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-6: US EPA (2015a)
		approximate air exchange rate of 0.25-1.0 per hour.
	Other factors considered in the guidance	Not addressed
Mitigation methods		Factors considered: • Prompt response (over-pressurization, increased ventilation, sealing utilities) • Active sub-slab depressurization • Monitoring • Institutional controls
Attenuation factors (AFs)	Media	Groundwater, soil vapour, sub-slab vapour
	Land use	Residential
	Derivation basis and AFs	Empirical data Groundwater to indoor air = 0.001 (except 0.0005 for fine-grained soil) Soil vapour to indoor air = 0.03 Sub-slab vapour to indoor air = 0.03

Table A-7
CA DTSC Advisory Active Soil Gas Investigations. CA DTSC and Los Angeles and San Francisco Regional WQCBs, July 2015, CA DTSC (2015).[1]

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-7: CA DTSC (2015)
CSM	Type of contamination	VOCs; specific discussion on hydrogen sulphides and methane
	Vapour source	Media: soil and groundwater as well as release mechanism considered
	Building factors	Building construction details
	Subsurface factors	soil type; soil geology and hydrogeology
	Proximity to source	Location and depth of PCOCs
	Preferential pathways	Fractures Sand lenses Sewer and utility corridors Well decommissioning considerations
	Other factors considered in the guidance	An emphasis is placed on defining data quality objectives based on investigation goal; preparation of work plan
Vapour sampling locations	Indoor air	
	Outdoor air	
	Soil vapour	Number, location and depth dependent on CSM and data objectives General recommendations: • Delineate in 3-dimensions • Based on site-specific lithologic information

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[1] CA DTSC has a new Draft Supplemental Guidance: Screening and Evaluating Vapor Intrusion dated February 2020 (https://dtsc.ca.gov/vapor-intrusion/).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-7: CA DTSC (2015)**
		• Sample spacing based on historical site use and potential contaminant- release points • Initial spacing can be based on a 50 ft by 50 ft grid or based on historical or suspected site use • If no historical information available, may use a grid spacing of 100 ft by 100 ft for screening • Once areas of contamination are identified, use more focused or biased approach: close interval grid or radial or step-out sampling pattern such as 10- to 20-foot grid pattern • Initial vertical delineation such as multi-level sampling at 5-, 10-, 15-feet • Boring logs and field instrument readings from soil cuttings or cores should be used to select the correct depths to collect soil gas samples • Probes should be installed at depths with elevated vapour readings • Maximum soil gas sampling depth should be near the capillary fringe. Soil gas wells or probes should not be installed too close to the water table because low flow conditions might be encountered due to the high moisture content • Nested soil gas wells may be installed in the annular space of groundwater monitoring wells to serve as a dual-purpose well if both vapour and groundwater monitoring are required • Minimum sample depth typically < 5 ft unless site-specific conditions dictate otherwise. This is to avoid the effect of barometric pressure changes and breakthrough of ambient air • Soil gas samples collected adjacent to a building should be at depth immediately above the contamination source • Ideally, numerous vertical profiles of soil gas should be developed at the site to accurately locate subsurface sources. Once located, soil gas collection can be targeted at these depths site-wide.
	Sub-slab	if a building is determined to have a moisture barrier and/or a tension slab, special care should be given when hand-drilling through the concrete slab permanent sampling points should be installed so repeated sampling can be conducted Sub-slab holes should be advanced three to four inches into the engineering fill below the slab At least two sub-slab probes should be installed at each residential structure, with one probe installed in the centre of the building's foundation. Probes should be installed in inconspicuous areas, such as utility closets or beneath stairs. Sub-slab probes should not be installed near the edges of the foundation due to the effects of wind
	Shallow soil vapour	Defined as less than 5 ft. (1.8 m) Effects of barometric pressure and temperature Breakthrough of ambient air
	Spatial variability	Location with respect to building walls and foundation

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-7: CA DTSC (2015)
		Depth to source Effect of subsurface heterogeneity High purge volume (HPV) method (sub-slab sampling) to obtain large volume-integrated samples
	Other factors considered in the guidance	Not addressed
Vapour sampling frequency	Seasonal	With respect to sub-slab sampling (minimum of two events)
	Rainfall or soil moisture conditions	Significant rainfall defined as >0.5” in one day Waiting period based on soil type Reference for drainage curves provided for different soil types (Appendix G)
	Groundwater fluctuations	
	Barometric pressure changes	Monitoring and pressure effect on sampling based on sample depth and vadose zone permeability Periods of large barometric pressure changes can result in dilution of soil gas sample by atmospheric air
	Temporal variability	Sub-slab sampling Passive soil gas sampling methods
	Other factors considered in the guidance	
Sampling and analysis methods	Laboratory	Key factors include: • data quality objectives; • target compounds; • detection limits; • sample containers; • sample transport; • analytical methods; QA/QC: holding times; duplicates and blanks; Shut-in tests:

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-7: CA DTSC (2015)
		• prior to purging or sampling • Minimum measured vacuum of 100” water • With sampling canister attached (valve closed) • Use “T-fitting” for vacuum gauge and observe for at least 1 minute • No noticeable change with calibrated gauge and sensitivity at least 0.5” water • Not a replacement for leak test Leak tests: • At every soil gas well each time a soil gas sample is collected • Liquid (e.g., hexane, pentane, diflouroethane and n-propanol) or gaseous compounds (e.g., He or SF_6) • Procedures described in Appendix C Flow rates and vacuum: • Sampling and purging flow rates of 100 – 200 mL/min • Vacuum < 100” water • If purge volume is excessive (e.g., deep probe and large diameter tubing), flow rate may be > 200 mL/min but vacuum must be maintained < 100” water • Procedure for soil gas sampling in low permeability soil (Appendix D) • Passive soil gas sampling recommended for screening purposes in low permeability soils Passive soil gas sampling uses (Appendix A): • To delineate contaminant plumes, contaminant sources, and hot spots; • To identify potential preferential pathways where sewer and utility corridors provide vapour migration pathways into and around buildings. • To identify preferential pathways resulting from lithologic variability; • To collect soil gas in areas where active soil gas samples are difficult to obtain such as low-permeability lithology, high-moisture soils and shallow groundwater conditions. When the depth to groundwater is within five feet of the surface, the capillary fringe may prevent sample collection by active soil gas methods due to the high soil moisture content • To evaluate whether a release has occurred. Active soil gas data should be collected following the detection of subsurface contamination by the passive method.
	Field GC	Not addressed
Multiple lines of evidence	Multiple media	Not addressed
	Pressure	Not addressed

Topic if applicable	Sub-topic if applicable	Listing of applicable factors — Table A-7: CA DTSC (2015)
	monitoring	
	Indicators, surrogates, and tracers	Not addressed
	Building pressure control test	Not addressed
	Other factors considered in the guidance	Passive and active sampling methods for investigation of naphthalene
Ambient air assessment	Indoor air sampling	Not addressed
	Outdoor air sampling	Not addressed
	Building operations	Not addressed
	Field GC monitoring	Not addressed
	Sampling and analysis methods	Not addressed
	Background sources	Not addressed
	Other factors considered in the guidance	Not addressed
Mitigation methods		Not addressed
Attenuation	Media	Not addressed

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-7: CA DTSC (2015)
factors	Land use	Not addressed
	Derivation basis	Not addressed

Table A-8
US EPA Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites, US EPA (2015b).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-8: US EPA (2015b)
CSM	Type of contamination	PHCs found in gasoline, diesel, and jet fuel (e.g., benzene, trimethylbenzenes (TMBs), naphthalene) Volatile chemicals other than PHCs that may be found in petroleum fuels, such as ethers, alcohols, and other fuel additives (e.g., methyl tertiary-butyl ether (MTBE), tertiary-butyl alcohol (TBA), ethylene dibromide (EDB), and 1,2-dichloroethane (1,2DCA)) Methane, which is generated from anaerobic biodegradation of PHCs and other constituents of petroleum fuels (especially ethanol), and organic matter in soil
	Vapour source	LNAPL from leaking underground storage tanks – typically gas stations Phase partitioning: • LNAPL trapped within soil pore spaces (i.e., residual LNAPL) • Dissolved in soil moisture • Adhered onto the surface of, or absorbed into, soil solids • Vapours in soil gas • Accumulations of mobile LNAPL on and in the capillary fringe • Dissolved in groundwater LNAPL sources contain a significantly larger fraction of aliphatic compounds and relatively insoluble hydrocarbons, especially if the source is large or unweathered
	Building factors	Building size Extent of impermeable surface covering surrounding the building (e.g., asphalt, concrete)
	Subsurface factors	• Vapour source hydrocarbon concentration, flux, and composition (including methane) • Oxygen demand (i.e., the oxygen required to biodegrade the available hydrocarbons and any other organic matter present) and oxygen availability • Soil type and properties (including texture and moisture content) • Availability of essential micronutrients • Ambient temperature in the subsurface • The pH of the soil and groundwater

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-8: US EPA (2015b)
	Proximity to source	Distance between vapour source and the building Lateral inclusion zone: Buildings directly above contamination sources, whether as mobile LNAPL, residual LNAPL, or PHCs dissolved in groundwater; Buildings outside the lateral inclusion zone generally may be excluded from further assessment for PVI unless: • Site conditions change (e.g., groundwater flow direction changes, contaminant plume migrates beyond the lateral inclusion zone, development or redevelopment of nearby properties) • Preferential transport pathways are present Vertical separation distance: based on the thickness of clean, biologically active soil between a contaminant mass and the lowest point of an overlying receptor (e.g., building basement floor, foundation, or crawl space surface) Not all buildings within the lateral inclusion zone will be threatened by PVI due to aerobic biodegradation of PHCs provided there is sufficient vertical separation distance between the receptor and the vapour source Vertical separation distances: • 6 ft for dissolved phase source • 15 ft for LNAPL source Precluding conditions apply
	Preferential pathways	Natural: fractures in rock, solution channels in karst terrain, bedding planes, joints, high permeability layers Man-made: utility corridors including sewer lines themselves, trenches, excavations
	Other factors considered in the guidance	In-depth review of fuel composition and biodegradation Vapour migration processes Vapour plume and migration pathways into a building Review of database studies in support of the vertical separation distances
Vapour sampling	Indoor air	
	Outdoor air	

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-8: US EPA (2015b)**
locations	Soil vapour	Recommended where considerations of lateral inclusion zone; vertical separation distance; and associated precluding conditions, and where: • A building with the shortest side no longer than 66 feet, overlies LNAPL and the vertical separation distance is less than 15 feet, but not in direct contact with the building basement floor, foundation, or crawl space surface. • A building, of any dimension, overlies dissolved PHC contamination and the vertical separation distance is less than 6 feet, but not in direct contact with the building basement floor, foundation, or crawl space surface. Otherwise, paired indoor air and sub-slab sampling is recommended. Collect near-slab (exterior) shallow soil gas samples paired with deep (near source) soil gas samples
	Sub-slab	Paired with indoor air sampling (see section on ambient air assessment)
	Shallow soil vapour	At near slab depth and from each side of the potentially impacted building and as close to the building as possible Paired with deep/near source soil vapour sample (see above)
	Spatial variability	Not addressed
	Other factors considered in the guidance	Further assessment may be unnecessary for those buildings outside the lateral inclusion zone unless: • Preferential transport pathways are present that connect PHC vapour sources to receptors • Impermeable surface cover (e.g., concrete, asphalt, ice, very large buildings) is so extensive that there is concern whether there is sufficient oxygen in the subsurface to support biodegradation • Soil conditions are inhospitable to microorganisms (e.g., dry soils with less than 2% soil moisture by dry weight) such that biodegradation is insufficient to mitigate the threat of PVI
Vapour sampling frequency	Seasonal	Transport of petroleum vapours affected by weather effects: • temperature trends and fluctuations • precipitation • barometric pressure changes • wind Cycling of heating and cooling systems inside buildings in response to seasonal and weather effects may also influence vapour intrusion Seasonal effects may also influence the formation and migration of dissolved plumes and LNAPL, which in turn affect the

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-8: US EPA (2015b)
		lateral inclusion zone for vapour assessment
	Rainfall or soil moisture conditions	Frozen or ice-covered soil may reduce oxygen availability in the subsurface for aerobic biodegradation of petroleum hydrocarbons A certain amount of soil moisture is necessary for microorganisms to live; not enough and they are not actively degrading PHC vapours; too much and reoxygenation is impeded, possibly leading to anaerobic conditions at greater depths
	Groundwater fluctuations	Creation of a smear zone of residual LNAPL contamination, which can act as a long-term source of dissolved contamination during periods of high water table elevation and as a source of petroleum vapours during periods of low water table elevation when contaminants re-emerge from a previously submerged condition Groundwater levels in the vicinity of USTs may also be subject to the influence of water within the tank pit: • After rainfall events (and potentially snowmelt) water levels within tank pits are typically above the level of ambient groundwater; consequently, a groundwater recharge mound may form • This mound disrupts the local groundwater flow field and contaminants can migrate away from the tank excavation, potentially in all directions
	Barometric pressure changes	Wind and barometric pressure changes can produce pressure gradients inside buildings resulting in enhanced intrusion of PHC vapours Positive pressure inside buildings can both prevent intrusion of PHC vapours into buildings and facilitate oxygen transport through cracks in the foundation into the subsurface
	Temporal variability	Data on temporal changes in temperature, barometric pressure, wind speed and direction, relative humidity, and precipitation can aid in correctly identifying trends and result in a more accurate CSM
	Other factors considered in the guidance	Assessing potential changes in the vapour source: both mobile LNAPL and dissolved contaminant plumes are dynamic and may move from one monitoring event to the next Periodic monitoring of groundwater flow directions and plume migration are recommended, possibly over more than one annual cycle
Sampling and analysis methods	Laboratory	
	Field GC	
Multiple lines of evidence	Multiple media	Soil, soil gas, groundwater, and LNAPL Soil and groundwater concentrations of benzene and TPH used as thresholds for LNAPL source: • Benzene in soil > 10 mg/kg

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-8: US EPA (2015b)**
		• TPH in soil > 100 mg/kg • Benzene in groundwater > 5 mg/L • TPH in groundwater > 30 mg/L EPA recommends that groundwater samples be analyzed for PHCs and non-PHC fuel additives (e.g., alcohols, ethers, organic lead, lead scavengers) typically found in petroleum-based fuels, when appropriate
	Pressure monitoring	Not addressed
	Indicators, surrogates, and tracers	Not addressed
	Building pressure control test	Not addressed
	Other factors considered in the guidance	Detailed description of “clean biologically active soil” (Section 9) Field instrument screening at utility access point(s) as an initial step to determine if the utility is acting as a conduit for vapours. If the transport of vapours from the source area to the building could occur along utility conduits, then vapour sampling inside the utility conduits, manholes, or sumps should be considered in addition to vadose zone and sub-slab soil gas sampling Sites more affected by seasonal and weather effects: • Poor drainage around the building indicated by flooded soils • Area subject to permafrost/long lasting snow cover (based on altitude or latitude) • Shallow and highly variable water table
Ambient air assessment	Indoor air sampling	Only if vapour assessment is deemed necessary based on consideration of the lateral inclusion zone; vertical separation distance; and associated precluding conditions Generally recommended paired with sub-slab sampling, where soil vapour sampling (deep/ near source and shallow/ near slab) do not clearly demonstrate that biodegradation is sufficient to mitigate the threat of PVI into the building Paired sampling is intended for determining building-specific attenuation factor – and/or to distinguish between PVI and background sources (both indoor and outdoor)
	Outdoor air sampling	Only noted for assessing background sources
	Building operations	Heating systems generally operating in the winter months can create “stack effect” and lead to greater vapour intrusion due

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-8: US EPA (2015b)
		to building depressurization Cooling systems operating generally in the summer months can lead to pressurized basement and reduction in vapour intrusion and greater oxygen transport to the subsurface
	Background sources	Paired sampling of indoor air and sub-slab data Outdoor air sampling
	Other factors considered in the guidance	Not addressed
Mitigation methods		Not addressed
Attenuation factors	Media	Generic values from EPA (2015): • 0.001 for groundwater • 0.03 for sub-slab soil gas, and for deep (near-source) soil gas However, recommendation for UST sites is to use generic attenuation factors based on source strength and separation distance (Figures 9 and 10), where site conditions correspond to those used in the model simulations to derive them: • Building has a basement and that it is surrounded by homogeneous, uniform sandy soil that is directly exposed to the atmosphere and that preferential pathways for vapour migration into the building or through the vadose zone are not present • Vapour source not in direct contact with the foundation • 10 m 10 m square building
	Land use	Residential
	Derivation basis	Empirical and based on case studies of the vapour intrusion of chlorinated solvents such as TCE, which are not biologically degraded in aerobic unsaturated soil or sediment Generic attenuation factors in Figures 9 & 10 based on the modelling work including aerobic biodegradation of Abreu et al. (2009) Options to evaluate site-specific attenuation factors using computer modelling of PVI: • 3-D model of Abreu et al. (2009) accounts for biodegradation

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-8: US EPA (2015b)
		• 3-D model of Verginelli and Baciocchi (2014) accounts for biodegradation • Johnson and Ettinger model (JEM) does not account for biodegradation • BioVapor accounts for oxygen-limited aerobic biodegradation • PVIscreen is similar to BioVapor with added feature to conduct uncertainty analysis using a range of values for input parameters and conducting Monte Carlo simulations

Table A-9
Canadian Council for Ministers of the Environment (CCME) Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment. Volumes 1-4, CCME (2016).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
CSM	Type of contamination	Broad range of chemicals and site-specific Common types: Petroleum hydrocarbons including fuel additives and oxygenates; chlorinated solvents including stabilizers such as 1,4-dioxane; lighter and semi-volatile PAHs; elemental mercury May include hydrocarbon fractions based on carbon chain length and aromatic and aliphatic fractions (F1 and F2 as defined in CCME, 2008) Table 4-1 lists contaminants associated with various activities; volatile and semi-volatile contaminants are considered for vapour CSM
	Vapour source	Primary source: NAPL (vapourization and volatilization above the water table) Secondary source: dissolved phase plume in groundwater or soil contamination within the unsaturated zone Equilibrium partitioning models can be used to estimate vapour concentrations from NAPL, soil or groundwater Point sources and non-point sources consideration of potential breakdown products Buildings (pressurized building with vapour contamination source; a dry cleaner is possible example) can result in subsurface vapour plume Tanks (e.g. leaking underground storage tanks) can result in subsurface vapour plume
	Building factors	Foundation type; HVAC system; Effect of “rain shadow” and potential for drier soils beneath building; Effect of “oxygen shadow” and effect on O_2 availability for biodegradation Stack and wind effects Building foundation type can influence both the vapour intrusion migration rate as well as supply of O_2 to the subsurface for aerobic biodegradation (e.g. for degradation of petroleum hydrocarbons).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
		Building pressure can have large influence on vapour intrusion, which is in turn affected by indoor and outdoor temperature, number of storeys, degree of air leakage between floors, and presence of chimney, flues, exhaust fans and vents "Stack effect" in particular can create negative pressure, which is more likely during the heating season Commercial buildings typically have HVAC systems that affect the ventilation and pressure inside the building.
	Subsurface factors	Soil type Soil air permeability Soil heterogeneity Fresh-water lens Groundwater fluctuation Formation of interface plume Falling water table leading to increase in mass transfer rate and thus the need for seasonal evaluation Natural soil respiration in soil with high organic carbon content and effect on O_2 availability Key processes and thorough discussion on vadose zone processes: diffusion, advection, dispersion, sorption, partitioning between soil, water and gas phases, and biodegradation reactions
	Proximity to source	Lateral diffusion and reference to Health Canada guidance for vapour intrusion screening for buildings within 30m lateral distance of the contamination
	Preferential pathways	Utility conduits with granular backfill Contaminated groundwater in contact with sumps or drain tiles Elevator shafts
	Other factors considered in the guidance	A key consideration is spatial and temporal variability Transient soil vapour migration due to sorption and/or biodegradation or partitioning into soil moisture. Time for soil gas profile to reach steady-state may have implications for design of soil gas sampling program

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-9: CCME (2016)**
		The effect of barometric pumping on soil gas sampling and on O_2 availability below slabs is discussed Expedited site investigation (fewer phases as warranted based on practical considerations) Visualization of fate and transport mechanisms
Vapour sampling locations	Indoor air	Two type of samples: • “Exposure point” samples obtained to reflect exposure conditions (i.e., breathing height, near middle or room) • “Pathway samples” obtained to evaluate potential entry points for soil gas into a building (i.e., from cracks or utilities) Number of samples depends on study objectives, investigation phase, building type and operation For example, for small to moderate sized house with reasonably good ventilation, one sample per floor may be sufficient.; For a larger house, commercial building, or school, multiple samples are required to characterize indoor air quality It is noted that no standardized guidance for number of samples has been developed for VOC vapour intrusion. In the radon literature, one indoor air sample per 2,000 square feet is found in several guidance documents (e.g., USEPA, 1993).
	Outdoor air	Number and locations is site-specific Several samples obtained from multiple locations may be needed
	Soil vapour	Bottom-up approach is recommended starting with deep near source sampling where contamination in NAPL or dissolved phase above the water table Sample depth 0.5 to 1m above the water table based on capillary transition zone and water level fluctuations; water retention modelling may be used to determine transition height. Deep/near source vapour samples most stable (least affected by building and weather conditions); less affected by biodegradation and reach steady state conditions relatively quickly; more representative for a future building use Lateral sampling location: • site-specific depending on size and number of buildings • For large disperse groundwater plumes, a soil vapour probe spacing of several tens of meters may be adequate. • For smaller plumes and areas where steep concentration gradients are expected in groundwater, more closely spaced probes are warranted (e.g., 5 m to 15 m, or spacing similar to the size of a house). • Collected from at least two sides of the building; one sample from location of highest expected concentrations based on soil and groundwater data; within 10 m of the building (where practical) and generally 2-3 m away from building foundation.

Topic if applicable	Sub-topic if applicable	Listing of applicable factors / Table A-9: CCME (2016)
		Lateral transect useful where contamination source laterally removed from building Where there is no building, a minimum of two probes per APEC (additional probes may be needed for delineation purposes). Vertical profile sampling locations: • As close to the source and above the water table as practical, but above the capillary transition zone • Half the distance between the building foundation and the contamination source • Shallow soil vapour useful when contamination source near to the building and > 1.5 m below building foundation Vertical profiles and lateral transects can be used to evaluate biodegradation and/or to improve confidence in CSM on soil vapour transport and data quality Lateral transect locations, generally a minimum of 3: • Edge of contamination source nearest to the building • Mid-point between the source and building • Near the edge of the building (API, 2005). When the distance between the contamination source and building is greater than 30 m, additional probes should be considered. Additional sampling locations recommended where greater soil heterogeneity and uncertainty in vapour migration pathway
	Sub-slab	Immediately below foundation slab Minimum of 2-3 samples for small to moderate size houses and more for larger buildings Central location away from the foundation footings is preferred Can be affected by VOC in indoor air if building is pressurized (vapour extrusion)
	Shallow soil vapour	External to building, close, but outside peri- foundational area (2-3 m) Sampling depth: • 1 m below base of foundation or at least a 1m below ground surface • Maximum of 10 m based on practical considerations. With precautions such as plastic ground sheet and careful sealing of the probe verified by a leak test, valid samples from as little as 0.5 m depth can be obtained

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
		More likely to be affected by geologic heterogeneity, changes in near- surface conditions such as barometric pressure or temperature fluctuations, surface cover type (e.g., paved versus non-paved surface), and bioattenuation or biotransformation processes At sites where there is an oxygen shadow (and potentially drier soils) below the building, shallow external soil vapour samples may be non-representative of conditions below the building
	Spatial variability	Variability generally increases with increasing distance from the contamination source Related to zones more impacted by temperature and barometric pressure fluctuations Soil heterogeneity and moisture conditions Availability of oxygen for aerobically biodegradable chemicals Deep and near source locations relatively unaffected by near-surface changes; least affected by biodegradation; should represent the highest concentrations of soil vapour Greater spatial and temporal variability in shallow external soil vapour data than deep vapour data and greater potential for non steady-state conditions Sub-slab similar or greater spatial variability than shallow external soil vapour data; additional factors related to building foundation (cracks and openings) and building operation that can affect sub-slab vapour concentrations Lateral transects in deep/near source soil vapour sampling useful specially when source is laterally removed from the building High Purge Volume (HPV) sampling (McAlary et al., 2010) to obtain large volume (extent)-integrated samples for sub-slab sampling below large buildings
	Other factors considered in the guidance	Consider chloroform source from leaking water mains; or potentially from water used with grout to seal the probes during construction Shallow contamination below or near a building such as dry cleaners may require a different approach with more emphasis on sub-slab and indoor air and preferential pathways instead of a bottom-up approach, or when initial site screening using soil and/or groundwater data indicates the potential for significant risk associated with vapour intrusion
Vapour sampling frequency	Seasonal	Increased vapour intrusion during heating season due to stack effect Increase in temperature can result in increased volatilization due to effect of temperature on Henry's constant The amplitude in seasonal temperature variation decreases with increasing depth below ground surface, and at many sites,

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
		temperature effects will be insignificant. Seasonal changes due to HVAC operation of a building or natural ventilation through open doors and windows can impact ventilation rates and/or building depressurization Minimum of 2 sampling events to coincide with conditions most affecting temporal variability (see Temporal Variability section below) Single event may be justified if vapour data are less than concentrations of concern by more than 1-2 orders of magnitude
	Rainfall or soil moisture conditions	Sampling to be avoided after heavy rainfall events Based on drainage data, it is recommended to wait at least one day after a significant rainfall event (0.5 cm) for coarse-grained soils (sand or gravel) and several days for fine-grained soils Higher moisture in near surface soils beside the building and drier soils beneath the building can enhance soil vapour transport below the building Intensive snowmelt or rain and wetting fronts impact mass transfer and equilibrium condition between contaminant in water and gas phases Higher moisture in surface soils can impact O_2 availability for biodegradation Frost and snowmelt can potentially affect hydrocarbon flux to the surface and reduce O_2 flux to the subsurface; however one cold climate study (Hers et al., 2014) is referenced that showed little effect Repeat sampling with and without frost or snow cover is recommended
	Groundwater fluctuations	When water levels drop, contamination is exposed to soil gas, whereas transport of submerged contamination is reduced due to low diffusion rates in water
	Barometric pressure changes	Can potentially influence shallow soil vapour concentrations when there are thick coarse-grained unsaturated zones A conservative approach is to sample when barometric pressure is decreasing May not be practical to sample vapour at desired barometric pressure conditions, thus recommended to collect barometric pressure data from a few days before and after the sampling event to aid in the data interpretation
	Temporal variability	Changes in source contamination concentrations, seasonal variations in the water table, and conditions for hydrocarbon vapour bioattenuation

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
		Building operation or weather related variability for samples collected near to the building Long-term transient effects may be important if there is depletion of the contamination source through volatilization, leaching and/or biodegradation Sampling frequency should coincide with seasonal patterns for factors affecting soil vapour such as the water table elevation (i.e., high and low levels) and precipitation (soil moisture) (i.e., wet and dry season) Indoor air sampling more affected by weather conditions such as wind force, temperature differences and barometric pressure (most significant under severe winter conditions) In general, a minimum of two indoor air sampling events that capture possible seasonal variability (e.g., winter/summer) are required; however, additional sampling events may be warranted at some sites. During winter, many buildings in Canada are depressurized, which would generally be the most influential factor for vapour intrusion, although other factors such as soil moisture, temperature and water table elevation may also be important, which may be more favourable to higher vapour intrusion during summer. Repeat sampling may also be warranted, for example, if the subsurface source concentrations are changing over time (e.g., mobile groundwater plume). Radon analogy provided for sampling duration that accounts for temporal variability
	Other factors considered in the guidance	Not addressed
Sampling and analysis methods	Laboratory	Active sampling (active sorbent tubes or canisters) is discussed in depth on sampling methods including: probe installations, purging, equilibration, sampling containers, and leak testing Guidance on laboratory analytical methods, sample volumes and duration, and QA/QC procedures Passive soil vapour method: • Uncertainty associated with estimating concentrations from the mass data and potential for “starvation effect” • Can be deployed for few days to weeks providing time integrated results • Useful in mapping the location of subsurface plumes and for identifying pathways (in particular when placed in or along utility corridors) for determining locations for permanent probe placement. • Generally more accepted for indoor air sampling and for longer sampling duration (e.g., one week) • Review of passive diffusive samplers including passive diffusive badges
	Field GC	Portable GC used in the field to analyse grab samples usually collected in gas-tight syringes

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
		Greater certainty in compound identification if used with portable MS; Can provide for near real-time data used to modify programs while in progress, and potentially lower costs; Ability to collect repeat samples for assessing sampling, temporal, and spatial variability Generally higher detection limits, thus regulatory requirements need to be considered Field portable GC/MS (e.g., HAPSITE) may provide rapid quantification of VOCs to detection limits of approximately 1 µg/m^3
Multiple lines of evidence	Multiple media	Soil, groundwater, soil gas (including sub-slab) and indoor air Guidance on sampling and subsurface factors for estimating soil vapour concentrations from groundwater or soil data using partitioning models Comparisons of concurrent indoor, outdoor, groundwater, and soil vapour constituent ratios for identifying background sources and use of tri-linear plots
	Pressure monitoring	Barometric pressure monitoring and other meteorological data that can be obtained from nearby weather station or portable stations at the site to guide sampling time and interpretation of data Differential pressures measurements between the building, outdoor air and sub-slab soil vapour using sensitive instruments; particular attention to effect of HVAC in commercial buildings and building pressurization Assessing correlations with other weather data such as wind and temperature
	Indicators, surrogates, and tracers	Building ventilation tracer tests using inert gases such as CO_2 or SF_6 Naturally occurring radon data from sub-slab and indoor air can be used to estimate attenuation factor Tracers can also be used to evaluate preferential pathways such as sewers Helium tracer testing can be used to estimate soil air permeability and soil gas migration pathways Assessment of “marker chemicals”: chemicals generally not found in background air sources and which are associated with subsurface contamination (e.g. 1,1-dichloroethylene) CSIA to identify vapour sources; carbon isotope and radon examples provided

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
		For assessment of biodegradation, vertical sampling profile should include O_2, CO_2, and CH_4. N_2 is also useful as a quality control check and indicator of soil gas advection. Depleted O_2 and elevated CO_2 levels are indicators of aerobic biodegradation of hydrocarbons. Elevated CH_4 concentrations are an indicator of anaerobic biodegradation Analysis of hydrocarbon compounds that are less soluble and potentially less biodegradable than the BTEX compounds (e.g., cyclohexane, 2,2,4-trimethylpentane) may serve as useful tracers for hydrocarbon vapour transport
	Building pressure control test	May use HVAC to create conditions of positive and negative building pressure to confirm whether volatiles measured in indoor air are from subsurface or background sources. One way to control building conditions is to either extract or blow in air using a blower or fan (blower door test).
	Other factors considered in the guidance	For commercial buildings, possible to estimate the ventilation rate from HVAC system design. The air exchange rate should be calculated from the make-up volume, and not the total air handling volume. Discussion on risk-based screening of sites based on an exclusion (or inclusion) distance approach derived from empirical database studies for petroleum hydrocarbon sites: • The (vertical) separation distance from the contamination source beyond which the potential for petroleum vapour intrusion can be considered negligible • Bioreduction factors applied to vapour attenuation factors Key factors affecting aerobic biodegradation of petroleum hydrocarbon vapours are discussed: • Source type (i.e., LNAPL or dissolved source) • Source size • source vapour concentration • distance to the building from the vapour source • Building size • Surface cover beside building • processes that enhance O_2 recharge to subsurface (e.g., wind or barometric pumping). • Soil lithology • fraction of organic carbon soil physical properties In-situ tests to estimate tortuosity and soil air permeability Hydrogeological properties Flux chamber tests (static or dynamic) for estimating emissions to outdoor air – or above a crack on a concrete floor Tree coring as a screening tool, where tree core concentrations of chlorinated solvents related to soil and groundwater

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
		concentrations
Ambient air assessment	Indoor air sampling	Concurrent sampling with sub-slab and outdoor air concentrations as additional lines of evidence for assessing VOC sources Provides framework depicted in Figure 8-1 Communication with the occupants Building survey prior to sampling Preliminary screening with portable air monitoring instruments such as PID/FID may be used for identifying indoor VOC sources or targeting sampling locations at some sites; they may not be used to rule out the presence of background contaminants in indoor air; must consider sensitivity of instruments and detection levels
	Outdoor air sampling	May be needed to assess outdoor exposure to contaminant vapours; or for identifying background sources for indoor air assessment
	Building operations	Review of studies with reported air change rates Mixing of vapours between floors depends on HVAC system and air leakage between floors; Elevator shafts often include a sump and are not ventilated; they may represent points where migration and accumulation of soil vapours could occur Elevator shafts can also represent conduits for inter-floor migration of vapours
	Background sources	Household products Off-gassing from building products (i.e., carpeting, shower curtains, building insulation, pressed wood products, fabrics) Home heating (i.e., heating oil storage, combustion emissions) Tobacco smoke Attached garages (i.e., vehicle emissions, stored products) Volatilization from water (particularly when heated) as well as through activities occurring in the home or workplace Outdoor sources: vehicle or industrial air emissions that may enter the building through air leakage or ventilation Air sample collected from an attached garage may provide valuable data on potential background sources

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-9: CCME (2016)
		Adsorption of volatile contaminants onto building materials; and potential for subsequent desorption (e.g. for a period of time after mitigation of soil vapour intrusion) Discussion of methods for data collection and interpretation to discern background contributions from indoor sources using multiple lines of evidence
	Other factors considered in the guidance	Chemical transformations due to processes such as photo-oxidation are generally relatively slow processes (i.e., half-lives of days) and biodegradation is unlikely to be an operable process in an indoor environment.
Mitigation methods		Not addressed
Attenuation factors	Media	Soil vapour; review of reported empirical attenuation factors in context of assessing background sources
	Land use	Not addressed
	Derivation basis	Not addressed

TABLE A-10

New Jersey Department of Environmental Protection (NJ DEP) Vapor Intrusion Technical Guidance. Site Remediation and Waste Management Program, NJ DEP (2018).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-10: NJ DEP (2018)
CSM	Type of contamination	Broad range including petroleum and chlorinated hydrocarbons
	Vapour source	NAPL; groundwater; soil; vapour cloud (contamination in soil vapour with no collated contamination in the soil or groundwater; likely caused by subsurface vapour leaks or from downward vapour migration through slabs)
	Building factors	Determine building use (residential, day care, school, commercial, industrial), foundation type (slab-on-grade, crawlspace, basement), the depth of the lowest floor, and the size of the building footprint. Identify building pressure/ventilation in large buildings. Identify vapour entry points, which include poorly sealed utility lines that penetrate the foundation, cracks in the walls and floors, sumps, elevator pits, around the wall/floor juncture of floating floor construction or other breaches in the walls or slab. Determine if there is a wet basement or sump. Test water in basement or sump and investigate VI if there any detections of VOCs
	Subsurface factors	Factors considered include: • clean water lens • depth to saturated zone and stratigraphy • fluctuations in depth to saturated zone • complex hydrogeologic settings • proximity to preferential pathways • potential for contaminant degradation Clean water lens may be barrier to prevent volatilization into overlying buildings (criteria greater than 3 feet and greater than annual water table fluctuation) Valuable to understand soil stratigraphy, porosity and moisture content, permeability and/ or particle size distribution. Saturated soils outside of building can influence advection of vapours into a building. Significant VOC mass storage in the vapour phase within the vadose zone should be evaluated when conducting VI investigation (Yao et al. 2010, Carr 2016), noting that groundwater may not be impacted.
	Proximity to source	The following conditions trigger a VI investigation: • Ground water contamination in excess of the NJDEP Ground Water Screening Levels (GWSL) and within 30 feet of a building for PHC or 100 feet for non-PHC compounds • Free and residual product within 30 feet of a building for PHC or 100 feet for non-PHC compounds

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-10: NJ DEP (2018)
		Vertical screening distances are provided for screening of sites with petroleum hydrocarbon contamination
	Preferential pathways	Natural (e.g., shallow rock or vertically fractured soil) and anthropogenic (e.g., buried utilities) identified as important potential pathways for VI. Sewers are not specifically referenced.
	Other factors considered in the guidance	Not addressed
Vapour sampling locations	Indoor air	Obtain samples from 1st and 2nd building levels. Table 3-3 of this guidance provides recommended minimum number of indoor air samples based on square footage of building footprint.
	Outdoor air	Collect minimum of one outdoor sample
	Soil vapour	External soil vapour sampling not recommended for decision making except when not possible to obtain sub-slab samples (high water table) or when there is lateral vapour migration through basement walls.
	Sub-slab	Used to assess whether complete VI pathway exists May not be possible to obtain sub-slab samples when depth to water table is < 2 ft below slab Table 3-2 of this guidance provides recommended minimum number of sub-slab soil gas samples based on square footage of building footprint.
	Shallow soil vapour	Minimum depth is 5 feet below ground surface. If shallow groundwater precludes samples from > 5 ft depth alternative is to collect soil gas samples from below existing large impervious surfaces.
	Spatial variability	Due in part to spatial variability sub-slab data should not be averaged
	Other factors considered in the guidance	
Vapour sampling frequency	Seasonal	Assuming there are no other contradictory lines of evidence, a single round of indoor/ambient air samples may be sufficient Conduct indoor air sampling event between November 1 and March 31 (heating season) as generally “worst case” conditions for VI to occur.
	Rainfall or soil moisture conditions	Frequency not specified, but note rainfall in last 12 hours

Topic if applicable	Sub-topic if applicable	Listing of applicable factors — Table A-10: NJ DEP (2018)
	Groundwater fluctuations	Not addressed
	Barometric pressure changes	Frequency not specified, but obtain data
	Building operations	If vapour mitigation through sub-slab depressurization is occurring, turn system off and cap vents, and wait minimum 48 hours before sampling
	Temporal variability	Not addressed
	Other factors considered in the guidance	Not addressed
Sampling and Analysis Methods	Laboratory	Canisters analysed by USEPA Method TO-15 or Thermal Desorption tubes analyzed by USEPA Method TO-17 are acceptable methods. USEPA SW-846 Method 8260B is the most common method utilized for field screening of soil vapour samples.
	Field GC	Use of portable GC instrument referenced but no details
Multiple lines of evidence	Multiple media	Soil vapour, indoor and outdoor air
	Pressure monitoring	Pressure and ventilation data useful; no detailed provided
	Indicators, surrogates, and tracers	Not addressed
	Building pressure control test	Not addressed
	Other factors considered in the guidance	Not addressed
Ambient air assessment	Indoor air sampling	Either conduct staged program, sub-slab sampling followed by indoor air, if required, or conduct sub-slab and indoor air concurrently Wait minimum of 24 hours after sub-slab probe installation/sampling to avoid cross-contamination
	Outdoor air sampling	In general mitigation not required when outdoor air > indoor air concentrations

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-10: NJ DEP (2018)
	Building operations	Note building HVAC and ventilation
	Background Sources	Conduct building walkthrough; remove background sources at least 24 hours sampling Follow MLE approach Obtain sub-slab vapour and outdoor air samples to assist in interpretation Evaluate ratios of chemical concentrations for single point or single-chemical concentrations for multiple -points as part of forensic type analysis
	Other factors considered in the guidance	Not addressed
Mitigation methods		Mitigation method considered include: • Active and passive sub-slab depressurization • Sub-slab ventilation • Gas barriers • Sealing entry points • Alarms • Monitoring (detailed requirements dependent on system and comparison to screening levels)
Attenuation factors	Media	Soil vapour, groundwater
	Land use	Residential, non-residential
	Derivation basis	Empirical AF of 0.02 for soil vapour Johnson and Ettinger modelled AF for groundwater, with 10X reduction factor for petroleum hydrocarbons

TABLE A-11
Washington (State) Department of Ecology (WA Ecology) Guidance for Evaluating Soil Vapour Intrusion in Washington State: Investigation and Remedial Action (2009, revised in 2016 and 2018) and related materials (link), WA Ecology (2018).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-11: WA Ecology (2018)
CSM	Type of contamination	Volatile organic chemicals (VOCs) List of chemicals provided in WA Ecology's Cleanup Levels and Risk Calculation (CLARC) VI data tables. However, based on volatility and toxicity, additional site-specific chemicals may need to be assessed for vapour intrusion. Additional provisions for petroleum vapour intrusion
	Vapour source	NAPL; groundwater; soil
	Building factors	The CSM and tiered approach consider existing and future buildings and lateral distance to source.
	Subsurface factors	Not addressed
	Proximity to source	Screening of VI pathway based on 100-foot lateral distance from subsurface contamination except for petroleum hydrocarbons, where 30 ft lateral distance. Site conditions on applicability of the lateral screening distances are provided.
	Preferential pathways	• fractured bedrock, • utility trenches backfilled with highly permeable material, or • utility lines such as sewers that contain site-related VOCs • elevators and associated sumps, where present • utility penetrations into building structure
	Other factors considered in the guidance	Considerations for immediate action based on short-term health or safety: explosive or acutely toxic; spill inside structure; odour complaint; reported health problems; and including the following: • Free product directly below or close to the building • Flammable or explosive: cleanup levels must be < 10% LEL (a hazardous substance or mixture of hazardous substances) • Flammable, combustible, corrosive, or chemically reactive Provides indoor air Action Levels that are protective of short-term exposures to TCE including short-term TCE soil gas and groundwater screening levels, which are calculated to be protective of the indoor air action levels (Implementation Memorandum No. 22, 2018 and row on mitigation below).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-11: WA Ecology (2018)
Vapour sampling locations	Indoor air	Indoor air assessment is considered a Tier II stage of investigation for an existing building. At a minimum, the lowest occupied level of the building should be sampled and it is recommended that the maximum VOC concentrations measured from “occupiable” indoor areas be used when comparing to acceptable indoor air levels. Occupiable is defined as regularly occupied living spaces such as bedrooms, dining rooms, living rooms, family rooms, kitchens, etc. Determining the appropriate number is a site-specific determination and should be based on factors such as: • The extent of the subsurface contamination • Preferential pathways and likely points where vapours could enter the structure • Building construction and configuration • How the interior spaces and HVAC systems are configured • Areas where indoor air screening levels are more likely to be exceeded • Building occupants (e.g. residential use, workers, sensitive receptors, etc.) and where the occupants spend most of their indoor time.
	Outdoor air	At location upwind of the assessment building and concurrent with indoor air sampling to assess the background ambient contribution to indoor air concentrations. This would be part of Tier II assessment, where concentrations may be subtracted from the measured indoor air concentrations. Sampling location is recommended to be near the building being investigated, but not so close as to be influenced by VOC emissions emanating from that building; and at a height well above the ground surface (approximately 2-3 meters). It is also recommended to keep sampling location well away from trees, airflow obstructions, and point sources of VOC emissions. Outdoor air sampling may also be conducted to establish cleanup levels based on background concentrations and statistics. For this purpose, the samples should be collected upgradient of any area potentially influenced by the site.
	Soil vapour	A 100 ft lateral distance from the edge of contamination defined by an estimate of where VOC concentrations in shallow groundwater or soil decrease to their practical quantitation limits with the following limitations: • Low permeability surface covers such as concrete or asphalt • Preferential flow paths: ○ Very high permeability vadose zone such as karst, fractured bedrock, or clay deposits with fissuring ○ Sewer, gas or other utility lines – surrounding backfills more permeable than the native soil ○ Utility lines such as sewers that contain site-related VOCs. • Soil gas under pressure; e.g. methane mixed with other VOCs from landfill

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-11: WA Ecology (2018)
		• Expanding plume For petroleum hydrocarbons, a similar approach to the ITRC and US EPA PVI guidance documents is adopted (ITRC 2014 and US EPA 2015b). The approach is outlined in the Implementation Memorandum No. 14, in which the lateral inclusion zone for vapour assessment is 30 ft if the degree and extent of contamination is well-defined and the dissolved phase plume is stable or receding. Otherwise, the use of the US EPA (2013) technical paper is recommended to determine the lateral inclusion zone. US EPA (2015b) is referenced for determining the vertical screening distances for buildings within the lateral inclusion zone. As part of the Tier I screening assessment: • For existing buildings: collected laterally close to the building to be representative of soil gas beneath the building, but stepped-back to avoid drain systems next to the foundation drain next to the foundation, samples may need to be stepped-back from the building to avoid these drain systems. A set-back of several feet from the building wall is recommended unless the building plans or persons with knowledge of the foundation construction provide information that would indicate another distance is more appropriate. • For future building or empty parcel of land, it is recommended to provide adequate sampling coverage over the entire parcel, or bias the sampling to collect soil gas from the most highly-contaminated areas beneath the parcel. The guidance notes that soil gas samples should be collected just above the contaminant source (vertically), because samples collected near the source often display less spatial variability in measured concentration levels, and investigators can usually sample from a relatively small number of points (laterally). The number of samples is not specified, but stated that the following two factors be considered: a) the expected heterogeneity in the VOC concentrations in soil gas; and b) data objectives.
	Sub-slab	Samples are to be collected via small holes through the flooring near the centre of the floor space, away from perimeter locations where exterior walls meet the floor. It is noted that often more than one room is selected for sub-slab samples. There will also be cases where, because of the size of a basement, multiple sub-slab locations will be sampled. In all these cases it is generally preferable to site the sampling locations away from exterior walls and any floor/slab features or cracks that could pose a “short-circuiting” route for the collection. Locations with utilities and shallow groundwater that may be in contact with the slab or flooring are to be avoided. Sub-slab samples should not be collected from areas in the immediate vicinity of large floor cracks or drains, or near sumps. The number of sub-slab samples needed depends on the size of the slab/floor, the expected lateral homogeneity/heterogeneity of VOC concentrations in soil gas immediately below the floor/slab, and the intended use of the data. In Tier I screening assessment, multiple sampling locations will usually be required to ensure that the range of sub-slab soil gas VOC levels have been represented in the resulting data. For basements, it is possible that the primary entry points for vapours may be through the sidewalls rather than from below the floor. Sub-slab sampling may therefore need to be augmented with samples collected through the basement walls.

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-11: WA Ecology (2018)
	Shallow soil vapour	When samples are collected from shallower depths, well-separated in distance from the source, WA Ecology will generally require a larger number of collection points laterally. It is stated that shallow samples have the following advantages: • May provide an indication of how much attenuation has actually occurred over the portion of the vadose zone between the source and the measurement point. • May provide an indication of how concentrated soil gas VOCs are at a location nearer the building of concern. The disadvantages are: • Wide spatial variability in measured soil gas concentrations when the samples are collected distal from the subsurface source, at shallow depths, therefore requiring a denser sampling design, laterally, for shallow sampling than for sampling conducted nearer the source. • Increased possibility of diluting the collected soil gas with atmospheric air, samples should seldom be collected from depths shallower than five feet bgs (or less than two to five feet below the depth of the foundation) • Increased influence of barometric pumping effect for soil gas samples collected at depths shallower than 5 feet bgs. For this reason, it is noted that samples can sometimes be collected from a location below an impermeable slab, such as some driveway and parking lot covers, or a garage floor • When the subsurface VOC source is close to the ground surface or basement floor, the shallow soil gas samples may not represent soil gas at the same depth directly below the building being evaluated. Whenever relatively shallow samples are collected beyond the building footprint, the potential exists for underestimating soil gas concentrations immediately below the building. The uncertainty associated with adequately representing soil gas concentrations just below the building increases as shallow samples are collected further from the building of concern. Shallow soil vapour (< 5 ft) may be required If the depth to groundwater was less than 5 feet and access to the building of concern couldn't be obtained. In these cases, the sampling protocol should include using a tracer (such as lab grade helium) to help ensure that the vacuum applied to collect the sample was not significant enough to draw in atmospheric air. If the tracer is detected in the sample at greater than 5% of the concentration within the shroud, the result should be rejected. Appendix G of the ITRC guidance is recommended (ITRC 2014).
	Spatial variability	Generally noted to be greater at sampling locations further away from the contamination source and at relatively shallow soil vapour sampling locations. "Large Volume Purge Sampling" is recommended as an option to address spatial variability in sub-slab sampling. For further discussion, reference is provided to Section 7.0 of the Hawaii Department of Health (HDOH) Soil Vapor and Indoor Air Sampling Guidance (HDOH 2017).
	Other factors considered in the guidance	When groundwater is the only VI source, either sub-slab samples or soil gas samples just above the water table's capillary zone are recommended. For vadose zone VI sources, either sub-slab samples or soil gas samples just above the top of the soil contamination are recommended. Samples may need to be collected through the basement walls if the primary entry points of vapour are through the sidewalls of a

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-11: WA Ecology (2018)
		basement in addition to sub-slab sampling.
Vapour sampling frequency	Seasonal	See Temporal variability
	Rainfall or soil moisture conditions	It is recommended not to collect soil gas samples during or immediately following a heavy rain.
	Groundwater fluctuations	Not addressed
	Barometric pressure changes	Falling barometric pressure is noted to increase potential for vapour intrusion and to be considered as a factor in defining worst-case conditions for sampling indoor air.
	Temporal variability	For indoor air, time-weighted sampling is performed (i.e. summa canisters, sorbent tubes, or passive diffusive samplers), at least one sampling event conducted at or near maximum depressurization relative to sub-slab soil gas. Two approaches are recommended to determine the timing of the sampling event: 1. Scheduling sample collection during periods of cold ambient air temperatures, or 2. Mechanically creating a negative pressure within the building to achieve a maximum pressure differential so conditions are conducive to vapour movement across the slab and into the building (McHugh et al. 2012 and Holton et al. 2015). It is recommended to use pressure transducers and data loggers to document pressure differentials throughout the event to help confirm that sampling is being conducted when the potential for vapour migration toward the building is most likely to occur. If it is determined that conditions were not ideal for evaluating vapour intrusion potential (e.g. indoor air pressures were greater than soil gas pressures), additional sampling events are required. Additional factors considered in the guidance that may represent worst-case sampling conditions are falling barometric pressure and frozen or wet ground conditions, if soil gas contaminants preferentially migrate to the area beneath buildings. It is also noted that while greater building depressurization, coupled with lower outdoor to indoor air exchange rates, are more likely to occur during low temperatures, significant building depressurization can also occur at other times such as during storm events where barometric pressures fall quickly and high winds occur. The guidance generally recommends collecting at least two separate rounds of indoor air samples before screening out the VI pathway and using multiple lines of evidence that consist of sampling results from source areas and potentially affected media, site characterization data, and building-specific information. When a preponderance of the data support a conclusion that indoor air is not likely being impacted, fewer indoor air sampling events should be necessary to screen out the pathway. Time-integrated methods such as passive sampling may reduce the number of individual sampling events that would otherwise be performed over those periods. Continuous sampling can capture the short-term variability, but unless it is utilized over extended periods, it is possible to miss long-term variability. As part of Tier II assessment, sub-slab soil gas and crawlspace air samples are recommended to be collected at the same time,

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-11: WA Ecology (2018)
		or nearly the same time, as indoor air samples, often collected the day immediately before or after the indoor sampling event. In some cases, may choose to collect both indoor and sub-slab samples over the same period, if the collected soil gas volume is small. To avoid the potential for cross-contamination, installation of the sub-slab probe(s) can be delayed until shortly after the indoor air samples are collected. It may also be possible to install the probes prior to indoor air sampling if enough time is allotted for the concentrations to return to pre-installation levels. Since numerous factors can affect indoor air results and since the results can change by several orders of magnitude over short periods of time, having results from these other locations can help limit the uncertainty. For sub-slab sampling intended for Tier I screening assessment (i.e., indoor air data is not being collected), multiple separate sampling events may be necessary to assure that representative soil gas conditions have been measured. At least one sampling event should be scheduled when the building is likely to be depressurized (with respect to the subsurface). Often this event is scheduled for the winter heating season, when temperatures inside the building are significantly higher than outdoor air temperatures. For soil vapour sampling: The guidance states that two or more separate soil gas sampling events may be necessary, depending on the following factors: • measured soil gas VOCs are below, but close to screening levels • a fairly small number of locations were sampled the first time; or, • the investigator believes there could be considerable longer-term temporal (e.g., seasonal) variability in soil gas VOC concentrations at the depth being sampled, and the first sampling may not have represented average concentrations with a high degree of confidence. The guidance notes that one or two sampling rounds are often enough to determine if additional VI work is needed, however, it is much more difficult to generically recommend the minimum number of subsurface sampling rounds necessary to screen out the pathway. Shallow and sub-slab soil gas levels will generally have more temporal variability than groundwater or deep soil gas concentrations.
	Other factors considered in the guidance	Not addressed
Sampling and analysis methods	Laboratory	Active sampling and analysis are discussed in context of sampling duration, flow rates and purge volumes. In general, smaller purge and sampling volumes are recommended for collection of discreet samples (in location and depth) and other guidance documents are referenced for sampling procedures. In general, it is recommended to establish data quality targets that includes consideration of leak tracer testing (recommended threshold is 5% of the concentration within the shroud) and required laboratory reporting limits. The recommended analytical

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-11: WA Ecology (2018)
		method for most VOCs is TO-15. Some chemicals such as naphthalene, chlordane and heptachlor are noted for which alternative methods may be required or preferred. Passive sampling is discussed for soil gas sampling with following advantages: • offering longer-time averaged sampling durations • there is no advective gas flow as a result of sampling procedure • less costly • may be deployed in tighter and wetter soils than active methods. The results indicate mass of contaminant and there is a greater uncertainty in estimated concentrations than can be determined from active methods. The results are considered qualitative or semi-quantitative and not accepted as the primary line of evidence. The following references are provided for passive indoor air sampling: NAVFAC (2015) US EPA (2014a) McAlary et al. (2014)
	Field GC	Portable field sampling devices such as a “Frog,” “Hapsite,” ppbRAE photoionization detector (PID), or other similar instrument are noted for use to identify background indoor air sources or preferential routes of soil gas entry into the building.
Multiple lines of evidence	Multiple media	Soil gas (open field; sub-slab) Passive soil gas Groundwater Indoor air (including crawlspace) Outdoor air
	Pressure monitoring	Cross-slab pressure differentials
	Indicators, surrogates, and tracers	utilizing tracer compounds and VOC ratios Temperature, barometric pressure trends and pressure differentials …. Ecology acknowledges that investigations can’t always begin during cold weather months. Greater building depressurization, coupled with lower outdoor to indoor air exchange rates, are more likely to occur during low temperatures, but significant building depressurization can also occur at other times such as during storm events where barometric pressures fall quickly and high winds occur. Regardless of the time of year, Ecology recommends collecting pressure data and trends along with other meteorological information to help analyze the results.
	Building pressure control test	One of the two approaches recommended for indoor air sampling event is to mechanically create a negative pressure within the building to achieve a maximum pressure differential so conditions are conducive to vapour movement across the slab and into the building (McHugh et al. 2012 and Holton et al. 2015).

Topic if applicable	**Sub-topic if applicable**	**Listing of applicable factors** **Table A-11: WA Ecology (2018)**
	Other factors considered in the guidance	Flux chamber sampling Sampling soil gas at multiple depths for the following reasons: • To demonstrate and better quantify vadose zone attenuation. • To better locate the vapour source in the subsurface. • To investigate the effect that subsurface utility corridors or vadose zone stratigraphic heterogeneities may be having on contaminant transport. Tracer test can potentially be used to evaluate the influence of elevator shaft on vapour migration, where applicable.
Ambient air assessment	Indoor air sampling	Conducted at later phase of vapour intrusion investigation as part of the Tier II investigation for existing buildings. It is required when: 1.Measured soil concentrations exceed the Method A soil cleanup levels for unrestricted use by more than an order-of-magnitude; 2. Groundwater concentrations exceed the applicable screening levels for protection of indoor air quality; or 3. Soil gas sampling results exceed the applicable screening levels.
	Outdoor air sampling	Conducted at later phase of vapour intrusion investigation in conjunction with indoor air assessment where applicable Outdoor air data is intended for interpretation and adjustment of indoor air concentrations; or the guidance provides requirements for establishing background concentrations for adjusting cleanup levels.
	Building operations	Provides discussion on potential impact of heating, cooling, and ventilation of building on vapour intrusion that may result from changes in air exchange rate and pressure differentials.
	Background sources	Background sources are noted to include common household cleaners, solvents, paints, and adhesives; cigarette smoke; and, automobile exhaust from attached garages. The guidance recommends removing the sources If portable (several days before sampling begins) and ventilating the area.
	Other factors considered in the guidance	
Mitigation methods		Described for existing buildings or “built into” new structure; and in terms of entirely passive measures or incorporate active devices such as fans. Preemptive mitigation approach for residential buildings using sub-slab or sub-membrane depressurization system Consideration of air emissions and applicable permits; depending on the building size and cost/complexity of the mitigation, may be subject to other regulatory requirements (e.g., mechanical and/or other permits).

Topic if applicable	Sub-topic if applicable	Listing of applicable factors **Table A-11: WA Ecology (2018)**
		ASTM standards for radon mitigation should, at a minimum, be met. The guidance notes that some remediation systems such as SVE, soil excavation and treatment of groundwater (where vapour source is limited to the saturated zone) may be effective in protecting indoor air quality. Mitigation measures are noted specifically for short-term response action for TCE. US EPA (2014b) is referenced with added considerations for practicality and effectiveness. SSD design and implementation is recommended but noted that it may take time and in the interim, the following may be considered: • Increase in building ventilation/pressurization (e.g. through HVAC control) • Sealing potential conduits • Stop-gap responses that include actions such as temporarily relocating the receptor, and installing effective indoor air treatment (air purification units (APUs) or “air cleaners”) with reference to US EPA (2017).
Attenuation factors	Media	soil vapour, sub-slab, groundwater Default factor for groundwater data is 0.001 with the following assumptions: • No LNAPL • No preferential pathways (natural or man-made e.g. utility corridors) • No earthen floors or open sumps • Not very shallow water table (<15ft or within a few feet of building’s lowest floor) Recommended sub-slab attenuation factor is 0.03; and 0.01 for soil gas collected at greater depth – the threshold is 15 ft – i.e. <15 ft below base of foundation must use the sub-slab screening levels derived from attenuation factor of 0.03.
	Land use	Not addressed
	Derivation basis	Empirical derivation based on database study for sub-slab and crawl space vapour samples (US EPA 2015a and 2015b) May use JEM with conservative site-specific values that may result in lower attenuation factors, but with the following conditions: • For petroleum contaminated sites, Implementation Memo No. 18 indicates that soil gas sampling, coupled with the use of a predictive model may be sufficient to show the mass of contamination remaining is not sufficient to present a VI concern. • For chlorinated compounds, paired indoor air and sub-slab soil gas data would typically be necessary to provide the supporting data to confirm the modeling results. Other available information such as the building configuration; soil conditions; type and location of utilities; and plume stability data should also be evaluated. JEM not recommended to “back-calculate” soil and groundwater screening levels. BioVapor or PVIScreen may be used but not as the sole line of evidence.

Topic if applicable	Sub-topic if applicable	Listing of applicable factors Table A-11: WA Ecology (2018)

APPENDIX B

Review of Literature on Preferential Pathways

Literature Review

Select recent literature was reviewed because of the recent emerging knowledge on preferential pathways (Reichman et al. 2017; Riis et al. 2010; Pennell et al. 2013; Wallace and Friedrich 2017; Guo et al. 2017; ESTCP 2018). These studies indicate the importance of sewers and drains as preferential pathways.

During a VI study in Skuldelev, Denmark, Riis et al. (2010) discovered higher than expected VOC concentrations in IA at several houses. The researchers conducted a tracer gas study to assess potential pathways for VOCs and found elevated concentrations of PCE and its degradation by-products, trichloroethylene (TCE) and 1,2-dichloroethene, in the sewer line and plumbing fixtures. From the results, Riis et al. (2010) determined that sewer lines were the primary VI pathway for the studied properties and that impacts from sewer intrusion extended beyond the groundwater plume.

In a residential area in Boston, Massachusetts (US), researchers measured higher PCE concentrations in IA on the first floor of a home than in the basement IA of the same house (Pennell et al. 2013). Follow-up IA and sewer gas sampling and analysis indicated that the sewer gas from a faulty toilet connection was the primary source of PCE in IA.

Researchers from Arizona State University conducted a long-term VI continuous monitoring study at a house overlying a groundwater plume contaminated by 1,1-dichlorethylene (1,1-DCE), 1,1,1-trichloroethane (1,1,1-TCA), and TCE near Hill Air Force Base in Layton, Utah (Guo et al. 2017). The study methods included controlled-pressure-method testing, which included pumping of air from the house and IA sampling under different pressure conditions, soil gas sampling, and screening-level emission calculations. The study concluded that subsurface pipe networks, including sewer mains and land drains, were significant alternative VI pathways (i.e., in addition to subsurface soil vapour migration).

Wallace and Friedrich (2017) presented data for sewer and indoor air concentrations that demonstrated the migration of TCE in sewer water and air over a four block (1,600 ft or 490 m) area, which was separate and beyond the area of groundwater contamination. Elevated indoor air TCE concentrations were measured inside homes over the four-block area. Smoke testing was used to evaluate leaks in sewers. As venting of sewers was not practical, mitigation options considered included check valves or re-routing and abandoning the sewer.

Loll et al. (2016) describe that the subsurface contribution of VOCs to the indoor environment is a function of: a) sub-slab VOC concentrations and spatial distribution, b) vapour intrusion pathways – number and placement, c) differential pressure (subsurface to indoor), and d) building ventilation. Under typical Danish conditions, the pressure-driven contribution is estimated to be approximately 70-85% of the total contribution (diffusion + advection). Perfluorocarbon tracers (PMCP & PMCH) were released through commercially available emitters placed in target source locations (e.g., crawlspace, basement, soil gas probes and building cavity). Two-week passive samples were obtained in receptor locations for analysis of the tracer to enable qualitative evaluation of pathways and estimation of attenuation factors (AFs). The researchers concluded that two-week samples provide for a better indication of average vapour migration conditions than short-term samples.

A study conducted by US Department of Defence (DoD) Environmental Security Technology Certification Program (ESTCP) under the Strategic Environmental Research and Development Program (SERDP) (Dr. Tom McHugh of GSI is the primary investigator) consisted of research on identifying the presence or absence of utility VI (focused on sewers and tunnels), determining the significance of utilities for VI, and development of a CSM for the sewer/tunnel pathway (ESTCP 2018). Groundwater-to-sewer and sewer-to-indoor air AFs were estimated from analysis of approximately 400 samples for VOCs and perfluorocarbon. An AF of 0.03 was estimated as a reasonable upper-bound for the migration of VOCs in vapour from sewer-to-indoor air. An overall AF of 0.001 was recommended for the groundwater-to-sewer and sewer-to-indoor air pathways for cases where contaminated groundwater intersects the sewer. The research indicated that the primary pathway for migration of vapours into buildings was through sewers and tunnels and not through utility backfill.

The results demonstrated the presence of background sources of VOCs in sewer water at varying concentrations. Seasonal testing was conducted to characterize seasonal variability, which exceeded an order of magnitude for sewer air and water samples. A protocol was developed based on identifying higher risk sites (where sewer intersects contamination) and lower risk sites (where the sewer was in the vadose zone above impacted groundwater). A sewer investigation framework is provided consisting of tiered collection of samples of sewer air and water, and application of screening AFs. An accompanying investigation protocol includes recommendations for where, when and how to sample including:

- Conduct sampling at higher water periods when there are water table fluctuations such that the water table is above the sewer base.
- Collect samples between 9 am and 3 pm, when baseline flow is relatively low.
- Do not collect samples within 48 hours of a rainfall event of more than 0.1 inches.
- Minimize the opening in manhole covers when sampling.
- Measure water levels in sewer.
- Typically obtain samples from sewer air and sewer water for chemical analysis.
- Obtain air samples 0.3 m above the water level, typically in canisters either as grab samples or time-integrated composite samples

ESTCP (2018) conclude based on the results of the comprehensive research program where an attenuation factor of 0.03 was estimated as a reasonable upper-bound factor for the migration of VOCs in vapour from sewer-to-indoor air/utility tunnels into buildings. A conservative assumption would be that soil vapour near sewers would be in equilibrium with sewer air and that an attenuation factor of 0.03 may be reasonable for soil vapour to indoor air when there is a sewer pathway (direct connection). It is noted that the ESTCP (2018) research indicated that the primary pathway for migration of vapours into buildings was through sewers and tunnels and not through utility backfill.

References

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APPENDIX C

Example Case Study of Slab on Grade Industrial Building with Shallow Chlorinated Solvent Contamination

Introduction

The purpose of this case study is to illustrate the use of the guidance for a hypothetical site consisting of a slab on grade building with shallow chlorinated solvent contamination. The case study assumes that the practitioner has conducted a Stage 1 and 2 Preliminary Site Investigation (PSI) and that there are data on soil and groundwater quality available for sampling locations beside the building. The case study is intended to provide a practical summary of key steps in the guidance and illustrate the outcome with respect to the conceptual site model (CSM) and sampling strategy and plan. The case study provides one possible example of how to identify CSM factors and develop a sampling plan to address near-worst case conditions. Because only a summary is provided, not all the details of the guidance that should be considered are included. The reader should follow the approach and methods described in Sections 3 and 4 of the guidance when developing a CSM and sampling plan.

Background Information

The Stage 1 PSI indicates there is documented information that chlorinated solvents were disposed of in drains and pits inside and outside of a relatively small single-storey building with slab-at-grade foundation that was formerly used as a dry-cleaning facility (Figure C-1). The building is now used as a bicycle repair shop. The building consists of an open area and several small offices and lunchroom. The Stage 2 PSI consisted of a relatively limited number of boreholes beside the building that were completed as monitoring wells. The site geology consists of sandy soils, with silt layers. The depth to the water table is approximately 3 m below ground surface, with seasonal fluctuations of approximately 0.5 m. The results of soil and groundwater analyses indicated there were detections of chlorinated solvent compounds in groundwater (up to 50 µg/L), but no detections in soil at boreholes beside the building.[1]

Conceptual Site Model

A vapour CSM should be developed based on Section 3 of the guidance and factors described in Table 1. A summary of the CSM is described below:

- **Potential Contaminants of Concern (PCOCs)**: Tetrachloroethylene (PCE) and degradation or reaction products. The BC Contaminated Sites Approved Professional (CSAP) Society Practice Guideline (2009) PCOC list for dry cleaners is adopted.
- **Vapour Source**: The Stage 1 PSI identified that a sludge-type waste from the dry cleaner containing PCE was disposed of in shallow drains (pits) inside and immediately adjacent the building shown in Figure C-1. The construction and condition of drains and pits are unknown. The drains and pits likely connect to a sanitary sewer. It is a common occurrence for drains and pits to not be sealed and for degradation of sewer seals to occur over time through contact with PCE. Therefore, it is inferred that there is a relatively high probability that there is a shallow vapour contamination source that is very close to the building. While the concentrations of PCE in monitoring wells downgradient and beside the building were relatively low (less than 50 µg/L), there is also likely a groundwater contamination source below the building inferred to have resulted from releases associated with operations of the former dry cleaner.

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[1] It is possible for soil concentrations below a typical laboratory reporting limit to result in groundwater concentrations that are above reporting limit. For example, using the soil leachate partitioning described in BC Ministry of Environment and Climate Change (ENV) Protocol 13 (Equation A-1 in Appendix A of Protocol 13), and a groundwater PCE concentration of 50 µg/L, a soil concentration of 0.032 µg/g is predicted, which is less than a typical reporting limit of 0.05 µg/g.

- **Building and Environmental Factors**: There is an exhaust-only heating and ventilation system that operates continuously in winter, but less frequently in summer. Additionally, a small bay door is often open in summer, which will result in some natural ventilation. Because there is no ducted return air, there is the potential for building depressurization, with higher depressurization expected in winter when the heating system is operated at capacity. The site is in Vancouver, and therefore, the winter temperatures are not as extreme as in some other parts of BC. Because of the building height (one-storey) and differences between indoor and outdoor temperatures in Vancouver, the stack effect is expected to be of lesser importance for building depressurization compared to heating and ventilation. A site reconnaissance indicated chemical-like staining of the concrete foundation slab near pits suggesting the potential for contamination of building materials.
- **Subsurface Factors**: There is primarily coarse-grained sandy soil in the vadose zone. The silt layers are inferred to be discontinuous. Based on groundwater dissolved oxygen and redox results, it is inferred that the vadose zone below the building may be under aerobic conditions. Consequently, the potential for degradation of PCE to lesser chlorinated solvent compounds may be relatively low.
- **Spatial and Temporal Variability**: The annual seasonal fluctuation in the water table is approximately 0.5 m with lower water table levels in summer. The soil moisture is not expected to vary significantly below the building as the building prevents infiltration of water from occurring. Soil temperature is not expected to vary significantly because of the site location (Vancouver), heating provided by the building and shallow water table.
- **Current or Future Development and Land Use**: as described in Background Section above.
- **Preferential Pathways**: There are drains and branch sewers to the building that connect to a main sewer in the street. There is the potential for migration of PCE waste into the sewer pipe and volatilization of PCE in sewer air. Where biotransformation of PCE to degradation products has occurred in the subsurface there could be migration of other chlorinated solvents into the sewer. There is potential for migration of vapours in sewer air into the building. There is the potential for off-site migration of contamination in sewers.
- **Other CSM Factors**: Other factors described in Table 1 of guidance are not considered applicable or relevant. Specifically, a clean-water lens and interface plume are not relevant because these CSM factors describe processes that can occur when there is lateral migration (generally over relatively longer distances) of a dissolved plume in groundwater or in the interface (capillary transition zone) between groundwater and the vadose zone. For purposes of this case study, we focus on contamination sources and processes below and immediately adjacent to the building in the vadose zone and shallow groundwater. Water infiltration and snow and frost are not considered relevant because contamination is below the building. The site is not subject to tides. Generation of biogenic gases is not a significant process because of aerobic conditions and absence of a significant organic source.

Indoor Air Vapour Pathways

The assessment of vapour pathways for this case study example is limited to the on-site indoor air pathway. As indicated in Section 4.1 of the guidance, a sampling strategy should be developed. For this site, a top-down approach consisting of indoor air sampling and analysis is implemented because of the high probability for a shallow vapour source and complete vapour intrusion pathway. In addition, because it is important to identify sources and pathways, concurrent subslab vapour and sewer air samples are also obtained. External soil vapour sampling is also conducted because of the disposal pit located adjacent to the building and groundwater contamination. Because of possible multiple contamination sources (e.g., contamination in sewers, soil, groundwater and building materials) and potential for background sources of chlorinated solvents in air, a multiple lines of evidence approach is implemented to understand sources.

The questions in Section 4.3 on “Vapour Sampling Locations and Frequency” should be reviewed as they provide the linkage between the CSM and development of the sampling plan to identify worst-case conditions for vapour sampling.

1) Do changes in the water level affect vapour source concentrations? **Dissolved-plume concentrations are not expected to change because of water level fluctuations. There may be small changes in concentration gradient because of water level changes**. Is there likely an interface plume and increased volatilization from dropping water levels? **Increased volatilization is unlikely**.

2) Is there a fresh-water lens present between the vapour source and vapour sampling location? **No.** And is this likely to be a seasonally varying condition? **No**.

3) Are site conditions that would be sensitive to barometric pumping effects applicable? **No**.

4) Are durations of events such as barometric pumping, snowmelt, snow or frost cover, temperature in air or soil, spring freshet, or wind effects at the site and their effects on vapour concentrations significant for long-term vapour assessment? **None of the above factors are likely significant. There may be small fluctuations in soil temperature seasonally**.

5) Is there potential for aerobic or anaerobic biodegradation of PCOCs in the vadose zone? **The vadose zone is inferred to be under aerobic conditions. Aerobic degradation of PCE is negligible**. Is there potential for pressure-driven flow from methane generation (e.g. at landfills)? **No**.

6) Are there other factors affecting groundwater elevation and flow direction including tidal influences? (Section 2.3.3). **No**.

7) Do changes in water levels or groundwater flow directions affect the extent of the investigation zone? **No.**

8) Are preferential pathways a concern, or would become a concern during elevated water levels? **Yes**. Described above.

9) Are there effects of remediation system in operation at the site that can lead to longer-term temporal variations? **No.**

10) How do the building operations, and importantly HVAC, affect the building ventilation and pressures? **Yes. There is an unbalanced HVAC system, which is likely causing building depressurization, with higher depressurization in winter months. During summer months the HVAC system is mostly off. Some natural ventilation will occur**. Could there be future significant changes to the building foundation? **Unlikely**.

11) How does the potential for changes in future land use factor into the assessment (i.e., are land use and potential future changes clearly defined)? **Currently a commercial use (bicycle shop) and future uses unknown**.

The next step is to consider seasonal factors to identify near worst-case conditions using Table 4 in the guidance (Table C-1 below). These factors are needed in making decisions on the sampling strategy.

Table C-1: Seasonal factors and considerations in selection of sampling events – case study example

Seasonal factors	Site-specific consideration	Potential impact on vapour source and/or migration	Likelihood of worst-case or applicability to site-specific conditions Example Scenario (see text for more details)	
Higher water level	Distance from water table to building	Shorter migration distance	☒ not significant	A shorter migration distance would result in an increased gradient for diffusion from a groundwater source; however, the increase in diffusive flux would be small based on water table fluctuations. Additionally, the inferred shallow vapour source is expected to be a much more significant source of vapours.
Relatively higher temperatures in air or soil	Increase in Henry's constant and effective diffusion	Increased source from greater partitioning into vapour phase and transport rate in the subsurface	☒ not significant	Very small seasonal fluctuations in vadose zone soil temperatures are expected below the building. Small seasonal fluctuations in groundwater temperature (a few degrees) are expected. However, the effect on VI potential is expected to be negligible.
Relatively lower temperatures corresponding to heating of indoor air	Increase in building depressurization due to higher indoor air temperature relative to outdoor air (stack effect)	Greater vapour intrusion from subsurface to indoor air	☑ Winter (January/February) Of low significance	A slightly greater potential for stack effect would be expected in winter months. However, the stack effect is expected to be small because of the building height (one-storey) and moderate indoor-outdoor temperature differences. The depressurization through stack effect is expected to be much smaller than from HVAC operation.
e.g. Seasonal changes in building HVAC conditions	e.g. industrial building where un-balanced exhaust only HVAC system is operated at capacity in winter	e.g. higher depressurization in winter	☑ January/February	Relatively high VI potential in January/February
e.g. Seasonal changes in building HVAC conditions	e.g. building where HVAC is turned off during summer season	e.g. the effect on vapour intrusion is uncertain because while there is lower potential for building depressurization there may also be lower ventilation rates	☑ July/August	While the potential for VI in July/August is likely less than in January/February, because of the lower ventilation rates in summer, there may still be relatively significant potential for VI

Based on the above analysis, a sampling plan is developed. Note this is one possible example of a sampling plan. The sampling locations are as follows:

1) Indoor air – exposure samples. Because indoor air is inferred to be relatively well mixed within the open air of the shop, one sample is obtained from the shop area. One sample is obtained from an office.
2) Indoor air – pathway samples. Two samples are obtained from drains and pits.
3) Sewer air – one sample is obtained from manhole connection to the sewer.
4) Subslab vapour – three subslab vapour samples are obtained.
5) Soil vapour – one deeper soil vapour sample below the slab and three soil vapour samples beside the building are obtained.

The sampling times are based on the factors described in Table 4. Because the greatest potential for vapour intrusion is inferred to be during the winter season (January and February), two monitoring events are conducted during this season. Because of the potential for a lower ventilation rate in summer, one event is conducted during the summer season. One event during the summer season (July and August) is considered reasonable because of the inferred lower VI potential.

The differential pressures are measured between the building air and subslab soil vapour and building air and outdoor air several days before sampling and during the sampling event. In addition, information on the HVAC system including when operational and test-and-balance data, where available, and other building-related data (e.g., utility plans) should be obtained. Other supporting data includes analysis of soil and groundwater samples obtained during drilling for installation of vapour probes.

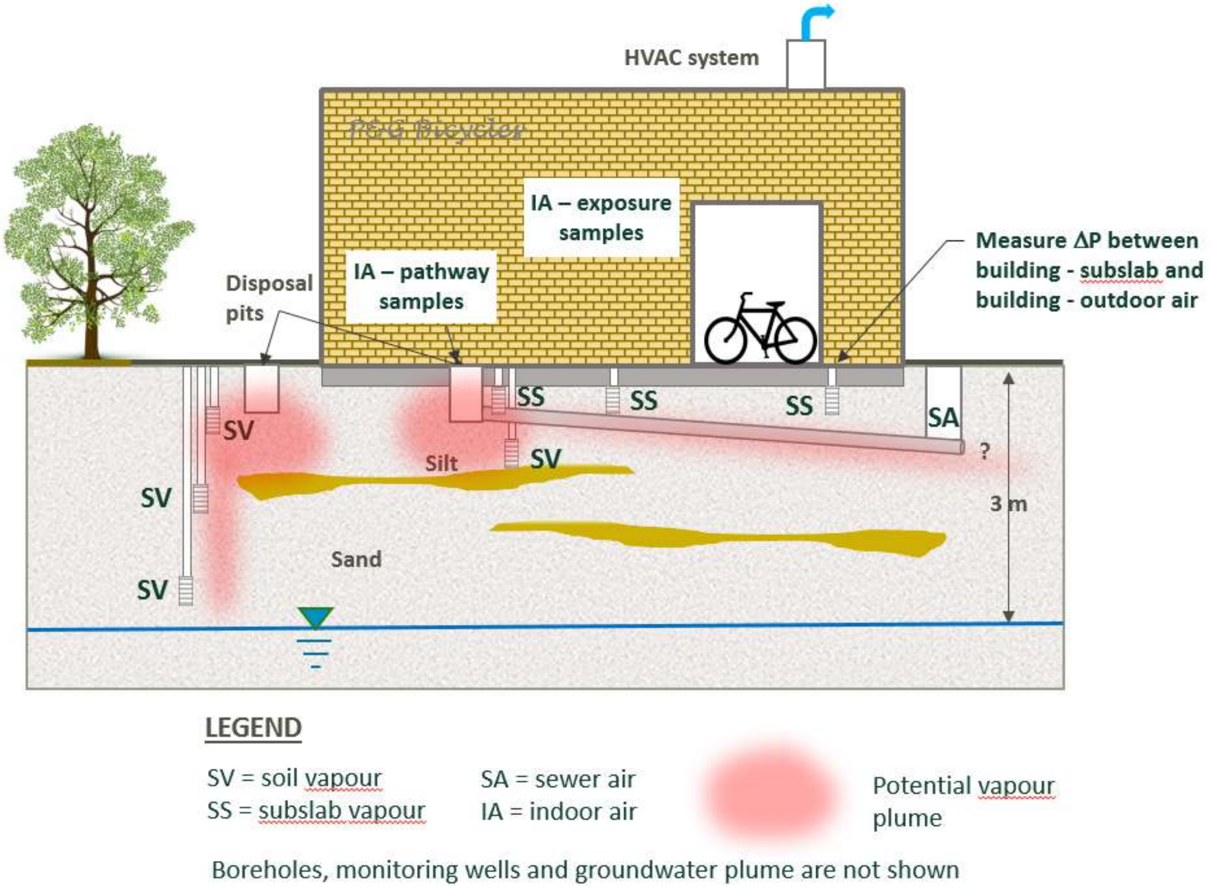

Figure C-1. Conceptual Site Model and Sampling Locations (elements of the Health Canada CSM Tool were used).[2]

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[2] eSolutionsGroup Ltd. 2015. Conceptual Site Model Builder Tool. Contractor report prepared for the Contaminated Sites Division, Safe Environments Directorate, Health Canada, Ottawa.

APPENDIX D

Estimation of Time to Approximate Steady-State Vapour Concentration

Introduction

This appendix provides practical considerations for the application of a model of transport by diffusion and three-phase linear partitioning between sorbed, aqueous and vapour phases as described in Johnson et al. (1999). This model is recommended in BC Environment Technical Guidance (TG) 4 for estimating the approximate time to reach near steady state soil vapour concentrations from a contamination source in the subsurface. As noted in Johnson et al. (1999), soil gas concentrations measured near a source will generally be representative of near steady state conditions, whereas it is necessary to consider the time to reach near steady state conditions since the release if measurements are taken away from the source zone. Model assumptions with respect to the analytical solution for one-dimensional transport by diffusion in porous media are presented for clarifying the conceptual model and its limitations, as well as references and case examples for the selection of the input parameters.

Conceptual Model and Derivation of Time Estimate

In this appendix, we expand on the derivation of the time estimate presented in Johnson et al. (1999). The model is based on a constant concentration source, which assumes the vapour contamination source (e.g., soil, sediment, NAPL or groundwater contamination) is stable in the subsurface. The model does not include advective flux (e.g., from thermal or pressure gradients in soil gas) or biodegradation, which can significantly affect the soil vapour distribution and time estimate for near steady state vapour concentrations.

The equation for transient soil vapour diffusion in unsaturated soil can be defined according to Fick's second law, with addition of retardation (Peterson et al. 1994) in one-dimension, as shown in Equation 1:

$$\theta_v \, R_v \, \frac{\partial C}{\partial t} = D^{eff} \, \frac{\partial^2 C}{\partial x^2}, \qquad Eq\ 1$$

where C is the vapour concentration, x is the distance from source, t is time, θ_v is the volumetric air content, R_v is the retardation coefficient (dimensionless), and D^{eff} is the effective diffusion coefficient. Parameters and units are further defined in the *Input Parameters* Section.

The solution to Equation 1 depends on the assumed initial and boundary conditions, which can be defined for various common scenarios. A representative scenario is a release in previously uncontaminated soil, assuming an initial condition of step-change in concentration at the source location defined at $x = 0$, and zero concentrations at $x > 0$. Johnson et al. (1999) approximate the time to reach near steady-state conditions to be on the order of, or greater than:

$$\tau_{ss} \approx > \frac{R_v \theta_v L^2}{D^{eff}}$$

where L is defined as the distance between the source and the measurement point (or x as in Equation 1).

Here, we expand on the approach taken by Johnson et al. (1999) by considering the conceptual model of diffusive transport from a source in a finite domain ($0 \leq x \leq d$) and two types of boundary conditions at $x = d$. For practical applications to vapour assessment, the boundary in one-dimension may represent the vertical distance to ground surface, pavement or building foundation or laterally to the extent of vapour assessment (e.g., 30 m).

Two simple and relevant scenarios are presented with analytical solutions and comparison between transient and the steady state solutions to approximate the time estimate for near steady state conditions, τ_{ss}. The scenarios considered are: 1) assuming zero concentration at $x = d$, or relatively low (negligible) concentration compared to the source concentration (C_0); and 2) no-flow or zero-gradient in concentration at $x = d$.

For both scenarios, non-dimensional variables are defined as follows:

$$T = \frac{Dt}{d^2} = \frac{D^{eff} t}{R_v \theta_v d^2} \qquad Eq\ 2a$$

$$X = \frac{x}{d} \qquad Eq\ 2b$$

Scenario 1: constant concentration at distance, d away from the source, where the concentration is negligible compared to the source concentration ($C(d,t) \sim 0$ for $t > 0$). The approach of the transient solution to the steady state solution is used to estimate the approximate time to reach near steady state conditions.

The analytical steady state solution, $C_{ss}(X)$, and the transient solution, $C(X,T)$ are defined in Equations 3a and 3b, respectively (Crank 1975):

$$C_{ss}(X) = C_0(X-1) \qquad Eq\ 3a$$

$$C(X,T) = C_0\left(1 - X + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{-1}{n}\sin(n\pi X)e^{(-Tn^2\pi^2)}\right) \qquad Eq\ 3b$$

Based on the results shown in Figure 1, an approximate time to reach a steady state solution is defined by

$$\tau_{ss} \approx \frac{d^2}{4D} = \frac{R_v \theta_v d^2}{4D^{eff}} \qquad Eq\ 4$$

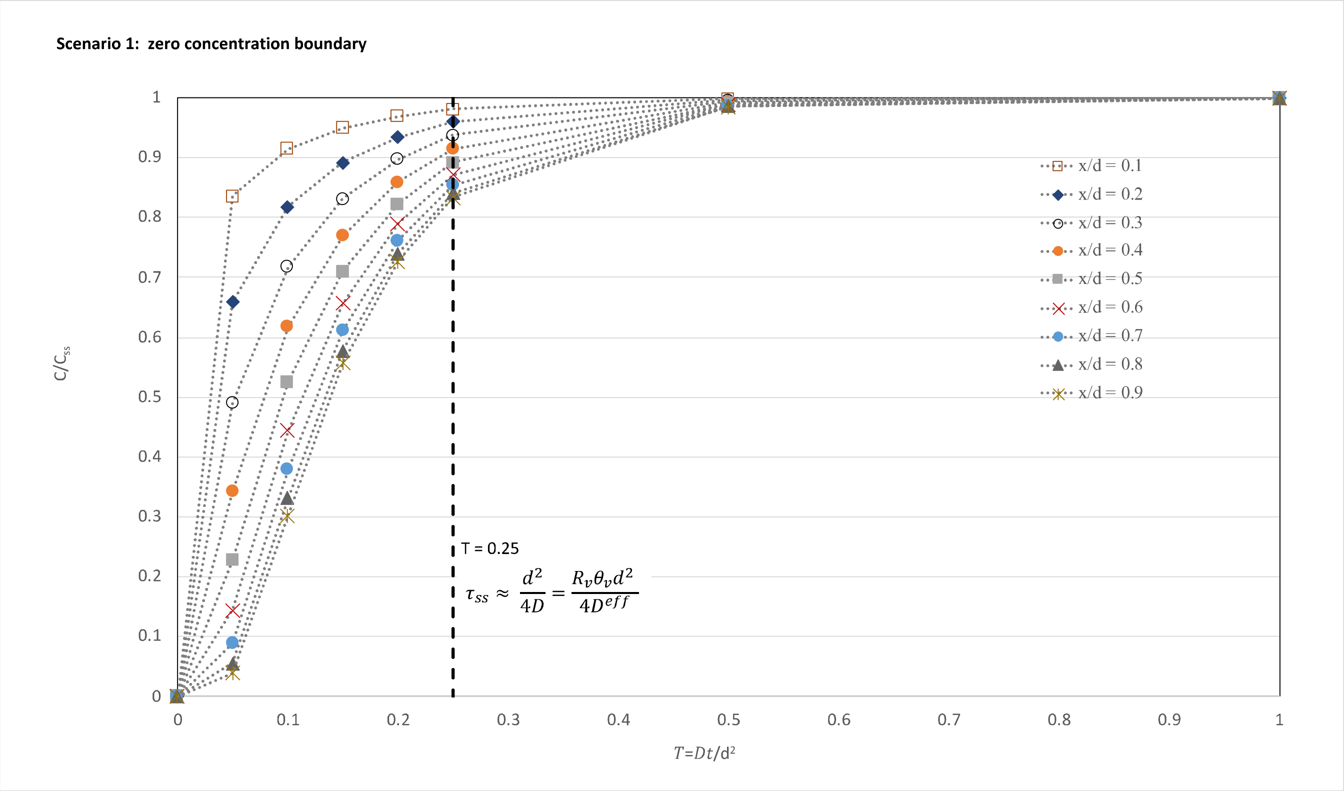

Figure 1: Change in concentrations with time relative to the steady state solution for scenario 1 based on Equation 3. The time estimate for near steady state condition is shown assuming T = 0.25 for all values of x/d.

Scenario 2: zero-gradient or no-flow at distance, d away from the source, where the boundary is assumed to be impermeable ($\frac{\partial C}{\partial x} = 0\ at\ x = d$). The approach of the transient solution to the steady state solution is used to estimate the approximate time to reach near steady state conditions.

The analytical steady state solution, $C_{ss}(X)$, and the transient solution, $C(X,T)$ are defined in Equations 5a and 5b, respectively (Crank 1975):

$$C_{ss}(X) = C_0 \qquad Eq\ 5a$$

$$C(X,T) = C_0\left(1 - \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cos\left(\frac{(2n+1)\pi(1-X)}{2}\right)e^{\left(-T(2n+1)^2\pi^2/4\right)}\right) \qquad Eq\ 5b$$

Based on the results shown in Figure 2, an approximate time to reach a steady state solution is defined by

$$\tau_{ss} \approx \frac{d^2}{D} = \frac{R_v\theta_v d^2}{D^{eff}} \qquad Eq\ 6$$

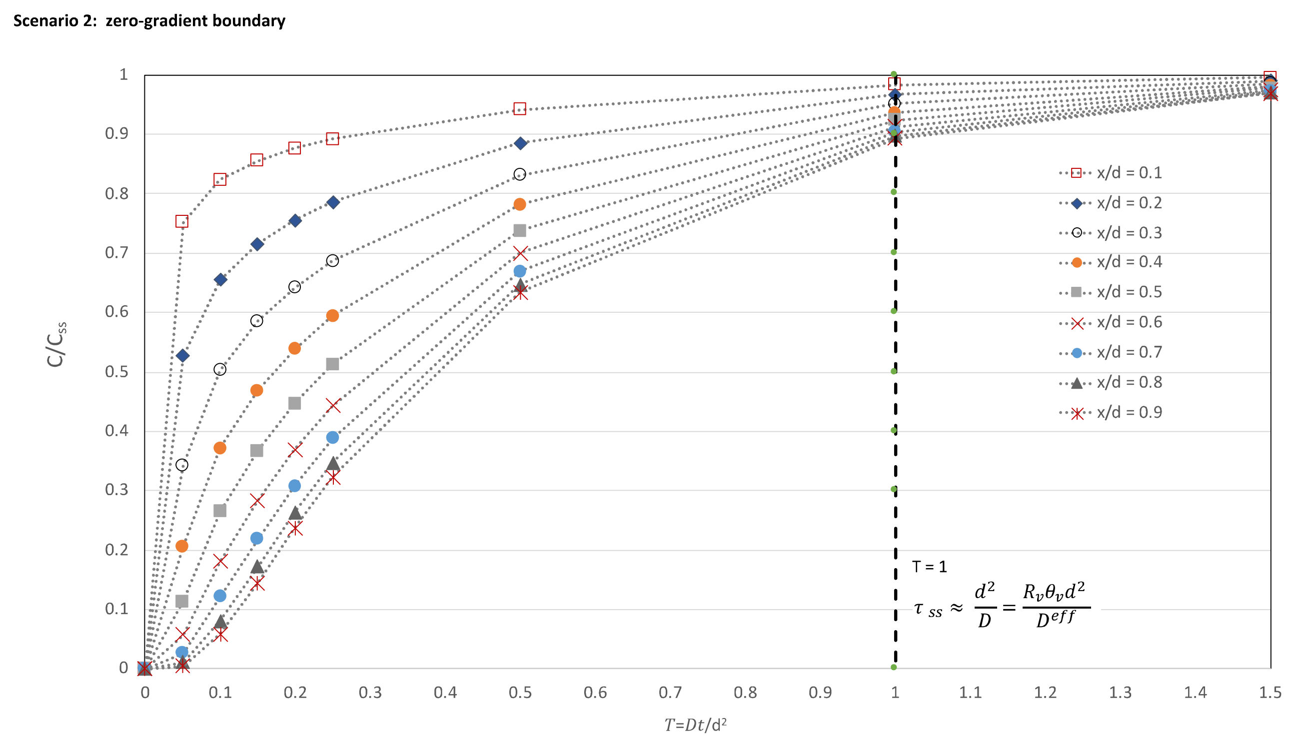

Figure 2: Change in concentrations with time relative to the steady state solution for scenario 2 based on Equation 5. The time estimate for near steady state condition is shown assuming T = 1 for all values of x/d.

These scenarios show that the time estimate is generally a function of the square of the distance from the source to the boundary (d) rather than distance x from the source. The approximations provided by Equations 4 and 6 can be further refined using Figures 1 or 2 and considering specific values of the relative distance represented by the ratio x/d.

Overall, the above analysis provides practical applications for some common scenarios for vapour assessment and highlights the importance of defining a conceptual model and relevant boundaries in assessing near steady state conditions. Depending on site specific conditions, an unpaved ground surface may be represented by scenario 1; and a paved ground surface or building foundation may be represented by the zero-gradient assumption in scenario 2. At most sites, there is likely some diffusive flow through pavements and foundations, as well as advective flow due to pressure gradients. While neither of the scenarios and the analytical solutions are ideal representations, we believe they extend the use of the time estimate and the approach proposed in Johnson et al. (1999) to simplified conceptual models related to vapour assessment and its application as recommended in TG 4.

The practical implications of considering the distance d to the relevant boundary and use of Equation 4 or 6 are summarized in Table 1 as compared to the Johnson et al. (1999) expression based on distance, L from the source and without consideration of distance to the boundary, d.

Table 1: Implications of the proposed time estimates as compared to the Johnson et al. (1999) expression, which uses L as the distance from source to the measuring point (i.e. x in Equation 1).

Scenario 1 (e.g., d = distance between source and unpaved ground surface; or 30 m lateral distance)	Use of the Johnson et al. expression under- and over-estimates τ_{ss} for $L < d/2$ and $L > d/2$, respectively as compared to Equation 4.	Use of the Johnson et al. expression with $L = d/2$ (i.e. at mid-point between the source and the boundary) is equivalent to Equation 4.
Scenario 2 (e.g., d = distance between source and paved ground surface or building foundation)	Use of the Johnson et al. expression underestimates τ_{ss} for L < d as compared to Equation 6.	Use of the Johnson et al. expression with $L = d$ is equivalent to Equation 6.

Input Parameters

Effective diffusion coefficient:

The effective diffusion coefficient can vary by orders of magnitude depending on soil type and moisture content. Where appropriate, chemical-specific properties can be used as illustrated in this appendix to estimate the effective diffusion coefficient, as opposed to the use of approximate properties to represent a surrogate chemical, which was the approach followed by Johnson et al. (1999).

The effective diffusion coefficient can be calculated from the Millington and Quirk (1961) relationship, shown in Equation 7:

$$D^{eff} = D^{air}\frac{\theta_v^{3.33}}{\theta_t^2} + D^{H2O}\frac{\theta_m^{3.33}}{H'\theta_t^2} \qquad Eq\ 7$$

The advantage of Equation 7 is that parameter values for different classes of soil are available and commonly employed in vapour intrusion assessments as presented in Table 2. Therefore, this approach is recommended for screening type approximation of τ_{ss}. Where appropriate, alternative models and measurements may be used to estimate the effective diffusion coefficient. In particular, Chou et al. (2012) show that the use of the Millington and Quirk (1961) expression overestimated the experimental data on tortuosity, and thereby the effective diffusion coefficient, for three different soil types (sand, sandy clay loam, and clay).

Soil sorption coefficient:

The soil organic carbon partitioning model is used to estimate the soil sorption partitioning coefficient. Assuming a single chemical component and three-phase equilibrium linear partitioining between sorbed, aqueous and vapour phases, the total soil concentration (C_T), which is the sum of concentrations in all phases, can be related to the soil vapour concentration (C_{vapour}) based on a mass balance between phases, as described in Equation 8 (ASTM 2015; Johnson et al. 1999). The retardation coefficient and soil organic carbon partitioning relationship is defined in Equations 9 and 10:

$$C_T = \frac{C_{vapour}\,\theta_v}{\rho_b}\,R_v \qquad Eq\ 8$$

$$R_v = 1 + \frac{\theta_m}{\theta_v\,H'} + \frac{\rho_b\,K_d}{\theta_v\,H'} \qquad Eq\ 9$$

$$K_d = K_{oc}\,f_{oc} \qquad Eq\ 10$$

where

C_T = total soil concentration (mg/kg-soil)
θ_m = volumetric water content [m^3-H_20/m^3-soil]
θ_v = volumetric air content [m^3-air/m^3-soil]
θ_t = total porosity [m^3-voids/m^3-soil]
H' = dimensionless Henry's Law constant
K_d = soil sorption partitioning coefficient [L/kg]
K_{oc} = soil organic carbon partitioning coefficient [L/kg]
R_v = retardation coefficient (dimensionless)
ρ_b = bulk density (kg/L)
f_{oc} = fraction of organic carbon (dimensionless)
C_{vapour} = soil vapour concentration (mg/m^3)
D^{air} = molecular diffusion coefficient in air (m^2/d)
D^{H20} = molecular diffusion coefficient in water (m^2/d)
D^{eff} = effective diffusion coefficient (m^2/d)

Example Model Results

The time to an approximate steady-state vapour concentration condition is estimated for scenario 1 (zero concentration boundary) and scenario 2 (zero-gradient boundary) using Equations 4 and 6, respectively, for two substances (trichloroethylene and 1,3,5- trimethylbenzene) and four soil textural types (sand, loamy sand, sandy loam and loam) with results presented in Figures 3 and 4. TCE is selected as a typical volatile chemical of concern and 1,3,5- trimethylbenzene (TMB) as a chemical with approximately one order of magnitude higher organic carbon partitioning coefficient. As noted in Johnson et al. (1999), the retardation factor, which is proportional to the organic carbon content, can vary by approximately an order of magnitude for many chemicals of concern.

The calculations are performed using physical-chemical properties in Table 2 and soil properties, effective diffusion coefficient and retardation coefficient properties in Table 3. The soil properties (volumetric water content and total porosity) are based on the values provided in the US EPA Superfund Johnson and Ettinger (J&E) model spreadsheet[1], which were derived using van Genuchten model parameters for US Soil Conservation Service (SCS) soil textural types. It is important to note that the assumed soil moisture content has a more significant effect on effective diffusion coefficient depending on soil type than the chemical specific diffusion coefficient.

The modeling predicts a relatively wide range in approximate times to steady-state soil vapour concentrations (Figures 3 and 4). The soil properties chosen are considered to represent a range of properties that could be encountered at many sites. Soil properties for additional soil textural types are provided in the US EPA Superfund J&E spreadsheet. Additionally, we note that different models are available for estimation of volumetric water content and total porosity, and/or measurements can be conducted on soil samples. Where warranted, a site-specific assessment should be conducted to determine appropriate model inputs.

Table 2. Physical-Chemical Properties

Parameter	**Symbol**	**Unit**	**Value**	**Value**	**Source**
Chemical			TCE	1,3,5-TMB	
Henry's Law constant (at 25°C)	H_i'	dimensionless	0.403	0.359	USEPA J&E spreadsheet[1]
Soil organic carbon partitioning coefficient	K_{oc}	L/kg	60.7	602	USEPA J&E spreadsheet[1]
Soil sorption partitioning coefficient	K_D	L/kg	0.304	3.01	Calculated value
Molecular diffusion coefficient in air	D^{air}	m^2/d	0.594	0.520	USEPA J&E spreadsheet[1]
Molecular diffusion coefficient in water	D^{H20}	m^2/d	8.81E-05	6.77E-05	USEPA J&E spreadsheet[1]

Notes:
TCE = trichloroethylene; TMB = trimethylbenzene; K_D calculated using f_{oc} in Table 2

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[1] https://www.epa.gov/vaporintrusion/epa-spreadsheet-modeling-subsurface-vapor-intrusion

Table 3. Soil Properties, Effective Diffusion Coefficient and Retardation Coefficient

Parameter	**Symbol**	**Unit**	**Value**	**Value**	**Value**	**Value**	**Source**
Soil type			US SCS Sand	US SCS Loamy Sand	US SCS Sandy Loam	US SCS Loam	
Volumetric water content	θ_m	m^3-H20/m^3-soil	0.054	0.076	0.103	0.148	USEPA J&E spreadsheet[1]
Volumetric air content	θ_v	m^3-air/m^3-soil	0.321	0.314	0.284	0.251	Calculated value
Total porosity	θ_t	m^3-voids/m^3-soil	0.375	0.39	0.387	0.399	USEPA J&E spreadsheet[1]
Fraction organic carbon	f_{oc}	dimensionless	0.005	0.005	0.005	0.005	Site-specific value
Bulk density	ρ_b	kg-soil/L-soil	1.7	1.7	1.7	1.7	Site-specific value
Trichloroethylene							
Effective diffusion coefficient	D^{eff}	m^2/d	0.0956	0.0821	0.0597	0.0372	Calculated value
Retardation coefficient (dimensionless)	R_v	dimensionless	5.41	5.68	6.41	7.56	Calculated value
1,3,5-Trimethylbenzene							
Effective diffusion coefficient	D^{eff}	m^2/d	0.0838	0.0720	0.0523	0.0326	Calculated value
Retardation coefficient (dimensionless)	R_v	dimensionless	45.9	47.1	52.2	59.4	Calculated value

Notes:
TCE = trichloroethylene; TMB = trimethylbenzene

As noted in the description of the conceptual model, neither scenarios are ideal representation of processes and boundary conditions, and are likely conservative based on the model limitations and assumptions. The case examples provide a screening type estimate using approximate times based on Equations 4 and 6. Figures 3 and 4 can provide screening type approximation, for example, if the source is at 5 m depth in loamy-sand soil below open ground surface, τ_{ss} ~ 140 days for TCE (Figure 3 and Equation 4); and τ_{ss} ~ 1300 days for 1,3,5-TMB (Figure 4 and Equation 4). Likewise, if the source is at 5 m depth in loamy-sand soil below a building foundation, τ_{ss} ~ 540 days for TCE (Figure 3 and Equation 6); and τ_{ss} ~ 5100 days for 1,3,5-TMB (Figure 4 and Equation 6). As illustrated, much longer times to steady-state vapour concentrations are predicted for 1,3,5-trimethylbenzene compared to trichloroethylene. This is because the K_{oc} of 1,3,5-trimethylbenzene is approximately ten times greater than for trichloroethylene.

The time estimates obtained using Equations 4 and 6 apply to all measurement points away from the source (relative to the boundary). In refining the estimate and level of effort, a suggested step-wise approach is:

1) Step 1: Use of either Equation 4 or 6 depending on the most appropriate boundary type and assuming slabs and pavements are zero-gradient, although it is recognized that at many sites, there can be non-zero diffusive transport.

2) Step 2: If the time estimate using step 1 is impractically long for the site objectives, refine the time estimate by considering the relative distance (x/d). Time estimates would be lower if measurement locations are at x/d < 0.5 (i.e., relatively closer to the source than the boundary). For example, for the above case example with source at 5 m depth in loamy-sand soil below a building foundation, if the measurement is planned at 4 m depth (x/d = 0.2), an acceptable time can be assumed using T = 0.5 (Figure 2), where the concentration is within 89% of the steady state concentration and the resulting time estimates are τ_{ss} ~ 270 days and τ_{ss} ~ 2600 days for TCE and 1,3,5-TMB, respectively. The uncertainty in measurement and acceptable thresholds for field duplicates can be used as a guide for a practical measure of how close to steady state would be acceptable.

3) Step 3: Use of other analytical or numerical models and/or monitoring (see *Limitations of the Modeling* Section).

Implications of the Modeling

In agreement with the major conclusion noted in Johnson et al. (1999), the vapour measurements taken near the source (relative to the boundary) can be assumed to represent near steady state conditions and the assessment for steady state conditions is needed when sampling is planned away from the source. The conceptual models with analytical solutions and results shown in Figures 1 and 2 can be used to estimate the approximate time to near steady state conditions. An important outcome of the models presented in this appendix is that this screening type estimate is a function of the distance between the source and an applicable boundary, rather than the distance from the source to the measurement point.

Overall, there are shorter times to reach approximate steady-state vapour concentrations for smaller distances between the vapour contamination source and the applicable boundary. Equations 4 and 6 are provided as approximations for measurements taken at any distance between the source and the boundary. Where applicable to refine this estimate, the relative distance from the source (x/d) can be used with Equations 3 and 5 (or the results showns in Figures 1 and 2) to adjust the time estimate as shown for the case examples above. Consequently, a strategy to reduce the potential effect of transient vapour migration on soil vapour concentrations is to obtain soil vapour samples near to contamination sources.

Furthermore, soil vapour transport is significantly retarded for substances with higher K_{oc} values. Such sustances will essentially take longer to reach steady state vapour concentrations. If there is the added process of biodegradation, in some cases substances may not migrate very far from the source.

Limitations of the Modeling

The model described in this appendix is limited to two types of analytical solutions for diffusion and three phase-partitioning for a homogeneous, uniform porous media in one-dimension. Because of the uncertainty in model processes and geologic conditions, the modeling results are considered order of magnitude estimates. If there are biodegradation of chemicals, advection, dispersion, and lateral diffusion (which would often occur), soil vapour transport distances may be reduced and vapour plumes may come to stable configurations in shorter time periods. Site specific conditions need to be taken into account in selecting the applicable type of boundary (scenarios 1 or 2) and reasonable distance d to the boundary for the use of Equations 4 or 6, and consideration should be given to soil vapour assessment at closer distance to source.

Where warranted, analytical or numerical models may be used to conduct more in-depth analysis that incorporate additional processes and geologic complexity. Such models include HYDRUS[2] , SESOIL[3] and VapourT (Mendoza 1995).

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[2] https://www.pc-progress.com/en/Default.aspx?hydrus-3d
[3] http://www.seview.com/aboutsesoil.htm

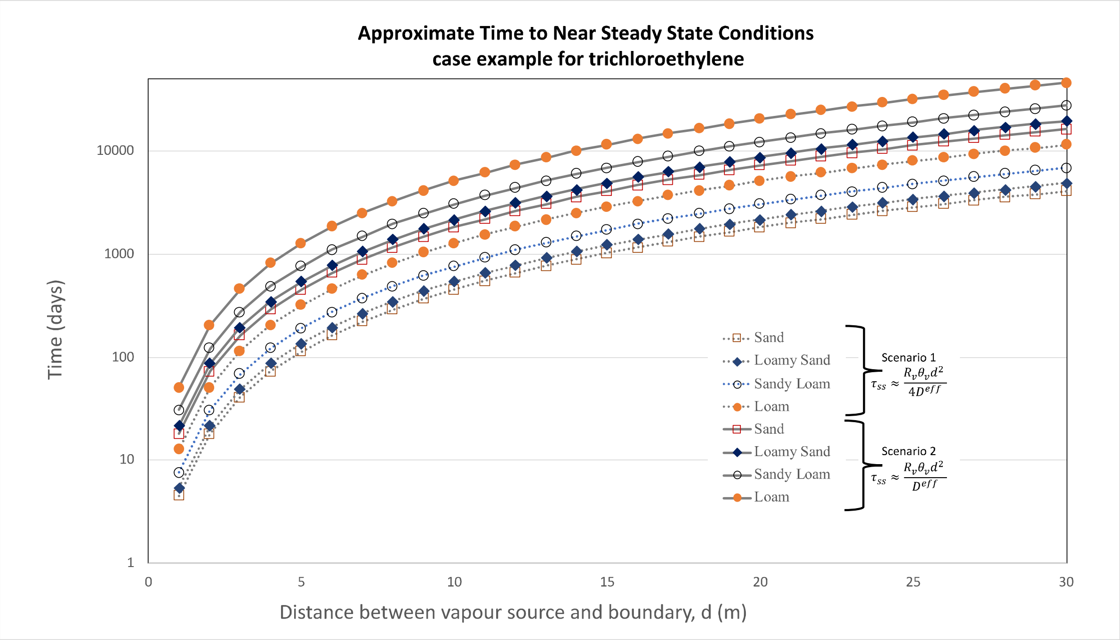

Figure 3. Time to approximate steady-state vapour concentrations as a function of distance to the applicable boundary for trichloroethylene using Equations 4 and 6 and input parameters provided in Tables 2 and 3.

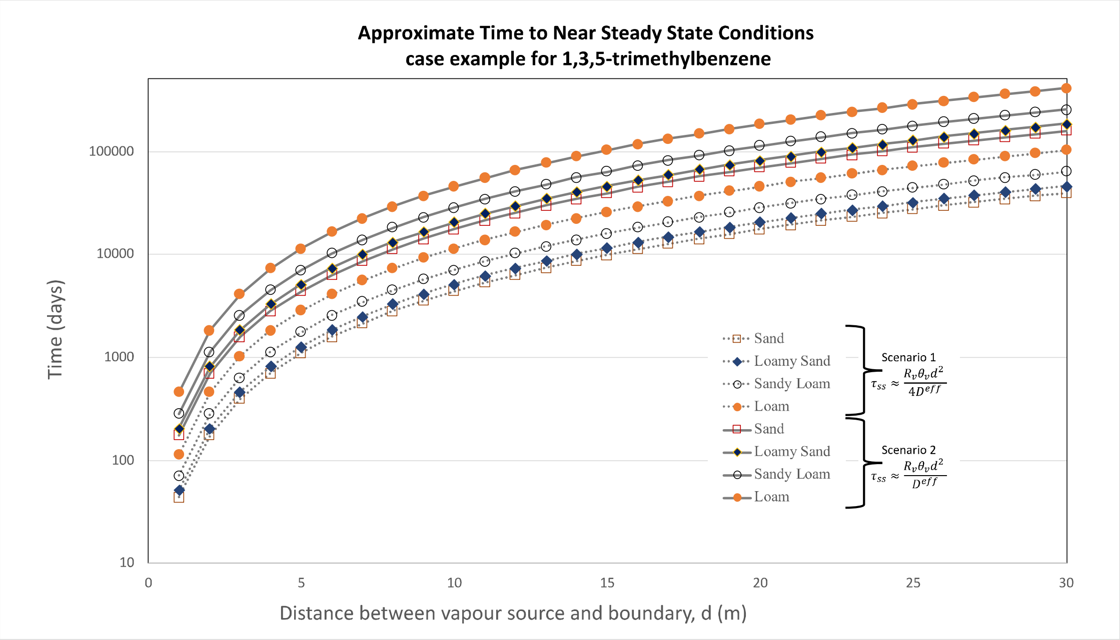

Figure 4. Time to approximate steady-state vapour concentrations as a function of distance to the applicable boundary for 1,3,5-trimethylbenzene using Equations 4 and 6 and input parameters provided in Tables 2 and 3.

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APPENDIX E

Breathing Height of Receptors for Determination of Air Sampling Height

The sampling height for indoor air and outdoor air should be representative of the most sensitive receptor. There are few guidance documents that address this issue. NJ DEP (2018) recommends that the height of the sample above the floor should correspond to the breathing zone (1.0 – 1.5 m) and located centrally in the room being investigated with consideration to the breathing zone of the most sensitive receptor. In CCME (2016), it is recommended that air samples be obtained at the breathing height; however, the height is not defined.

Measurement and modeling studies of VOCs and tracers in indoor air indicate there is attenuation of vapours and gases through chemical diffusion, and dispersion as a result of building air ventilation. While chemical concentrations may be elevated near sources, there is relatively rapid attenuation of concentrations in air with increasing distance from the source. Several studies have been performed to assess mixing of vapours from a point release inside building room air, as follows:

1) Cheng et al. (2011) report on results of a carbon monoxide (CO) tracer study where concentrations at varying distances from a source (C) were measured and divided by the CO concentration representing a well-mixed condition (Co) where additional attenuation would be negligible. The normalized concentrations (C/Co) at 0.5 m distance from the source ranged from approximately 2 to 5 for a reasonable range of air change rates. At 1 m from the source, the C/Co values were generally relatively close to 1 and less than 2 in all cases.

2) Furtaw et al. (1996) report on the results of a sulphur hexafluoride (SF_6) tracer experiment where at 0.4 m distance from the source, the C/Co (well mixed) values were as high as 2 but decreased to 1 (+/- 0.04) at 0.8 to 1.6 m distance.

3) McBride et al. (1999) report on results of SF_6 and CO tracer experiments. The experimental design was complex but generally indicated significantly higher concentrations at 0.5 m distance from the source but attenuated concentrations (relative to background) at 1 m distance.

4) Children's Health and the Environment WHO Training Package for the Health Sector World Health Organization (2008) includes consideration of chemical attenuation and breathing height https://www.who.int/ceh/capacity/Children_are_not_little_adults.pdf

The data reviewed suggest significant deviation from well-mixed vapour assumption at 0.5 m distance from a source but non-significant deviation at 1 m distance. While dimensionally the experiments were not designed to simulate soil vapour intrusion, the results are considered to approximate the migration of vapours upwards and laterally from a foundation point source and mixing in indoor air.

The most sensitive receptor for purpose of this guidance is a toddler. The standards derived under the BC Contaminated Sites Regulation (CSR) include consideration of a toddler for non-industrial land uses. Assuming a two-year old child, the breathing height of a standing toddler can be estimated from WHO statistics derived for Canadian children. Using the charts available at the links below, the median height of a 2-year old child is approximately 0.85 m. Assuming 0.05 m from the top of head to mouth, a height of 0.8 m is obtained. This is the same average breathing height (0.8 m) of toddlers reported by Zhou et al. 2017.

https://www.dietitians.ca/Downloads/Public/HFA-WFA_2-19_GIRLS_SET-2_EN.aspx

https://www.dietitians.ca/Downloads/Public/HFA-WFA_2-19_BOYS_SET-2_EN.aspx

For a toddler, there are further considerations relating to activity patterns. While a literature search did not uncover studies on such patterns, it would be reasonable to assume toddlers could spend part of their day crawling/sitting on the floor, standing, sitting in chairs, sleeping on beds of varying heights, etc. Based on best judgment, a breathing zone height of 0.5 to 0.8 m is recommended for toddlers and consequently, samples should be obtained from a height of 0.5 to 0.8 m for residential land uses. For commercial and industrial land uses, a breathing and sampling height of 1 to 1.5 m is recommended. Sampling height ranges are recommended as a single height would be overly-prescriptive and difficult to implement.

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