(DRAFT) TECHNICAL GUIDANCE FOR SOIL VAPOUR INTRUSION ASSESSMENT

Date: January 04, 2021

Ontario

Ontario Ministry of Environment, Conservation and Parks
PIBS# 8477

ACKNOWLEDGEMENTS

This guidance document was revised based on the initial draft prepared by Dr. Ian Hers, Ms. Jeanette Southwood, Mr. Michael Z’Graggen and Mr. Eric Hood of Golder Associates Ltd., under contract to the Technical Assessment and Standards Development Branch of the Ontario Ministry of Environment, Conservation and Parks (the Ministry). The initial draft of this guidance document also underwent a peer review by Dr. Todd McAlary of Geosyntec Consultants, Inc.

The Ministry also wishes to thank the vapour intrusion advisory group and all individuals who assisted in the development and review of this guidance document.

LIST OF ABBREVIATIONS AND ACRONYMS

ACH	Air change per hour
APEC	Area of potential environmental concern
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BAF	Bio-attenuation factor
BCMoECCS	British Columbia Ministry of Environment and Climate Change Strategy
Bgs	Below ground surface
BTEX	Benzene, toluene, ethylbenzene and xylenes
CCME	Canadian Council of Ministers of the Environment
CH_4	Methane
CO_2	Carbon dioxide
COPC	Chemical of potential concern
CSM	Conceptual site model
CSA	Canadian Standards Association
DCE	Dichloroethene
DNAPL	Dense non-aqueous phase liquid
ESA	Environmental site assessment
GW2	Groundwater to indoor air component value
HBIAC	Health based indoor air concentration
Hg	Mercury
HVAC	Heating, ventilation and air conditioning systems
ITRC	Interstate Technology & Regulatory Council
IAQ	Indoor air quality
I/C/C	Industrial/Commercial/Community
J&E	Johnson and Ettinger
LRL	Laboratory reporting limit
LNAPL	Light non-aqueous phase liquid
MassDEP	Massachusetts Department of Environmental Protection
MDEQ	Michigan Department of Environmental Quality.
MECP	Ontario Ministry of the Environment, Conservation and Parks
MOECC	Ontario Ministry of the Environment and Climate Change (currently known as Ministry of the Environment, Conservation and Parks)
MOE	Ontario Ministry of the Environment (currently known as Ministry of the Environment, Conservation and Parks)
MGRA	Modified Generic Risk Assessment
NAPL	Non-aqueous phase liquid
NJDEP	New Jersey Department of Environmental Protection

O_2	Oxygen
O. Reg.	Ontario Regulation
Pa	Pascal
PCE	Perchlorethylene
PHC	Petroleum hydrocarbon
PID	Photo ionization detector
ppm_v	Parts per million by volume
ppb_v	Parts per billion by volume
PVI	Petroleum vapour intrusion
QA/QC	Quality assurance/quality control
Q_{soil}	Advective soil gas flow rate into building
$Q_{building}$	Building ventilation rate
RA	Risk assessment
RPD	Relative percent difference
RMM	Risk management measure
RSC	Record of Site Condition
R/P/I	Residential/Parkland/Institutional
SABCS	Science Advisory Board for Contaminated Sites (British Columbia)
SCS	Site Condition Standards
SF6	Sulphur hexafluoride
S-IA	Soil to indoor air component value
SOP	Suggested operating procedure
SVSL	Soil vapour screening level
S-VOC	Semi-volatile organic compound
SVIMS	Soil vapour intrusion mitigation system
TCE	Trichloroethene (also referred to as trichloroethylene)
USEPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture
VOC	Volatile organic compound
VICV	Vapour intrusion component value

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CHAPTER 1 INTRODUCTION

This document provides technical recommendations in support of vapour intrusion assessment activities that are conducted at contaminated sites in Ontario or that may be required as part of a risk assessment submitted under the Ontario Regulation (O. Reg.) 153/04, made under the *Environmental Protection Act*, R.S.O. 1990, c. E.19.

1.1 Background

Vapour intrusion refers to the process by which volatile chemicals (or vapours) from a subsurface source, such as contaminated soil and groundwater, migrate into overlying buildings. Volatile chemicals may include volatile organic compounds (VOCs), selected semi-volatile organic compounds (S-VOCs), as well as some inorganic compounds (ITRC, 2007; USEPA, 2015a).

Vapour intrusion can be an important exposure pathway where people are exposed to elevated concentrations of volatile chemicals through inhalation of these chemicals in indoor air. If the vapour intrusion pathway is viable or complete, there may be the potential for safety concerns and/or adverse effects to building occupants. This guidance document is focused on evaluating the significance of vapour intrusion with respect to potential health risks associated with exposure to soil vapour. It does not address potential safety risks associated with explosion or asphyxiation risk from gases, which may arise from the accumulation of vapours in buildings or confined spaces.

This document is based on current standards of practice and is generally consistent with recent guidance from other jurisdictions. It should be noted however that the science of vapour intrusion and assessment techniques continue to evolve and it is expected that new methods will develop over time. Nothing in this document is intended to prevent the development and application of new approaches and technologies.

1.2 Objectives

This guidance document is intended to provide the reader with a basic understanding of the behaviour and migration of soil vapours in the subsurface under various site conditions and to provide a general framework for assessing and addressing vapour intrusion concerns. It is expected that this document will help both practitioners and Ministry staff assess sites where vapour intrusion may be a concern.

Some specific objectives of the guidance document are to provide:

- an overview of the site characterization and vapour intrusion assessment process (Chapter 2);
- general guidance on the conceptual site model (CSM) for vapour intrusion assessment process and an overview of the processes governing soil vapour fate and transport (Chapter 3);
- a step-wise process for evaluating vapour intrusion concerns (Chapter 4);
- guidance on the characterization of soil vapour, with emphasis on soil vapour sampling (Chapter 5);

- guidance on indoor air quality (IAQ) testing completed for the purpose of assessing vapour intrusion, with emphasis on indoor air sampling (Chapter 6); and,
- guidance on recommended minimum reporting and documentation requirements for vapour intrusion assessments (Chapter 7).

1.3 Relationship to Other Guidance Documents and Ontario Regulations

Over the past several years, there has been an increased recognition that vapour intrusion is an important exposure pathway at contaminated sites. There have also been significant advances in the understanding of vapour intrusion, and regulatory guidance has been developed by a number of agencies across North America.

This guidance document builds upon the existing guidance listed in Section 1.3.1 and, in particular, incorporates references and relevant components of Canadian Council of Ministers of the Environment (e.g., CCME, 2016a). Where warranted, modifications have been made to reflect the regulations and policies of the Ministry and the conditions in Ontario.

This guidance document reflects the current state of knowledge on vapour intrusion. Since vapour intrusion is a developing field of science, it is anticipated that the Ministry will update this document (or provide additional guidance) as needed to reflect refinements and advances in the scientific understanding of vapour intrusion.

1.3.1 Existing Vapour Intrusion Guidance

A number of agencies in Canada and the United States have published guidance on evaluating vapour intrusion at sites contaminated with volatile chemicals. However, the reader should check for updates of any guidance referenced in this document, as well as any other relevant guidance published by other agencies, as appropriate.

Some of the guidance materials available at the time of developing this guidance document are:

- Atlantic Risk-Based Corrective Action (Atlantic RBCA), 2016 (updated 2019). *Risk-Based Corrective Action) Version 3.0; For Impacted Sites in Atlantic Canada - Guidance for Vapour Intrusion Assessments*;
- Canadian Council of Ministers of the Environment (CCME), 2016a. *Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment - Volume 1 Guidance Manual*;
- Interstate Technology & Regulatory Council (ITRC), 2007. *Technical and Regulatory Guidance: Vapour intrusion Pathway: A Practical Guideline*;
- Massachusetts Department of Environmental Protection (MassDEP), 2016. *Vapour Intrusion Guidance: Site Assessment, Mitigation and Closure*;
- Michigan Department of Environmental Quality (MDEQ), 2013. *Guidance Document for the Vapour Intrusion Pathway*;

- New Jersey Department of Environmental Protection (NJDEP), 2018. *Vapor Intrusion Technical Guidance* - Version 4.1;
- United States Environmental Protection Agency (USEPA), 2015a. *Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air*;
- USEPA, 2008. Engineering Issue - *Indoor Air Vapor Intrusion Mitigation Approaches*; and,
- Science Advisory Board for Contaminated Sites in British Columbia (SABCS), 2011. *Guidance on Site Characterization for Evaluation of Soil Vapour Intrusion into Buildings*.

Available guidance materials specific to Petroleum Vapour Intrusion (PVI) include:

- ITRC, 2014. *Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management*;
- USEPA, 2015b*. Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank*; and,
- USEPA, 2013. *Evaluation of Empirical Data to Support Soil Vapour Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds*.

1.3.2 Ontario Regulation 153/04

The soil vapour screening and assessment process outlined in this guidance document can assist in cases where an environmental site assessment (ESA) and/or a risk assessment (RA) is conducted for the purpose of submitting a Record of Site Condition (RSC) for filing in the Environmental Site Registry under O. Reg. 153/04. However, this document alone does not necessarily provide all the information and evaluation required under O. Reg. 153/04 (URL: https://www.ontario.ca/laws/regulation/040153).

Any RA and/or RSC prepared and submitted under O. Reg. 153/04 that includes an assessment of vapour intrusion must meet all the mandatory requirements specified *Environmental Protection Act* and O. Reg. 153/04. Additional information can be found in the brownfields redevelopment website (URL: https://www.ontario.ca/page/brownfields-redevelopment).

CHAPTER 2 OVERVIEW OF THE VAPOUR INTRUSION ASSESSMENT PROCESS

This section provides an overview of the recommended vapour intrusion assessment process, key considerations when implementing this process (e.g., consideration of multiple lines of evidence), as well as a brief discussion on possible approaches when communicating with various stakeholders.

2.1 Vapour Intrusion Assessment Framework

A three-step assessment approach is recommended to assess the vapour intrusion pathway, with increasing levels of complexity, information and data requirements as one progresses through the step-wise process (as illustrated in Figure 2.1). The following sections provide an overview of each step of the assessment process. Additional details and guidance for the completion of each step are provided in Chapter 4.

2.1.1 Development of the Conceptual Site Model

A robust CSM should be developed to facilitate an understanding of site conditions and to support the planning and completion of supplementary site investigations and assessments, as required. The CSM integrates available information relevant to the site conditions that may potentially affect the vapour intrusion pathway (refer to Chapter 3 for further details on CSM development along with a description of processes governing the fate and transport of volatile chemicals).

The CSM typically includes both a descriptive and diagrammatic presentation of chemical sources, release and transport mechanisms, exposure media, exposure pathways and receptors. It is important that the CSM continues to be updated as new information and data become available during each step of the investigation.

2.1.2 Overview of Preliminary Vapour Intrusion Assessment (Step 1)

The preliminary assessment is a qualitative screening step that uses relatively simple criteria to categorize sites according to their potential for adverse effects associated with vapour intrusion. This step can be also used to identify sites that require immediate mitigative action to protect the health and safety of building occupants, as well as candidate sites for further vapour intrusion assessments.

The preliminary assessment often starts with an evaluation as to whether the site represents an immediate concern for safety and/or adverse effects, followed by a determination as to whether any subsurface source of volatile chemicals is present and close enough to a building to be of potential concern for vapour intrusion. This process also involves a comparison of measured soil and groundwater concentrations to generic site condition standards (SCSs, as prescribed by O. Reg. 153/04) and/or corresponding vapour intrusion component values (VICVs). Such VICVs include the soil to indoor air (S-IA) component values and groundwater to indoor air (GW2) component values (refer to Section 4.1.2 for further information).

If the preliminary assessment indicates the potential for adverse effects associated with vapour intrusion, a subsequent assessment (e.g., Step 2: screening level assessment) would typically be considered. Additional discussions and guidance with respect to the preliminary assessment process is provided in Section 4.2.

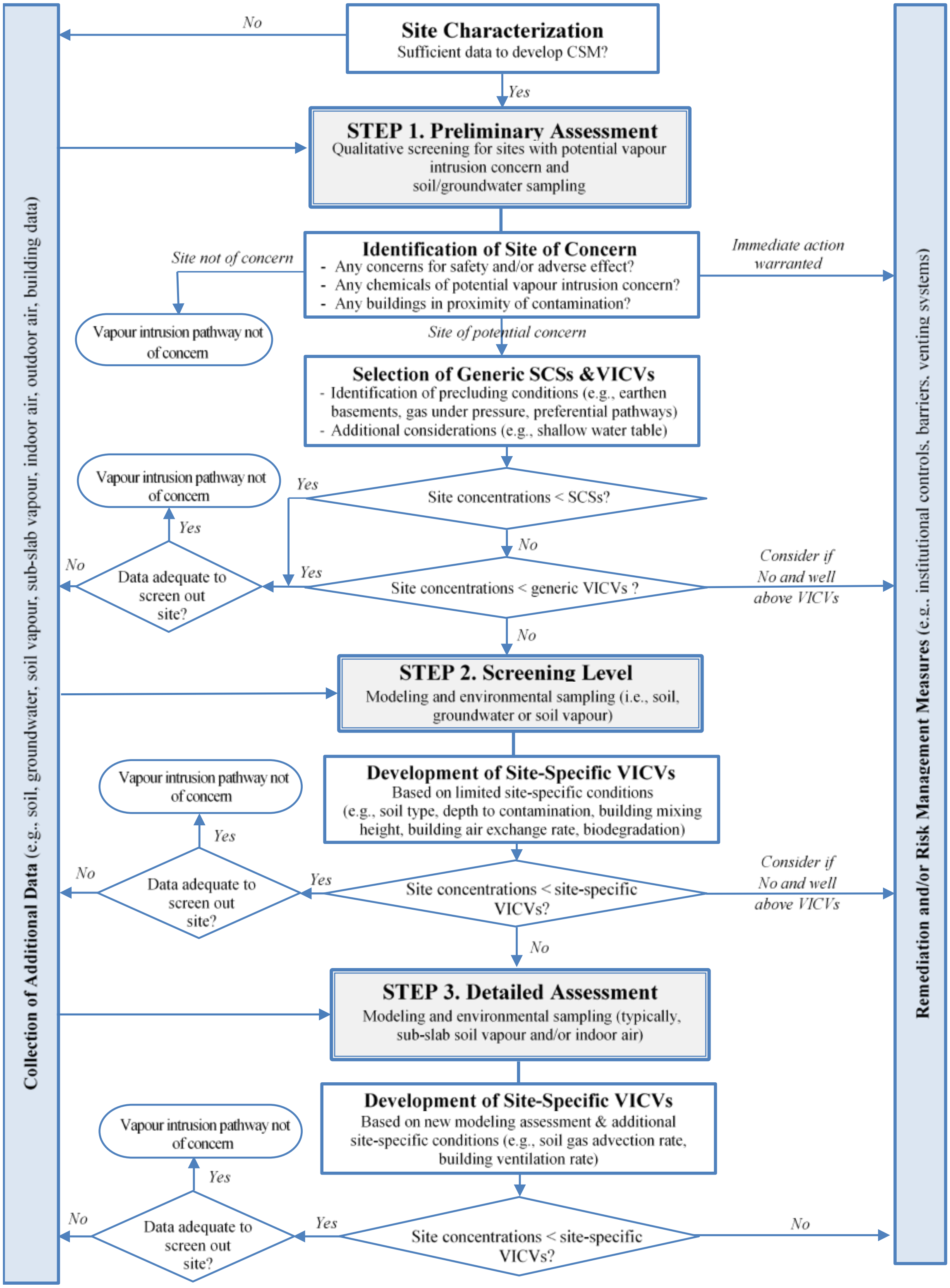

Figure 2.1. Flowchart for Vapour Intrusion Assessment

2.1.3 Overview of Screening Level Vapour Intrusion Assessment (Step 2)

Screening level assessments typically rely on limited site-specific data, relatively simple predictive models or empirical factors, and conservative assumptions. In many cases, the assumptions and models employed are similar to those employed in the derivation of generic soil and groundwater SCSs, with minor modifications made where appropriate. For instance, the model developed by Johnson and Ettinger (1991), referred to herein as "J&E model", is often used to derive both generic and site-specific VICVs. Site screening for vapour intrusion can be performed by comparing measured concentrations of chemicals in soil, groundwater, and/or soil vapour to the derived VICVs.

This guidance document provides an approach and recommended input parameters for a screening level assessment using the J&E model. Given that available data are often limited at the screening level stage, the purpose of this assessment is to produce VICVs that are based on the modification of only certain input parameters and only within specified ranges.

A screening level assessment can be completed using the Ministry's Approved Model, which is used to develop property specific standards as part of a Modified Generic Risk Assessment (MGRA) to support filing an RSC under O. Reg. 153/04. The Approved Model is a spreadsheet-based model that utilizes the J&E model to generate different VICVs (MOECC, 2016a, 2016b). Further information on the use of this model for assessing the vapour intrusion pathway is provided in Section 4.1.3.

If the results of a screening level assessment conclude that derived VICVs are exceeded for any volatile chemical, then a detailed vapour intrusion assessment would typically be required. Additional discussion and guidance regarding the screening level assessment process is provided in Section 4.3.

2.1.4 Overview of Detailed Vapour Intrusion Assessment (Step 3)

A detailed vapour intrusion assessment includes all key components of the screening level assessment, but generally incorporates more detailed site-specific data. This may include additional soil and groundwater data, soil vapour data (including sub-slab data), and indoor air data, as well as data that are related to the effects of biodegradation. Multiple monitoring events are also typically recommended, to better assess the spatial and temporal variability of soil vapour concentrations at a site.

As with the screening level assessment, contaminant fate and transport modeling remain an important part of the detailed vapour intrusion assessment. The additional site-specific information collected as part of the detailed vapour intrusion assessment often allows for the use of more complex models and/or the selection of more model inputs. Such models may better reflect actual site conditions, as compared to screening level assessment models.

The detailed assessment may also include the derivation of toxicity reference values for chemicals lacking published values, or where new toxicity data are available. Additional discussions and guidance with respect to the detailed assessment process is provided in Section 4.4.

2.2 Guidance Application and Implementation Process

The vapour intrusion assessment approach described in this guidance document applies to contaminated sites where subsurface contamination includes volatile chemicals. However, it does not apply to landfills, where the generation of gases through the anaerobic decomposition of organic materials may lead to significant pressure-driven gas flow.

Although this guidance is structured to reflect a sequential phased approach, starting with screening of sites through the use of subsurface data, it does not preclude either an iterative (i.e., non-sequential) approach or a top-down approach:

- An iterative approach may be warranted where additional testing of subsurface concentrations is conducted as follow-up to indoor air testing to assess whether the vapour intrusion pathway is of concern. When IAQ results are borderline or inconclusive, it may be appropriate to rely on a combination of measurements from different media to decide on appropriate responses to protect human health (ITRC, 2007).
- A top-down approach typically involves more immediate efforts to address potential vapour intrusion impacts. Such efforts may include testing of indoor air (and other media) early in the assessment process and/or proactively implementing risk management measures (RMMs). Such an approach may be appropriate in some instances.

The approach to assessing vapour intrusion may also depend on the exposure scenarios. For a scenario where contamination is below existing occupied buildings and where exposures are potentially current and on-going, there will often be a focus on near-building soil vapour and indoor air characterization. For a scenario where there is no existing building, potential future exposures are predicted based on subsurface concentrations measured close to contamination sources. This guidance applies to both scenarios, although different approaches may be warranted.

It is important to recognize that vapour intrusion is a complex pathway that may be driven by different site factors and conditions. As such, the following should be taken into consideration when assessing the vapour intrusion pathway using the approach described in this guidance:

- A robust CSM is crucial to determine whether a site should be screened in or out during the assessment process and it should be updated as new information and data become available during each step of the investigation.
- Data and information used for the assessment should undergo detailed quality assurance and quality control (QA/QC) in order to ensure that the data collected are representative of site conditions. Some key considerations associated with the use of soil and groundwater data for assessment of the vapour intrusion pathway are provided in Section 4.3.1.
- A comprehensive evaluation of the vapour intrusion pathway that considers multiple lines of evidence is recommended before drawing conclusions on risks posed by this pathway. The lines of evidence include concentrations in different environmental

media and locations along the anticipated migration pathway, as well as information on site conditions and factors that could influence vapour migration (refer to Section 4.5 for further information).

- In cases when the site undergoes changes after the assessment is conducted and there is a potential that these changes may have altered the vapour intrusion pathway (e.g., change in land uses, new construction, new utility lines, etc.), additional monitoring of site conditions may be warranted to assess whether conditions assumed at the time of the assessment will continue to apply.

2.3 Vapour Intrusion Mitigation

RMMs should be implemented in instances where site characterization information, such as IAQ data, indicates that actions should be taken to address elevated levels of volatile chemicals entering buildings through vapour intrusion. RMMs typically involve efforts to prevent or mitigate the effects of vapour intrusion on building occupants. Additional information on RMMs is provided in Section 4.6.

2.4 Community Outreach

Depending on the circumstances, community outreach may be an important component of a soil vapour assessment program. Where community outreach is warranted, provincial and local regulatory agencies will, to varying degrees, be involved in the process. At the regional or local level, this may include Health Units and/or municipal officials.

Although each site will tend to have its own unique set of circumstances, there are several good practices that should generally be followed during community outreach efforts:

- notify potentially affected parties, including residents and business owners, early in the assessment process;
- ensure communication lines with potentially affected parties remain open throughout the duration of the assessment; and,
- ensure all communications are clear, comprehensible, appropriate in tone and as consistent as practicable.

Given that vapour intrusion relates to potential impacts to human health, potentially affected parties may find the process stressful. Additionally, potentially affected parties may be inconvenienced by measures undertaken to address vapour intrusion concerns (e.g., indoor air sampling in their home) and may resist samples even being collected. Efforts should be made to ensure that all communications are honest, respectful and delivered with tact.

A strong communications program is essential to educate and reassure the local community in a meaningful and sensitive manner, and to build trust with potentially affected parties. It is often helpful to communicate the potential risks from vapour intrusion in the context of risks from other chemicals, such as those commonly associated with background sources in indoor air.

Several successful community outreach programs have involved creating and maintaining ongoing lines of communication by contacting residents door-to-door to discuss the program directly, when requesting access and/or providing information packets. Other communication tools include community meetings, articles published in community newsletters, project newsletters mailed to residents and project websites to disseminate relevant information.

CHAPTER 3 CONCEPTUAL SITE MODEL

This section begins by describing the elements of a CSM and outlining the information required for the development of a CSM. This is followed by an overview of the processes and factors influencing vapour intrusion into buildings. Further guidance on CSM development, including fate and transport processes, is provided in Section 4.5 of the CCME (2016a) guidance manual.

For petroleum hydrocarbons (PHCs), aerobic biodegradation is a key attenuation mechanism that can result in a substantial reduction of the PHC vapour concentration over a relatively short distance in the vadose zone. A detailed CSM for PVI is provided in the ITRC (2014) and USEPA (2013) technical documents. An overview of this process is provided in Appendix I.

3.1 What is a Conceptual Site Model?

A CSM is a visual representation and narrative description of the physical, chemical, and biological processes occurring, or that have occurred, at a contaminated site. The CSM will convey how the site became contaminated, how the contamination was and is currently being migrated in the subsurface, where the contamination will ultimately end up, and whom it may affect (CCME, 2016a). To the extent possible, the CSM should provide information on the three-dimensional nature of contamination and physical characteristics of the site, as supported by maps, cross-sections and site diagrams.

A well-developed CSM provides decision makers with an effective tool that helps to organize, visualize, communicate and interpret existing data, while also identifying areas where additional data are required. The CSM should be considered dynamic in nature and should be continuously updated as each stage of the investigation program is completed (US EPA, 2015a).

3.2 Information Needed to Build a Conceptual Site Model

A CSM used for evaluating the risks associated with soil vapour at a contaminated site should provide a summary of the following:

- the source and distribution of contamination (history of contamination, present conditions, and potential future conditions);
- the receptors (i.e. building occupants) that could be exposed to the contamination (under both present and future land use scenarios);
- the partitioning or release mechanisms for chemicals to soil or groundwater; and,
- the fate and transport pathways between the vapour source (i.e., contaminated groundwater and/or soil, and presence of non-aqueous phase liquid [NAPL]) and the receptors (under both present and future land use scenarios).

The CSM should also provide all relevant data from the site, including the following:

- information on historical and current land uses, potential sources and types of volatile contamination, and known and suspected releases or spills that may have occurred at or near the site;
- concentrations, distribution and extent of a chemical of potential concern (COPC) in different media (soil, groundwater, soil vapour and indoor air);
- form of contamination present (dissolved chemicals in groundwater, part of the soil matrix and/or as NAPL);
- approximate distances from the soil vapour sources to buildings (vertical and lateral);
- hydrogeological information including depth to groundwater, seasonal variations in water table, groundwater flow direction, hydraulic conductivity, lateral and vertical hydraulic gradients;
- geological information including soil units present at the site, textural classification for each soil unit, and zones of unusually high or low permeability;
- vadose zone soil properties including water content, porosity, fraction of organic carbon, bulk density and soil-air permeability;
- location and characteristics of subsurface utilities (which may act as preferential pathways of exposure) including connections to buildings and their proximity to contamination sources;
- climatic conditions, including factors that could influence seasonal differences in vapour intrusion potential such as temperature, snow cover and frost;
- weather conditions during field investigation and sampling programs;
- information on buildings (present and future) including location, type of building (e.g., residential or commercial or mixed use, number of units); building size and height; foundation type (e.g., crawlspace, basement, slab-on-grade); foundation details (e.g., construction type, condition/cracks, utility penetrations, sumps); properties of sub-grade soils, and heating, ventilation and air conditioning (HVAC) system; and,
- information on background sources of volatile chemicals in indoor air, including indoor sources, outdoor sources, building materials and consumer products.

It is recognized that not all of the above information may be required to complete a vapour intrusion assessment under this guidance.

3.3 Fate and Transport Processes for Vapour Intrusion

The fate and transport of a chemical from a subsurface source to its ultimate concentration inside a building are controlled by various processes. These processes are typically categorized into one of four conceptual “compartments”:

- chemical transfer to the vapour phase (e.g., source partitioning) in the vadose zone;
- fate and transport of soil vapour in the vadose zone;
- soil vapour intrusion into the building envelope; and,

- mixing of vapours within the building.

3.3.1 Chemical Transfer to Vapour Phase

Volatile chemicals may be present in one or several media and phases (e.g., dissolved chemicals in groundwater, part of the soil matrix and/or as NAPL). Chemical transfer to the vapour phase may occur through partitioning of NAPL present above the water table into soil vapour (vapourization) or partitioning of dissolved chemicals in soil-water above the water table into soil vapour (volatilization). NAPL is often referred to as a primary source of vapours while the dissolved phase plume and soil contamination are referred to as a secondary source.

The distribution of NAPL relative to the water table will have a large influence on its potential to vapourize and migrate into indoor air. As discussed below, if NAPL is present below the water table, then volatilization will be relatively limited since mass transport through groundwater is relatively slow due to the low diffusion rate of chemicals in water. In addition, vertical dispersion of chemicals tends to be relatively limited in groundwater flow systems. Note that NAPL may also contribute to dissolved phase concentrations in groundwater.

For chemicals present only as a dissolved phase in groundwater, the distribution of the chemicals below the water table will determine their potential to volatilize and eventually migrate to indoor air. If volatile chemicals are present near the surface of the water table, volatilization into the soil may readily occur. In contrast, if there is a layer of uncontaminated or “clean” groundwater above contaminated water (e.g., a clean water lens), then the rate of volatilization will tend to be less, as the mass transport of chemicals is controlled by diffusion and dispersion between the contaminated and uncontaminated groundwater. That said, the formation of a clean water lens is affected by several factors including recharge rate, vertical gradients and evapotranspiration. The mass transfer from groundwater to soil vapour is potentially increased through water table fluctuations, either seasonal or tidally-induced.

Where soil contamination is the potential source of vapours, chemicals sorbed to soil particles will partition into porewater and soil vapour present within the vadose zone. The distribution of the chemicals between these different phases (sorbed, aqueous, and vapour phases) can be predicted using a three-phase partitioning model. However, given the variability in partitioning relationships, the characterization of soil vapour is generally recommended as part of a vapour intrusion assessment, particularly when soil data exceed applicable VICVs.

3.3.2 Fate and Transport in the Vadose Zone

The fate and transport of soil vapour in the vadose zone is controlled by the following key mechanisms:

- diffusion;
- advection; and,
- biological and chemical transformations.

Note that unless there is a constant replenishment of the chemical source, the processes will not reach an equilibrium state (i.e., concentrations of chemicals will remain dynamic and transient over time and space), as the source material will be depleted through biodegradation, volatilization and dissolution (e.g., through the infiltration of surface water).

While partitioning plays an important role in chemicals transferring to the vapour phase (refer to Section 3.3.1 above for additional details), it continues to affect chemicals as they migrate through the vadose zone. Chemicals will continue to transition between various phases and states (i.e., dissolved in water, sorbed to soil, or volatilized in air as soil vapour) in the vadose zone, with significant implications regarding the fate and transport of the chemicals, as discussed below.

3.3.2.1 Chemical Diffusion in the Vadose Zone

Diffusion is the movement of molecules from an area of higher concentration to an area of lower concentration, as influenced by their kinetic energy. The rate of diffusive transport is largely a function of the concentration gradient, the nature of the medium through which the diffusion is occurring, and the temperature of that medium.

Diffusion coefficients in air are about four orders of magnitude higher than in water; therefore, diffusive flux is much higher through the air-filled soil pores than water-filled soil pores. Consequently, the total porosity and the nature of that porosity (e.g., water-filled versus air-filled, connectivity of pores, etc.) have a significant influence on the diffusive flux. Fine-grained soil layers with high soil moisture content can act as a “barrier” to significant soil vapour transport.

3.3.2.2 Chemical Advection in the Vadose Zone

Advection is the movement of chemicals as a result of the flow of a fluid through an environmental medium (e.g., water or air). Driving forces for gas-phase advection are:

- pressure gradients due to barometric pressure variation;
- groundwater movement; and,
- density gradients due to composition and temperature variation.

At most contaminated sites, gas-phase diffusion tends to be a more important process for soil vapour transport than gas-phase advection; although gas-phase advection may become the dominant transport mechanism under certain conditions. Such conditions include areas of under-pressurization (typically in the shallow vadose zone close to a building), and areas within the vadose zone of very high permeability (e.g., gravel and cobbles).

3.3.2.3 Biological and Chemical Transformation

Biological and chemical transformations may represent important processes in the vadose zone (as well as within building envelopes) for certain chemicals. Of particular note, both aerobic and anaerobic biodegradation can have significant impacts on the fate of certain chemicals (notably PHCs and other organic compounds):

- Aerobic biodegradation of certain organic compounds (e.g., PHCs) typically involves the mineralization of the compounds (i.e., transformation into carbon dioxide, water, and other non-toxic compounds), although incomplete transformations to generally less toxic compounds may also occur. Recent empirical and modeling studies show that PHC compounds can undergo substantial bio-attenuation over a relatively short distance under suitable environmental conditions. Additional discussions with respect to PHC biodegradation and investigative approaches to evaluate the potential vapour intrusion risk associated with PHC vapours are provided in Section 4.4.2 and Appendix I.
- Anaerobic degradation of organic compounds typically leads to the production of smaller organic compounds (in relation to the “parent” compound) and/or biogenic gases. In some cases, these “daughter” compounds may be more toxic that the “parent” (e.g., vinyl chloride being produced through anaerobic degradation of tetrachloroethylene (PCE)). Biogenic gases, such as methane (CH_4) and carbon dioxide (CO_2) are generated through fermentation and methanogenic reactions of biogenic waste, landfilled materials, and in some naturally occurring high organic-carbon soils. These anaerobic degradation processes may be important with respect to potential safety concerns associated with biogenic gases (e.g., asphyxiation and/or explosions), but may also affect the fate and transport of volatile chemicals for vapour intrusion, particularly in saturated settings where anaerobic biodegradation of organic matter may lead to degassing (bubbling) and ebullition (gas transport). While anaerobic biodegradation is common in saturated settings (i.e., below the water table), it tends to be much less common in the vadose zone, where soil air tends to have adequate levels of oxygen (O_2) to support aerobic biodegradation and preclude anaerobic biodegradation. However, note that, anaerobic biodegradation can still occur in the vadose zone, when O_2 is depleted (e.g., due to the presence of high levels of organic compounds in soil).

3.3.3 Soil Vapour Intrusion through the Building Envelope

When buildings are depressurized relative to subsurface soil, the primary process for soil vapour intrusion is typically soil gas advection through openings in the building envelope. Such openings may include un-trapped drains, sewers, perimeter cracks at the building wall and floor slab interface, utility service penetrations, expansion joints, and shrinkage cracks. In a few cases, building features such as elevator pits and wall cavities have been documented as important pathways for vapour intrusion. Recent research has indicated the importance of sewers as pathways for vapour intrusion into residential dwellings. Diffusion may also occur through openings and cracks in the building envelope and may be influenced by the properties of dust-filled cracks, the type of concrete construction (i.e., poured concrete or concrete block), and subsurface moisture vapour barrier, if present.

The main driving forces for soil gas advection tend to be building depressurization and barometric pressure fluctuations. The primary mechanisms for building depressurization are:

- stack effect (sometimes called the chimney effect), where the less-dense warm air rises in buildings, thereby drawing both ambient air and soil vapour into the lower part of the building;
- wind effect, where the force of wind on buildings creates non-uniform pressure distributions, potentially causing increased intrusion of soil vapour in some parts of a building;
- mechanical exhaust systems (e.g., mechanical equipment that brings in less outdoor air than is removed, resulting in negative indoor pressure); and,
- indoor combustion.

The relative effects of these depressurization mechanisms are heavily influenced by the nature of the affected building, including its size, design (including preferential pathways), construction and current condition, as well as usage. The overall effect (i.e., rate of soil vapour intrusion) is largely a function of the extent of depressurization as well as site-specific conditions such as soil permeability, foundation backfill properties, potential preferential pathways (e.g., sewers and utility tunnels), and building foundation construction. Additional details on the influence of key building characteristics and climatic conditions are provided in Sections 6.2.2 to 6.2.4.

3.3.4 Mixing of Vapours inside the Building

Vapours inside enclosed spaces will diffuse as a result of chemical concentration gradients and disperse through air movement as a result of building ventilation. Mixing between building floors will depend on the building type (e.g., residential versus commercial), HVAC system operation and air leakage between floors. Most models used for screening level assessment assume uniform and instantaneous mixing of vapours within the enclosed space. Additional information on mixing of vapours inside the building is provided in Section 6.2.5.

CHAPTER 4 VAPOUR INTRUSION ASSESSMENT PROCESS

This chapter addresses approaches and methods for the evaluation of the significance of the vapour intrusion pathway and describes the step-wise framework for vapour intrusion assessment.

4.1 Introduction

The step-wise framework for vapour intrusion assessment was presented in Chapter 2 and consists of the following steps:

- Step 1: preliminary assessment;
- Step 2: screening level assessment; and,
- Step 3: detailed assessment.

The above process is consistent with recent developments in science and regulatory policy for vapour intrusion assessments (e.g., ITRC, 2007; MDEQ, 2013; MassDEP, 2016; NJDEP, 2018; SABCS, 2011; USEPA, 2015a). The assessment process was previously summarized in the flowchart shown in Figure 2.1.

The vapour intrusion assessment process should begin with gathering all readily available site data and developing an initial CSM. As the site characterization process is often completed in phases, it is essential that the CSM be updated as new information is obtained. Also, the assessment process often involves comparing site-specific data to applicable VICVs for the respective medium (i.e., soil, groundwater, soil vapour and/or indoor air). Further discussion on the adequacy of data used in the assessment and the selection of appropriate VICVs is provided in Sections 4.1.1 and 4.1.2. A short guide to using the Ministry's Approved Model as part of a MGRA under O. Reg. 153/04 to support the vapour intrusion assessment is also provided below in Section 4.1.3.

As noted in Section 2.2, while the assessment process is described in this chapter as a progression of steps, which start with the collection of site information and subsurface data, this guidance does not preclude concurrent implementation of the steps, which may be more appropriate for some sites. For example, the decision of when to sample indoor air in addition to the subsurface media should be made with consideration to the relative urgency of obtaining the results needed to support decision making for a given site. There may be some situations (for example where initial indoor air testing indicates potential vapour intrusion impacts) where further indoor air sampling should be conducted concurrently with subsurface sampling, in order to provide a more refined estimate of exposure to support decision making in the short term. It is important to highlight that vapour intrusion investigations may follow an iterative approach rather than simply proceeding through sequential, independent steps.

4.1.1 Data Reliability and Usability for Vapour Intrusion Assessment

Data used for each assessment step should undergo a detailed QA/QC procedure in order to ensure that the collected data are representative of site conditions. It is generally recommended that historical data be reviewed to confirm whether those data are suitable and reliable to use in the vapour intrusion assessment. The following, at a minimum, should be evaluated when reviewing historical data:

- Are site data (e.g., groundwater and soil vapour measurements) adequate to capture both spatial and temporal variability? This is needed in order to determine a reasonable maximum and typical concentration of a COPC in the subsurface.
- Do site data meet the minimum data quality objectives established for the site? A key objective of vapour intrusion assessment is to select reliable sampling and analysis methods with appropriate laboratory reporting limits (LRLs). As discussed in Section 4.3.1, there are some challenges in bulk soil sampling and analysis (e.g., the potential for VOCs loss during soil sampling). Care should be exercised during sample collection and/or alternative approaches should be used to minimize the impacts associated with those methods (e.g., using an air-tight coring device/container).

4.1.2 Vapour Intrusion Component Values

As discussed earlier, assessing the vapor intrusion pathway often involves site characterization and comparison of subsurface or indoor air data against applicable risk-based concentrations that are protective of vapour movement of a chemical from a subsurface source to indoor air and human exposure (collectively referred to as vapour intrusion component values or VICVs). VICVs incorporate health based indoor air concentrations (HBIACs), which are used to evaluate the potential risk to human health from concentrations of a chemical in indoor air (refer to Section 6.5.4 for further details regarding HBIACs). The HBIACs can be used in conjunction with appropriate vapour attenuation factors and partitioning components to calculate the following VICVs:

- S-IA component values: soil concentrations that are protective of vapour movement of a chemical from soil to indoor air and human exposure.
- GW2 component values: groundwater concentrations that are protective of vapour movement of a chemical from groundwater to indoor air and human exposure.
- Soil vapour screening levels (SVSLs): soil vapour concentrations that are protective of vapour movement of a chemical from subsurface vapour to indoor air and human exposure.

Measured soil and groundwater concentrations can be compared to generic SCSs and/or S-IA and GW2 component values developed by the Ministry as part of a preliminary assessment step (see Section 4.2.5). Where available, site-specific data (e.g., soil properties) should be utilized in the development of VICVs to account for conditions that are more representative for a given site (refer to Section 4.3 and Section 4.4 for further information).

The presence of odours may also pose a potential issue to building occupants and therefore should be addressed as part of the vapour intrusion assessment. Odour based component values can be calculated using odour threshold values, as described in Section 6.2 of the MOE (2011a) rationale document.

4.1.3 Approved Model

The Ministry developed an Excel-based model spreadsheet as part of the MGRA under O. Reg. 153/04 which is referred to as the “Approved Model”. The Approved Model allows the user to incorporate a limited number of site-specific conditions (e.g., soil properties, depth to groundwater, etc.) to generate property specific soil and groundwater standards, including site-specific S-IA and GW2 component values, that can be used for assessing the vapour intrusion pathway.

The Approved Model is also a useful tool for the assessment of soil vapour and indoor air data. For instance, built into the Approved Model is the SVSL tool, where based on the site-specific information provided, corresponding SVSLs for volatile chemicals are calculated and can be used as part of a risk assessment or vapour intrusion assessment program. Another useful feature of the Approved Model is that it contains the HBIACs, which can be found on the “Human Health” worksheet (columns V and AB) of the model.

Instructions on how to use the Approved Model are provided in the MOECC (2016b) *A Guide to Using the “Approved Model” When Submitting a Modified Generic Risk Assessment (MGRA).* Both the MOECC (2016a) Approved Model and the MOECC (2016b) guidance document are available on the brownfields redevelopment website (URL: https://www.ontario.ca/page/brownfields-redevelopment). Note that the Approved Model may be updated by the Ministry from time to time to reflect advances in science.

4.2 Preliminary Vapour Intrusion Assessment (Step 1)

The preliminary assessment step involves a qualitative screening of the site to evaluate the potential for vapour intrusion and to identify site conditions that may warrant immediate assessment and possible mitigation measures. Preliminary assessment can be completed at an early stage of the site assessment program, but requires some site-specific data, as described in Section 4.2.1.

Key qualitative components for the preliminary assessment include the following:

- evaluation of whether the site represents immediate concerns for safety and/or adverse effects, such as explosive gases or conditions that would represent an asphyxiation risk;
- determination of whether any chemicals present at the site are of potential concern for vapour intrusion (e.g., through consideration of chemical volatility and toxicity); and,
- evaluation of whether buildings are located in sufficiently close proximity to the contamination to be of potential concern.

This screening process should also include a comparison of measured soil and groundwater concentrations to the applicable SCSs and/or corresponding VICVs (S-IA and GW2), where applicable.

Although the steps are presented below as a progression, they should be conducted concurrently in an integrated manner. Relevant aspects of the assessment should be updated when new information is obtained.

4.2.1 Site Investigation

A preliminary assessment requires certain site-specific data to develop an initial understanding of the potential risk posed by vapour intrusion at a site. Depending on the nature and reliability of available data, it is possible to determine whether the vapour intrusion pathway is of concern and/or whether further site investigation is warranted at early stages of the site investigation program.

The initial site investigation (i.e., as part of a Phase One ESA) is a key component of characterizing a site and it is recommended that basic site information in support of preliminary vapour intrusion assessment efforts be obtained at this stage. For example, site reconnaissance and a review of historical site information can provide some relevant information with respect to:

- Potentially Contaminating Activities;
- Areas of Potential Environmental Concern (APECs);
- volatile chemicals that may have been used or disposed of at the site;
- odour complaints and/or adverse physiological effects reported by building occupants; and,
- basic information on the existing and future use of buildings, land use designation, and historical releases/spills at the site.

If the evaluation of available information indicates that volatile chemicals are potentially present in soil and/or groundwater in the subsurface underlying or in close proximity to buildings, additional investigation (i.e., as part of a Phase Two ESA) should be completed. This may include characterization of the following:

- lateral and vertical extent of one or more volatile chemicals in soil and/or groundwater;
- hydrogeological conditions;
- soil properties; and,
- consideration of possible preferential pathways.

Such efforts are necessary to identify the extent of current contamination, as well as the potential for future migration and/or transformation of contaminants. This information can then be used to evaluate the distance criteria described in Section 4.2.4.

For preliminary assessments, maximum concentrations in soil and groundwater are generally used to determine whether further assessment is required. Therefore, it is important that the contamination source areas be properly assessed to identify maximum concentrations.

Once the source has been adequately assessed, the next key step generally involves the delineation of the extent of the plume. Delineation should be conducted assuming that the lateral and vertical extent of a volatile chemical in soil or groundwater extends from the sampling locations where volatile chemicals are present at concentrations equal to or greater than the applicable SCS (and/or VICVs) to the next clean sampling locations.

Early phases of the investigation will often include soil vapour data obtained using field screening methods (e.g., photoionization detector or combustible gas detector) at existing groundwater monitoring wells screened over the water table. While this information cannot be used to delineate the extent of contamination or to demonstrate that the applicable SCS or VICVs for a volatile chemical has been met at a site, it may prove useful in qualitatively evaluating areas of potential concern and identifying areas requiring additional characterization.

4.2.2 Does the Site Represent an Immediate Concern for Safety and/or Adverse Effects?

The first step of a preliminary vapour intrusion assessment is to identify whether there are immediate concerns regarding safety or adverse effects. Examples of conditions that may indicate a need for immediate actions include the following:

- **Potentially Explosive Conditions**: Vapour concentrations within a building, sump, drain or other utility that exceed or are close to the explosive limit represent a significant safety hazard through explosion or fire. The lower explosive limit for CH_4 is 5% (50,000 parts per million by volume (ppm_v)) in air, while the limit for gasoline vapours is approximately 1.4% (14,000 ppm_v) (IHSA, 2013; MOECC, 2016c). The accumulation of vapours may also represent an asphyxiation hazard in rare circumstances.
- **Odours:** Reports by building occupants of chemical odours that do not appear to be from indoor or ambient sources may be an indication of potential vapour intrusion and should be investigated. While the presence of odours may not necessarily indicate that there is a safety or health risk, strong odours may indicate a high concentration of a COPC in indoor air. In some cases, the odour thresholds of some chemicals are lower than risk-based air concentrations.
- **Physiological Effects**: Exposure to elevated levels of vapours could result in physiological effects such as headaches, nausea, eye and respiratory irritation. The sensitivity of individuals to these effects varies widely. The physiological effects may, or may not, be attributable to vapour intrusion but should be investigated.
- **Direct Contact**: There is an increased risk for vapour intrusion in buildings with wet basements or sumps in direct contact with contamination. This is particularly the case when there is NAPL at the water table.

Site information indicating immediate concerns for safety and/or adverse effects may come to light in various ways, including reports from building occupants or owners. Depending on site conditions, a more pro-active approach such as a door-to-door survey involving the use of questionnaires designed specifically to evaluate potential vapour-related concerns (such as those described above) may be warranted.

If any of the above conditions are present, immediate action should be considered to investigate possible concerns for safety and/or adverse effects and, where necessary, some certain RMMs should be implemented. For reports of odours and physiological effects, the outcome may depend on whether these effects could reasonably be expected to be associated with subsurface contamination. Based on the investigation, the testing of IAQ and/or the implementation of RMMs may be necessary.

4.2.3 Are There Chemicals of Potential Concern for Vapour Intrusion?

There are a number of screening approaches used to identify a COPC for vapour intrusion. Generally, different physical and chemical criteria are relied on for assessing the volatility of a chemical (SABCS, 2011; US EPA, 2015a).

In this guidance, a chemical is defined as volatile if it meets one or more following criteria:

- a Henry's Law constant greater than 1×10^{-5} atm-m^3/mol; or,
- vapour pressure greater than 1.0 millimeter of mercury (equivalent to 1.0 Torr).

Also, a chemical that is sufficiently volatile to cause vapour concentrations above the applicable HBIAC should be retained for further assessment (and is referred to as "COPCs for vapour intrusion"). The approach is generally consistent with the US EPA (2015a) guidance, in which a volatile chemical is considered to be "potentially toxic" via vapour intrusion if:

- vapour concentration of the pure component exceeds the HBIAC when the subsurface vapour source is in soil; or,
- saturated vapour concentration exceeds the HBIAC when the subsurface vapour source is in groundwater.

This volatility and toxicity screening approach accounts for the fact that some S-VOCs with high toxicity may pose a potential risk via vapour intrusion. The screening of COPCs for vapour intrusion assessment can be further refined with the consideration of the potential mobility of those chemicals in the subsurface. Further details and guidance on the consideration of volatility, toxicity and mobility are presented in Appendix II.

Additional consideration should be given to potential breakdown products of chemicals in the subsurface that may increase the risk associated with vapour intrusion. As an example, vinyl chloride is generally interpreted as more toxic than its parent compounds (various other chlorinated compounds such as PCE, etc.).

Consideration should also be given to chemicals that may pose risks related to more acute impacts. Such impacts may include explosions (e.g., due to CH_4), asphyxiation (e.g., due to CO_2), and odours (e.g., due to hydrogen sulphide).

If there is no COPC identified for vapour intrusion, further assessment of this pathway is not warranted. Otherwise, further assessment should be completed as part of the next screening step.

4.2.4 Is Contamination Sufficiently Close to a Building to Pose a Vapour Intrusion Concern?

Vapour concentrations generally decrease with increasing distance from a subsurface vapour source. Eventually, such concentrations will attenuate to levels below which vapour intrusion is not of concern.

The distance from a vapour source within which buildings may be affected by vapour intrusion (referred to as "inclusion distance") is a complex function of various site-specific conditions. Such conditions may include contamination source size and geometry, soil properties, chemical-specific properties, and potential biological or chemical transformations within the subsurface environment.

Some model predictions (Abreu and Johnson, 2005, 2006; Lowell and Eklund, 2004; Mendoza, 1995) and empirical data (Folkes et al., 2009) suggest that soil vapour migration tends to be insignificant at distances of approximately 30 m from the edge of the subsurface contamination. The use of a 30 m inclusion distance (which can be applied either laterally or vertically from the edge of a subsurface vapour source) has been suggested by a number of jurisdictions for use with contaminants that do not readily biodegrade under aerobic conditions (BCMoECCS, 2017a; MassDEP, 2016; NJDEP, 2018; USEPA, 2015a).

For chemicals that readily biodegrade (e.g., certain PHCs and benzene, toluene, ethylbenzene and xylene (collectively referred to as BTEX)), an inclusion distance of 10 m is recommended to account for the effects of biodegradation. Additional details pertaining to the assessment of potential vapour intrusion for PHCs are discussed in Appendix I.

It is noted that there are a number of precluding conditions that may justify greater inclusion distances. Such conditions include, but may not be limited to, the following:

- soil vapour under pressure;
- an expanding zone of contamination that is migrating toward the building;
- an extensive low permeability cover between the contamination source and building structures (e.g., good quality concrete or asphaltic pavement), as such cover may reduce the normal dissipation of vapours, increase lateral migration, and limit oxygen replenishment (which may affect aerobic biodegradation rates); and,
- preferential transport pathways present within the inclusion distance, consisting of a direct connection between contamination and the building being assessed.

For chemicals that readily biodegrade, there may be other conditions present at the site that can limit the bio-attenuation of vapours in the subsurface. Additional discussion related to such conditions, and more generally to soil vapour assessments at sites affected by PHCs and/or BTEX is provided in Appendix I.

If any precluding condition is identified, professional judgement and/or additional assessment is necessary to evaluate whether buildings should be evaluated for potential vapour intrusion risk even if they are located further than 30 m (or 10 m for PHCs) from the edge of the contamination area. It is also noted that the full extent and location of the contamination source should be established when determining the extent of the contamination area and the inclusion distances.

Under the preliminary or screening level assessment, it is generally assumed that a building could be constructed anywhere on the site. Therefore, consideration of the inclusion distances may not be always appropriate for screening purposes, unless the inclusion distances are maintained as part of RMMs. Consideration should also be given to the locations (or potential locations) of off-site buildings that fall within the inclusion distances.

4.2.5 Comparison to the Generic SCSs and/or VICVs (S-IA and GW2)

As part of the preliminary assessment process, the site-wide maximum concentrations found in soil and groundwater are often compared to the applicable SCSs and/or corresponding VICVs. An evaluation as to whether measured data are suitable and reliable to use in the vapour intrusion assessment (refer to Section 4.1.1 for further details) and whether applicable SCSs and/or corresponding VICVs are appropriate for use at a given site should be completed.

If the SCSs and/or corresponding VICVs are found to be appropriate and the data is reliable, soil and groundwater results can be compared to the applicable generic SCS as the first screening step, and then to the S-IA and/or GW2 component values as the next screening step. The results of this comparison can then be used to evaluate whether vapour intrusion is a potential concern at the site.

4.2.5.1 Applicability of Generic SCSs and VICVs (S-IA and GW2)

S-IA and GW2 component values are derived using a partitioning model coupled with the J&E model along with consideration of a number of generic assumptions and inputs. Details on the modeling approach and key assumptions used to develop the generic SCSs and corresponding VICVs are presented in the MOE (2011a) rationale document.

If conditions at a site are significantly different from one or more of the assumptions used to develop the generic values, such values may not be appropriate for use in evaluating site-specific soil and/or groundwater data. It is recommended that site conditions be evaluated to determine whether the use of generic SCSs or corresponding VICVs is appropriate at a given site. If the evaluation indicates that the use of such values is not reasonably protective of the vapour intrusion pathway, site-specific VICVs can be developed using a screening level or detailed vapour intrusion assessment.

The following list includes some key site conditions that may limit the applicability of the generic SCS and corresponding VICVs at certain sites.

- **Buildings with high susceptibility to soil vapour entry:** If buildings at a given site have characteristics that vary significantly from the generic assumptions (e.g., earthen floors, deteriorating basements, crawlspaces, etc.), this could result in a reduction in vapour attenuation between the subsurface and the building. Under such circumstances, the S-IA and GW2 component values may be non-conservative and inappropriate for use at the site.

- **Significant preferential pathways:** The development of SCSs and corresponding VICVs assumes that preferential pathways for vapour migration are not present. Preferential pathways may be caused by shallow fractured bedrock, gas under pressure/landfill gas, utility conduits that provide a direct connection to the enclosed space of the building. If preferential pathways are present at the site, the S-IA and GW2 component values may be non-conservative and inappropriate for use at the site.

- **Contaminated soil zone with a volume larger than 350 m^3**: The development of SCSs and corresponding S-IA relies on assumptions of a finite volume of impacted soil with specific dimensions (13 m by 13 m by 2 m or approximately 350 m^3). As such, if contaminated soil at a particular site has a volume or dimensions that are greater than what are assumed, S-IA component values may be non-conservative and inappropriate for use at the site.

- **Presence or suspected presence of NAPL below or near to the building**: The J&E modeling used in the development of the SCSs assumes that NAPL is not present. Component values derived using the J&E model (e.g., S-IA) are unlikely to be appropriate for sites where NAPL is present or suspected to be present as they may overestimate attenuative process (e.g., source depletion).

4.2.5.2 Additional Considerations

When conducting a comparison of the measured soil and groundwater concentrations at a given site against the applicable generic SCSs and/or VICVs, the following site conditions should also be considered:

- **Shallow depth to groundwater contamination:** If the separation distance between the groundwater and the bottom of the building slab is less than what was assumed in the development of the generic standards (see Section 7 of the MOE (2011a) rationale document), it is generally recommended that Table 6 and 7 SCSs and/or corresponding GW2 component values be used as part of the preliminary assessment process. Such situations include the depth to the water table of less than 3.0 m below ground surface (bgs) and the building slab located well below the assumed depth used in the generic modeling (Table 4.2).
- **Very high gas permeability media**: Buildings constructed on vertically or near vertically fractured bedrock, karst, cobbles or other media with very high gas permeability should use the Table 6 or 7 SCSs and/or corresponding GW2 component values in the preliminary assessment process, regardless of the depth to contamination. This is because soil gas advection within the unsaturated zone (i.e., beyond the soil zone near the building), which is caused by barometric pumping or other environmental factors, can be important in these scenarios.

4.3 Screening Level Vapour Intrusion Assessment (Step 2)

If the preliminary vapour intrusion assessment indicates that subsurface contamination may pose a potential risk to existing or future buildings via vapour intrusion, a subsequent screening level assessment is warranted to develop site-specific VICVs.

4.3.1 Site Characterization

A screening level assessment of vapour intrusion will typically require additional site characterization data beyond what’s typically available in the preliminary assessment. In addition to the use of data from soil and groundwater, the screening level assessment approach also incorporates soil vapour and possibly indoor air as assessment media. An overview of advantages and disadvantages associated with the characterization of different media is included below, followed by a discussion of specific considerations for soil, groundwater and soil vapour testing.

While there are advantages and disadvantages with each media (which are summarized in Table 4.1), often the best strategy is one based on a multiple lines of evidence approach (e.g., sampling of soil, groundwater, soil vapour, and indoor air). This allows the identification of data relationships and comparison of analytical results to generic and/or site-specific VICVs for each medium. A multiple lines of evidence approach is often found to appreciably strengthen the conclusions of a soil vapour assessment and increase confidence in the findings.

Table 4.1. Comparison of Different Media for Vapour Intrusion Investigations

Media Investigated	Indoor Air Evaluation Method	Principal Issues
Soil	Partitioning model combined with soil vapour to indoor air fate and transport model	Partitioning model highly uncertain (generally considered conservative). Significant spatial variability. Detection limits of some chemicals too high to meet S-IA component values. Negative bias due to potential losses during sampling and analysis.
Groundwater	Partitioning model combined with soil vapour to indoor air fate and transport model	Partitioning model uncertain. Imprecision of soil vapour transport model requires conservative attenuation factors. Moderate to high spatial variability. Moderate to low temporal variability.
Soil vapour	Soil vapour to indoor air fate and transport model	More direct indication of potential exposure but moderate to high spatial and temporal variability (particularly for shallow soil vapour). Deep and near source soil vapour tends to be more stable seasonally (also refer to Table 5.1) and is generally recommended for use in screening level assessment.
Sub-slab soil vapour[1]	Sub-slab soil vapour to indoor air model (primarily dilution in indoor air) or empirical attenuation factor approach	Closest representation of potential vapours migrating into building, but intrusive. High spatial and moderate to high temporal variability. Exfiltrating 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.

Notes: [1] Air within a crawlspace can be sampled as a substitute for sub-slab soil vapour. Depending on crawlspace ventilation and connection to house, there may be very little to no attenuation between the crawlspace and house (i.e., use attenuation factor of 1).

Limitations of results for each type of media are reduced if decisions are supported by consistent results for more than one type of media. Conclusions drawn from the collected results will also depend on the amount of data and the variability within the data. Data adequacy is a critical consideration when planning site characterization programs and interpreting results, particularly when sites may be “screened out” of the assessment process prior to completing more detailed studies.

There are several key points that should be considered as part of the site characterization and screening process, where applicable:

- Sufficient data should be obtained to characterize the spatial variability in soil, groundwater and soil vapour concentrations such that a reasonably detailed CSM describing the distribution and extent of contamination can be developed.
- Sufficient data should be obtained to characterize the temporal variability in groundwater, soil vapour, and indoor air concentrations. Sampling should be biased towards reasonable worst-case conditions.
- The number of samples (i.e., sample frequency) needed to delineate contaminant plumes will tend to increase as the geological variability or complexity increases.
- The site characterization process for all media should begin with an evaluation of contamination source areas to characterize maximum concentrations. Initial screening of the site should generally be conducted using maximum concentrations. This is done to avoid the risk of a false negative determination (i.e., failing to identify the potential for adverse effects).
- Where applicable, data can be collected to assess vertical distributions of chemicals in addition to horizontal distributions. This information helps to provide a better understanding of vapour behaviour in the subsurface at a site. For example, vertical profiles of PHC vapours and fixed gas (O_2, CO_2, CH_4) concentrations are helpful for characterizing the extent and nature of biodegradative processes at a site.
- If individual buildings are screened at a site, sufficient assessment should be completed to characterize variability surrounding the building. This will vary from site to site and should be decided in the context of the CSM.

4.3.1.1 Soil Data

While soil data will often be obtained as part of site characterization programs, there are some specific challenges to the use of soil data for vapour intrusion screening (USEPA, 2014):

- Soil sampling, handling and preparation may result in significant losses of chemicals through volatilization and biodegradation. Such losses may be reduced through field preservation using solvents (e.g., methanol or bisulphate, where applicable [MOE, 2011b]); however, the use of solvents also tends to cause higher LRLs, which may be above the levels protective of the vapour intrusion pathway.
- Depending on the chemical type and soil properties (e.g., texture, structure, moisture content and fraction of organic carbon), there may be significant spatial variation in soil concentrations. This variation may be not evaluated as part of sampling programs; especially at the screening level assessment stage.
- There are uncertainties associated with determining chemical partitioning in the vadose zone. Predicted vapour concentrations are typically estimated by assuming

an equilibrium relationship between concentrations of a chemical in sorbed, aqueous, and vapour phases, which may oversimplify the complexity of chemical partitioning between different phases.

- Poor correlations have been observed in studies comparing measured soil vapour data to results predicted using soil data, particularly for chemicals associated with dense non-aqueous phase liquid (DNAPL) sources such as chlorinated solvents.

Considering the limitations described above, it is important to note that soil samples for volatile chemicals should undergo a detailed QA/QC procedure in order to ensure that the samples that are collected are representative of site conditions. For example, care should be exercised during sample collection and, where appropriate, alternative technologies (e.g., using appropriate coring devices, such as air-tight coring device/container) and/or methods (e.g., purge-and-trap extraction as outlined in USEPA (2002) Method 5035A) may be necessary to minimize VOC losses.

In addition to soil chemistry data, information pertaining to soil stratigraphy and the physical properties of relevant soil units may provide valuable information in assessing vapour intrusion. Continuous soil cores help to provide soil stratigraphy information, and physical testing of soils may provide further useful information on soil texture, density, moisture and structure.

It is noted that S-IA component values are sometimes lower than LRLs. In such cases, it may not be appropriate to rely on soil data as the sole line of evidence to rule out the vapour intrusion pathway. Instead, more direct lines of evidence (e.g., soil vapour and indoor air sampling) should be considered.

4.3.1.2 Groundwater Data

Groundwater samples for evaluation of vapour intrusion should be collected as near as practicable to the water table, and the assessment should include water level monitoring to assess seasonal water table elevation fluctuations. This is because VOC mass transfer from groundwater to soil vapour occurs when chemicals in pore-water volatilize into soil vapour, which is facilitated by water table fluctuations (Rivett, 1995).

The use of relatively short well screens situated across the water table is generally recommended when evaluating the vapour intrusion pathway. When well screen lengths increase, there is increased blending of groundwater across the screened interval. This may result in either over-estimation or under-estimation of concentrations at the top of the aquifer. For example, at locations where light non-aqueous phase liquid (LNAPL) is present, longer well screens may under-predict concentrations near the top of the aquifer. Alternatively, for a situation where there is a clean water lens or contamination source below the water table (e.g., DNAPL), longer well screens may over-predict concentrations near the top of the aquifer.

In some cases, deeper groundwater quality data is also important to assess potential risks associated with vapour intrusion that may occur in the future. For example, a COPC present at depth within a groundwater system could pose a vapour intrusion concern if the COPC were to migrate closer to the water table, either naturally or through human intervention. Therefore, site characterization programs should also include investigation of vertical concentration variability in groundwater, either through the use of nested or clustered wells (i.e., wells in close proximity with different elevations) or through vertical profiling using a depth-discrete groundwater sampling technique.

When there are relatively steep vertical concentration gradients and increasing concentrations with depth in shallow groundwater, particular care should be taken in selecting the concentration for screening purposes. When small-scale discrete samples are analyzed (e.g., Geoprobe method, Hydropunch, Waterloo profiler or similar), the concentration data for a sample taken just below the water table may not be adequately representative of broader conditions influencing soil vapour concentrations. Under such conditions, efforts should be undertaken to ensure that enough data is collected to develop appropriately conservative estimates of maximum shallow groundwater concentrations.

Groundwater quality data is often a key component of a vapour intrusion assessment. As such, concentration gradients and water table fluctuations should not be ignored when evaluating the potential for vapour intrusion.

4.3.1.3 Soil Vapour Data

Soil vapour sampling and analysis avoids uncertainties related to mass transfer and phase partitioning, and therefore provides valuable data for assessing potential vapour intrusion and indoor air concentrations. However, empirical data often show a high degree of spatial and temporal variability. As such, special care is required during the design of a sampling program (e.g., methods, locations, frequency, etc.) as well as sample collection (e.g., appropriately trained staff, adequate QA/QC, etc.) to properly characterize soil vapour.

Depending on the study objectives and site conditions, soil vapour samples can be obtained near the source, external to the building footprint and/or immediately beneath the building slab. Key considerations for selecting soil vapour sampling locations are provided in Section 5.3.

4.3.2 Determination of Site-specific Vapour Intrusion Component Values for Screening Level Assessment

Under a screening level assessment process, site-specific VICVs may be developed for soil, groundwater and/or soil vapour. The derivation of VICVs is based on HBIACs and vapour attenuation factors that are developed either empirically or through the use of the J&E model.

Where modeling efforts are undertaken at this stage, the process is constrained such that only selected readily measurable input parameters (e.g., soil texture, vertical separation distance from building to contamination source, biodegradation adjustment) can be varied from the default model inputs, and then only within specified ranges. This is consistent with the process for the MGRA (MOECC, 2016b, 2016c). Since evaluation of multiple environmental media can improve the confidence in the assessment, it is recommended that site-specific VICVs be developed for all media tested.

Direct comparisons of indoor air concentrations to HBIACs may also be considered in the screening level vapour intrusion assessment. Additional details on IAQ assessment are discussed in Chapter 6.

Site-specific screening levels are derived using the following sequence of steps:

- determine soil texture (Section 4.3.2.1);
- determine land use (Section 4.3.2.2);
- estimate vertical separation distance from lowest point of building to vapour contamination source (Section 4.3.2.3);
- derive attenuation factor (Section 4.3.2.4);
- adjust attenuation factor to account for aerobic biodegradation, as appropriate for applicable chemicals (Section 4.3.2.4);
- calculate site-specific VICVs for soil, groundwater, and soil vapour (Section 4.3.2.5); and,
- evaluate data consistency, adequacy and uncertainty and determine next steps (Section 4.5).

4.3.2.1 Soil Texture

The fate and transport of volatile chemicals in soils is in part dependent on soil properties. Under O. Reg. 153/04, there are two (2) soil grain size groups, coarse textured and medium/fine textured, that are used to derive the generic SCSs. Coarse textured soil is defined as soil with greater than 50 percent by mass of particles that are 75 micrometres or larger in mean diameter. Medium/fine textured soil is defined as soil that contains 50 percent or more by mass of particles that are smaller than 75 micrometres in mean diameter.

In addition to coarse and medium/fine soil textures, specific soil types can be determined as outlined in Figure 3-7 and Chapter 3 of the soil survey manual, available on the U.S. Department of Agriculture's (USDA) webpage for soil texture (URL: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167).

Samples for grain size analysis should be collected for each area where volatile chemicals are present in soil and/or groundwater at elevated concentrations. During the initial stages of site characterization, the coarsest soil typed observed at the site (based on the USDA classification) should generally be used for calculations of the site attenuation factor. In cases where the soil type has not been or cannot be determined, then the "sand" soil type should be used as a reasonably conservative assumption.

As confidence in the site characterization increases, it may be more appropriate to select the soil type based on the soil type interpreted to most strongly influence soil vapour migration. Such a soil type may be more consistent with the median soil type across the site (as opposed to the coarsest).

It should be noted that the clay-type soils of the USDA classification (clay, silty clay, and sandy clay) should not be used to determine site-specific VICVs. This is because these soil types have the potential to fracture, which would make the default soil properties potentially non-representative. If such soils are present, parameters consistent with silt should be used, as a conservative assumption. Additional considerations should be given as to whether fractures in clay-type soils, if present, could potentially allow for increased vapour transport into overlying buildings.

4.3.2.2 Land Use

There are three land use categories, as defined in O. Reg. 153/04:

- Agricultural or Other Use;
- Residential / Parkland / Institutional (R/P/I) Use; and,
- Industrial / Commercial / Community (I/C/C) Use.

If a site involves mixed uses, the most sensitive use category should be selected for the purpose of vapour intrusion assessment. The selected land use dictates certain input parameters for the vapour intrusion assessment model that are specific for that use. (e.g., exposure inputs and building characteristics).

4.3.2.3 Vertical Separation Distance to Vapour Contamination Source

The separation distance to the vapour contamination source is the vertical distance between the lowest part of the building foundation and the vapour contamination source. When contamination is limited to dissolved chemicals in groundwater, the vertical separation distance is the distance between the building and the highest observed water level. When soil or soil vapour measurements are made, the vertical separation distance is the distance between the building and the measurement point. For soil vapour, the top of the screen of the vapour probe is the measurement point which should be located between the contamination source and the building foundation.

It is also noted that highly permeable media (e.g., fractured bedrock, karst, cobbles), if present, between the impacted area and a building, can result in an enhanced (or un-attenuated) migration of soil vapour. Under such conditions, it may be more appropriate to exclude this media from the determination of vertical distance.

4.3.2.4 Vapour Attenuation Factor

Vapour attenuation refers to the reduction in a subsurface source concentration relative to an indoor air concentration, during the transport process, and entry into a building. The vapour attenuation factor (“alpha” or “α”) is defined as the ratio of the indoor air concentration (typically reported in parts per billion by volume (ppb_V)) to the measured or estimated soil vapour concentration (ppb_V) at the point of interest. Alpha can be derived either empirically or through the use of the J&E model, as outlined in the following sub-sections.

4.3.2.4.1 Default Sub-slab Alpha ($\alpha_{sub\text{-}slab}$)

For sites where the vertical separation distance between the contamination source and current/future building foundation of less than 1 m, alpha should be fixed at a reasonably conservative and empirically-derived value. This approach is consistent with those used by a number of jurisdictions (e.g., BCMoECCS, 2017a, 2017b; CCME, 2015, 2014). The following are default sub-slab alpha values used in the development of generic SCSs and corresponding VICVs for shallow soil sites (Table 6 and 7 SCS):

- Under a R/P/I building setting, an empirically-based sub-slab alpha value of 0.02 is used to derive VICVs. This value corresponds to the upper end of the empirical range (92nd percentile) as presented in the CCME (2014) protocol document.
- For an I/C/C building setting, an alpha value of 0.004 is used to derive VICV. This value is adjusted from the R/P/I value, based on generic assumptions for soil gas advection rate (Q_{soil}) and building ventilation rate ($Q_{building}$).

Further details regarding the selection of default sub-slab alpha values are presented in the MOE (2011a) rationale document.

It is noted that as more empirical data become available the empirical sub-slab vapour attenuation factors may be adjusted. When determining an empirical attenuation factor, it is important to consider the most up-to-date information. An appropriate rationale for the selected attenuation factor should also be provided.

4.3.2.4.2 J&E Derived Sub-slab Alpha ($\alpha_{J\&E}$)

The J&E model can be used to calculate attenuation factors for situations where the vertical separation distance is greater than 1 m between the contamination source and the current/future building foundation and the subsurface materials are unconsolidated deposits (i.e., not rock or other fractured materials). Attenuation factors can be calculated for both current and future building scenarios. If the built form of one or more future buildings at the site is unknown at the time of assessment, it may be appropriate to use default sub-slab attenuation alpha values.

Attenuation factors calculated using the J&E model rely on site-specific soil properties (Section 4.3.2.1) and the distance from building to contamination source (Section 4.3.2.3). The model accounts for the attenuative process during the migration of the vapour from the point of measurement (for soil vapour and soil measurements) or the highest measured water table (for groundwater measurements) to the base of the building (i.e., sub-slab), as well as attenuative processes related to the difference between the sub-slab soil vapour concentration and the indoor air concentration measured within the building.

When calculating attenuation factors for soil vapour and soil measurements, the J&E model only considers soil vapour migration within the unsaturated soil zone. When calculating attenuation factors for groundwater measurements, the J&E model also considers soil vapour migration through the capillary transition zone.

Further details on the J&E model are included below. It should be noted that the J&E model does not directly account for biodegradation, and therefore model results need to be adjusted to account for biodegradation, where appropriate. Details on this correction are also discussed below.

Key site-specific inputs to the J&E model

Soil-specific parameters for the J&E model are determined based on the selected soil types for the unsaturated zone and capillary transition zone (for groundwater source only). Different soil types can be selected for each of these zones in the Approved Model.

Materials used around the building substructure are also accounted for in the model. In Ontario, a layer of coarse and clean granular materials (referred herein to as “gravel crush layer”) is required under any new building by the Ontario Building Code. This layer is modeled using the following inputs:

- dry bulk density of 1.6 g/cm^3;
- total porosity of 0.4 vol/vol;
- water-filled porosity of 0.01 vol/vol; and,
- thickness of 30 cm.

Other default building-specific input parameters for calculating attenuation factors using the J&E model are provided in Table 4.2 (below).

Table 4.2. Recommended J&E Model Input Values*

Parameter	**R/P/I**	**I/C/C**
Depth to underside of basement/foundation slab (cm)	158	11.25
Gravel crush thickness beneath basement/foundation slab (cm)	30	30
Enclosed space length (cm)	1225	2000
Enclosed space width (cm)	1225	1500
Effective enclosed space height (cm)	366	300
Air exchange rate per hour (hr^{-1})	0.30	1
Depressurization (Pa) (not directly used in Q_{soil} calculation but representative values)	4	2
Basement floor thickness (cm)	8	11.25
Floor-wall crack width (cm)	0.10	0.10
Ratio of crack area to total subsurface area	0.0002	0.0002
Soil temperature (^oC)	15	15
Soil gas advection flow (L/min) - coarse - fine	 8.45 1.0	 9.8 1.5

Notes: * Used in the derivation of generic SCSs (MOE, 2011)

Site-specific building parameters can be used with the J&E model; however, default parameters are generally recommended for the screening level assessment. At the detailed assessment stage, there is opportunity to modify building parameters. It is important to note that, where site-specific building parameters are used, the effect of any changes to existing or planned buildings at the site on the calculated attenuation factors would need to be assessed. This is necessary to ensure that the calculated attenuation factors still represent adequately conservative estimates of the relevant processes.

One of the key parameter inputs is the soil gas advection rate into a building (Q_{soil}), which represents the rate at which soil vapour enters a building from the sub-slab. In the J&E model, it can be calculated using an analytical solution, referred to as the "perimeter crack model", for two-dimensional soil vapour flow to a small horizontal drain. The soil gas advection rate calculated using this method is a function of the soil-air permeability, building depressurization, building foundation properties, and building size. However, the use of the perimeter crack model can be problematic, in that the model represents a highly simplified representation of a comparatively complex and site-specific process. Estimated Q_{soil} values are very sensitive to the estimated soil-air permeability, and consequently a wide range in flows can be predicted. Also, the user may input combinations of soil and hydrogeological parameters that are not internally consistent and that may produce unreasonable Q_{soil} estimates (Johnson, 2005). For the above reasons, the use of the J&E "perimeter crack model" for calculating Q_{soil} is not recommended at the screening assessment stage. The recommended Q_{soil} values are presented in Table 4.2. Further details regarding Q_{soil} values can be found in the MOE (2011a) rationale document.

Correcting J&E model results to account for biodegradation

The attenuation factors calculated using the J&E model do not account for biodegradation. For sites affected by chemicals that may readily degrade aerobically (e.g., certain PHC and BTEX), such attenuation factors may over-estimate the potential vapour intrusion risk for these chemicals. Attenuation factors calculated using the J&E model can, however, be adjusted to account for biodegradation using bio-attenuation factors (BAFs). The corresponding equation is as follows:

Adjusted Attenuation Factor = "J&E based Vapour Attenuation Factor" / BAF

Generally, the effect of aerobic biodegradation on readily biodegradable compounds in the subsurface is accounted for by applying the following empirical BAF values:

- For situations where there is at least 1 m of clean soil under the building being assessed, a BAF value of 10 is used.
- For situations where there is at least 3 m of clean soil under the building being assessed, a BAF value of 100 is used.

Further details on biodegradation (particularly related to PHCs) are provided in Appendix I.

4.3.2.4.3 Key Limiting Conditions

There are some specific conditions that may result in significantly enhanced vapour migration into a building, referred to as limiting conditions. Under such conditions, the use of empirical and/or J&E model-derived attenuation factors may be inappropriate. Examples of key limiting conditions include, but may not be limited to, the following:

- buildings with high susceptibility to soil vapour entry (e.g., dirt floor, stone foundation);
- gas under pressure; and,
- significant preferential pathways (e.g., utility conduits, fractured bedrock).

If a key limiting condition is identified at a given site, additional assessment may be necessary to confirm the absence of potential vapour intrusion risk. In some instances, the use of conservative attenuation factor estimates (e.g., default sub-slab values) may address certain key limiting factors (e.g., presence of preferential pathways such as fractured bedrock).

4.3.2.5 *Calculation of Vapour Intrusion Component Values*

The soil vapour screening levels (SVSLs) are calculated as follows:

$$SVSL = HBIAC / \alpha_v \quad (\mu g/m^3) \qquad \text{(Equation 4.1)}$$

where:

$HBIAC$ = health based indoor air concentration ($\mu g/m^3$)

α_v = vapour alpha (adjusted based on criteria described above) (dimensionless)

The groundwater component values developed for the vapour intrusion pathway (GW2) can be calculated as follows:

$$GW2 = HBIAC/(H * \alpha_{gw} * 1000) \quad (\mu g/L) \qquad \text{(Equation 4.2)}$$

where:

α_{gw} = groundwater alpha (adjusted based on criteria described above) (dimensionless)

H = Henry's law constant (dimensionless)

All other parameters as previously defined.

The soil component values developed for the vapour intrusion pathway (S-IA) can be calculated as follows:

$$S\text{-}IA = HBIAC * (\eta_w + K_d * \rho_b + H * \eta_a) / (H * \rho_b * \alpha_{soil} * 10^6 \text{ cm}^3/\text{m}^3) \quad (\mu g/g \qquad \text{(Equation 4.3)}$$

where:

ρ_b = dry soil bulk density (g/cm^3)

η_a = air-filled porosity of soil (cm^3/cm^3)

η_w = water-filled porosity of soil (cm^3/cm^3)

K_d = soil-water partitioning coefficient (cm^3/g)

α_{soil} = soil alpha (adjusted based on criteria described above) (dimensionless)

All other parameters as previously defined.

4.4 Detailed Vapour Intrusion Assessment (Step 3)

A detailed vapour intrusion assessment should be considered in situations where the screening level assessment is unable to rule out the potential for unacceptable vapour intrusion risks or where site conditions are very complex or considerably different from the CSM assumed for models used to derive generic component values or used for screening level assessments.

A detailed assessment may include the collection of indoor air, sub-slab vapour, soil vapour, and outdoor air samples. Additionally, site-specific building properties may be assessed. This additional information may be used to develop site-specific VICVs using different models and/or different input parameters than those limited under the screening level assessment. Note that any modifications to the default input parameters should be supported through site-specific data (e.g., soil type, depth to water table, building conditions). Also, the presence of any conditions that may invalidate the use of the applied model(s) should be assessed.

4.4.1 Determination of Site-specific Inputs for Detailed Assessment

Determination of site-specific inputs can be challenging since only some input parameters may be directly measured; for others, qualitative observations, literature values and/or professional judgment may influence the selection of reasonable input parameters. The text below describes approaches and procedures for estimating input parameter values for use in the J&E model.

4.4.1.1 Water-filled Porosity, Total Porosity and Bulk Density

As part of a detailed vapour intrusion assessment, efforts may be undertaken to more accurately assess relevant parameters related to soil porosity and moisture levels. This may include:

- direct measurement of such parameters through soil sampling;
- improved estimation of such parameters via modeling based on site-specific information (e.g., soil type); and/or,
- improved modeling of the distribution of such parameters (e.g., use of more discrete layers in the J&E model).

When soil samples are obtained below the building, a direct measurement approach may be reasonable. Care must be taken to minimize soil disturbance when collecting soil samples since this will result in inaccurate measurements. Where possible, soil sampling techniques that minimize disturbance should be used (e.g., Shelby tube sampler).

Where it is not possible to obtain soil samples below the building or where a future scenario is being evaluated, the use of water retention models may provide for more accurate predictions of soil moisture relative to the corresponding default inputs. Such models generally predict porosity-related parameters based on grain-size distributions or assumed characteristics for specific soil types (e.g., Fredlund et al., 1997; Schaap et al., 2001; van Genuchten, 1980). Another option may be the use of a normalized parameter for soil moisture, consisting of the water-filled porosity divided by the total porosity (“water saturation”), to guide selection of reasonable soil moisture inputs for different soil types (Johnson, 2005).

Improved modeling of the distribution of soil porosity and moisture can be achieved through the introduction of additional discrete model layers. Such efforts may be useful when modeling the water-filled porosity through the capillary transition zone (particularly if there is a thick capillary transition zone), as this value would be expected to vary significantly across this zone.

4.4.1.2 Soil Gas Advection Rate (Q_{soil})

In a detailed vapour intrusion assessment, alternative values may be used for Q_{soil} (i.e., values other than those presented in Table 4.2). Selected values may be based on:

- Empirical attenuation factors and a specified range of values for the ratio of $Q_{soil}/Q_{building}$. Johnson (2002, 2005) used mass balance principles to show that the $Q_{soil}/Q_{building}$ ratio is equal to the ratio of indoor air concentrations divided by sub-slab vapour concentrations (i.e., the sub-slab vapour to indoor air attenuation factor). The Q_{soil} value could be calculated from this ratio, if the building air exchange rate and volume are known (i.e., $Q_{building}$ is known). Typically, the $Q_{soil}/Q_{building}$ ratio is between 0.0001 and 0.05 (Johnson 2002, 2005).
- A specified value for Q_{soil} (based on values from tracer tests). The tracer test concept is based on characterizing soil vapour concentrations below the slab, indoors and outdoors. If the building ventilation rate is known, and if advection is the main process for vapour intrusion, then Q_{soil} can be calculated from the mass flux values. The tracer is a chemical that moves in a similar way to the target COPC and could include a natural tracer like radon or an injected tracer such as helium or sulphur hexafluoride (SF_6). If the proposed Q_{soil} value is based on published literature, a detailed rationale must be provided as to why the proposed value is applicable to the site and existing buildings.

In many cases, it will not be feasible to measure Q_{soil} using tracer tests. For these situations, the recommended approach is to start with the default soil vapour flow rates and to normalize Q_{soil} such that $Q_{soil}/Q_{building}$ remains roughly constant and near the mid-point of the empirical range of sub-slab alphas. This constraint is considered reasonable based on previous comparisons of model predictions to measured sub-slab vapour attenuation factors. There are other possible approaches to adjusting the Q_{soil} based on the ratio of Q_{soil} to building foundation area or perimeter crack length; however, the differences between these approaches and one based on the $Q_{soil}/Q_{building}$ ratio tend to be relatively small.

Building pressure measurements can also be used to refine estimates of Q_{soil}. Such measurements can be useful in determining whether there is, in fact, a pressure gradient that would result in vapour intrusion. Some commercial buildings may be positively pressurized, effectively eliminating the contribution of soil vapour advection to vapour intrusion.

Soil air permeability tests can also be used to refine the estimated soil-air permeability input in the perimeter crack model, or other models used to simulate soil vapour flow. These tests can be performed by using a pump to extract soil vapour from a small well or probe, and then measuring pressure and flow. There are several mathematical solutions that can be used to estimate soil air permeability from this data, including those referenced in Garbesi et al. (1996) and Johnson et al. (1990). It is noted that if the intent is to estimate Q_{soil} (i.e., test near foundation soil), then both the test procedure and interpretation may be complicated by the presence of the foundation and disturbed soils.

4.4.1.3 Building Mixing Height

As part of a detailed site assessment, estimates of the building mixing height may be refined. Such efforts may rely on an evaluation of the ventilation system design and/or observational data. In some cases, mechanical or HVAC engineers can provide useful information on mixing heights.

For multi-storey buildings, estimating cross-floor mixing and leakage may lead to better estimates of the building mixing. It may also be important to evaluate thermal stratification for some buildings, since this may affect mixing of vapours within the building.

4.4.1.4 Building Ventilation Rate

Default air change rates used to calculate the SCS are 0.3 air change per hour (ACH) for the R/P/I scenario and 1.0 ACH for the I/C/C scenario (MOE, 2011a). Empirical data demonstrate a wide range of air exchange rates, depending on types of homes, weather, and location (refer to Section 6.2.3 for further details).

As part of a detailed assessment, ventilation rates may be refined through building-specific information. This may include an assessment of HVAC design information, qualitative observations regarding site use (e.g., open doors and windows), or direct measurements. Direct measurements of building ventilation rates can be completed using tracer tests (e.g., method outlined in the ASTM International (ASTM) standard E-741-11[2017]).

It should be noted that measured ventilation rates are specific to the building and environmental conditions under which the test was performed. As such ventilation rates measured at a limited number of testing events may not provide appropriate estimates for either worst-case or typical ventilation rates, both of which may be useful in assessing vapour intrusion risks.

4.4.1.5 Building Size

As part of a detailed assessment, the building size can be measured and used in the vapour intrusion assessment. All things being equal, predicted indoor air concentrations decrease as the building size increases. This is due to increased mixing of soil vapour with indoor air, as there is comparatively more indoor air in a larger building. That said, considerations should also be given to internal building partitions and HVAC layouts when assessing the effect of building size on the vapour intrusion pathway.

As discussed in Section 4.4.1.2, Q_{soil} and $Q_{building}$ are interrelated and a typical ratio of $Q_{soil}/Q_{building}$ ranges between 0.0001 and 0.01. If the building air exchange rate and building size are known, then $Q_{building}$ can be calculated, but should be also evaluated as to whether $Q_{soil}/Q_{building}$ is within a reasonable range.

4.4.1.6 Building Foundation Integrity

The building foundation integrity is modeled using a perimeter crack in the foundation. The ratio of the area of such a crack to the total floor area of the lowest floor, referred to as the crack-to-total subsurface area ratio (η) or "crack factor", is commonly used to represent the building foundation integrity. The default values for the crack factor and crack width used in the development of the generic VICVs are 0.0002 and 0.1 cm, respectively (MOE, 2011a).

Field data and modeling work (Nazaroff, 1992; Nazaroff et al., 1985; Revzan et al., 1991) indicated crack ratios on the order of 0.0001 to 0.001 (or 10^{-4} to 10^{-3}) for residential houses. This range corresponds to perimeter crack widths of about 0.1 to 0.2 cm for residential sized buildings. Such widths may represent a reasonable starting point for more detailed assessments of building foundation integrity.

While a perimeter edge crack between the foundation walls and base is relatively common, there may also be un-trapped drains, shrinkage cracks in concrete, and/or small cracks surrounding utility penetrations. If the building has a poor-quality foundation, a somewhat higher crack ratio may be justified. Alternatively, if the foundation is of high quality or is coated with a sealant (e.g., epoxy) or other floor coverings, a lower crack ratio may be warranted.

4.4.2 Petroleum Vapour Intrusion

Both empirical and modeling study results have demonstrated that biodegradation can limit the migration of chemicals in soil vapour that readily biodegrade under aerobic condition (e.g., certain PHC and BTEX). As such, the vapour intrusion process for such chemicals may be significantly different to that of recalcitrant chemicals, such as chlorinated hydrocarbons, under the same environmental settings.

Given that many complex interactions involved in biodegradation, the majority of studies have focused on empirical estimation of the effects of biodegradation on PHC vapours (Davis, 2009; Lahvis et al., 2013; USEPA, 2013). This includes empirical estimates of the required thickness of biologically active clean soil (roughly analogous to the vertical inclusion distance) required to biodegrade PHCs and other relevant chemicals (e.g., BTEX) to levels below applicable VICVs *(*ITRC, 2014; USEPA, 2013, 2015b). This work suggests the vertical inclusion distances may be used as an alternative step for evaluating the potential for PVI.

Further information related to the vapour intrusion assessment at PHC impacted sites is included in Appendix I.

4.4.3 Indoor Air Quality Testing

IAQ testing provides the most direct assessment of potential vapour intrusion impacts; however, as discussed previously, IAQ often shows significant temporal and spatial variability and may be influenced by background sources. Further details regarding the planning and implementing of an IAQ testing program are presented in Chapter 6.

4.5 Data Evaluation and Next Steps

It is important to evaluate the collected data for consistency, adequacy and overall uncertainty, as the conclusions drawn from each assessment step will dictate the next steps. Key questions pertaining to data evaluation that should be addressed at the end of each assessment step include:

- Are predictions consistent with the CSM and internally consistent for different media and sampling locations?
- Are the data adequate to evaluate vapour intrusion potential, particularly in cases where the assessment process indicates that no further action is warranted?
- What is the overall uncertainty in each assessment step and how can this influence decision making (e.g., acceptable uncertainty may be higher for a value well below its corresponding VICV as compared to a value that is very close to its VICV)?

Vapour intrusion is a complex pathway that generally requires the use of a multiple lines of evidence approach. Some key lines of evidence that should be considered in the assessment of the vapour intrusion pathway include, but may not be limited to, the following:

- chemical analysis of different media (soil, groundwater, soil vapour, and indoor air);
- building-specific parameters (e.g., pressure testing, ventilation rates);
- hydrogeological and biological characteristics of the subsurface (e.g., groundwater levels, soil properties, and biodegradation);
- modeling of soil, groundwater, soil vapour concentrations; and,
- presence of preferential pathways.

Different lines of evidence may lead to different conclusions regarding the potential for vapour intrusion risk. As such, it is important that all available lines of evidence be evaluated and weighed, especially to support “no-further-action” decisions. Such an approach helps to improve the confidence in conclusions regarding whether the vapour intrusion pathway is of concern and likely to be of concern at a particular site, particularly when results are borderline (e.g., marginally exceed applicable VICVs) or inconclusive.

Additional assessment and/or considerable judgment are necessary to examine whether one or more lines of evidences are appropriate to override another. Decisions to consider or exclude one or more lines of evidence in the vapour intrusion assessment should be technically justified and documented. For example, when subsurface media measurements indicate the potential for vapour intrusion (e.g., soil vapour measurements exceeding SVSLs), indoor air can be assessed as a more direct line of evidence. It is noted, however, that the use of indoor air measurements may not be a definitive indicator, due to the temporal and spatial variability of indoor air concentrations. It is recommended that this variability be taken into account when evaluating the analytical results and determining next steps. The multiple-lines-of-evidence approach used as a cross check to assess the quality of soil vapour and indoor air data is discussed further in Sections 5.8 and 6.5.

4.6 Risk Management Measures

When it has been determined that the vapour intrusion pathway is (or is suspected to be) complete, proactive measures, including risk management measures, can be used to reduce and/or eliminate the potential risk associated with the vapour intrusion pathway. The preferred long-term measure is to remediate the vapour sources, thereby completely eliminating the potential vapour intrusion exposure pathway. Examples of source remediation methods include soil excavation, in situ soil vapour extraction, bioremediation, and natural attenuation.

The implementation of RMMs may be warranted at (or near) buildings of concern to provide effective protection from the vapour intrusion pathway. This may be as either an interim measure until the remediation of a subsurface source is completed, or as part of a more long-term solution. Depending on site conditions (e.g., risk levels and site use) and cost analysis results, risk management options may include, but may not be limited to, the following:

- institutional controls (e.g., by imposing restrictions to building access or activities or to building locations in relation to the subsurface source);
- reduction in vapour entry points into buildings (e.g., sealing any openings that allow for direct intrusion of soil vapours, including major cracks in floors and walls, gaps around utility lines, open sumps);
- prevention of vapour entry through pressure gradient changes (e.g., sub-slab depressurization, building over-pressurization);
- removal of contamination in sub-slab soil vapour (e.g., sub-slab soil vapour extraction); or,
- removal of contamination in indoor air (e.g., increasing building ventilation or indoor air treatment).

There are several resources available that provide guidance or details on common practices regarding the selection, installation, and long-term monitoring of vapour intrusion mitigation systems (ASTM, 2015, 2013; ITRC, 2007; USEPA, 2008, 2015a). It is noted that the selection of appropriate RMMs will depend to some degree on building-specific conditions, access constraints, owner and occupant preferences and practical considerations. It is important to be aware of the information in the guidance resources listed above and to provide sufficient design detail and performance monitoring data to justify and defend the selection and performance of any mitigation measures.

A number of RMMs for vapour intrusion are listed within the MOECC (2016a) Approved Model, as follows:

- building with no first storey R/P/I use;
- passive soil vapour intrusion mitigation system (SVIMS);
- active SVIMS;
- building prohibition; and,

- building with storage garage.

While these RMMs are meant to be used as part of a MGRA under O. Reg. 153/04, they may be considered, where appropriate (and in consultation with the Ministry's local district offices), for non-MGRA sites. For additional details on the design, application and requirements for preparing and implementing maintenance, inspection, and monitoring programs for each of the above RMMs, please refer to the "RMM Description" worksheet of the MOECC (2016a) Approved Model or the MOECC (2016b) guidance document.

CHAPTER 5 SOIL VAPOUR CHARACTERIZATION

This chapter was developed in parallel with the following guidance documents:

- CCME (2016a) *Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment - Volume 1 Guidance Manual*; and,
- SABCS (2011) *Guidance on Site Characterization for Evaluation of Soil Vapour Intrusion into Buildings*.

Therefore, there are text and tables common to this chapter and Chapter 7 of the CCME (2016a) guidance manual and Chapter 3 of the SABCS (2011) guidance document. Where warranted, modifications have been made to reflect the policy of the Ministry and the conditions in Ontario.

5.1 Context, Purpose and Scope

Soil vapour characterization programs will vary from site to site, depending on site-specific conditions, project-specific objectives, and potential constraints. As such, this chapter outlines key principles and factors that should be considered in developing a sampling strategy, rather than a standardized template to be applied at every site. A summary of ancillary data that may assist with the interpretation of soil vapour data and evaluation of vapour intrusion is also provided in this chapter. Further guidance can be found in Chapter 7 of the CCME (2016a) guidance manual.

5.2 Study Objectives

The overall goal of a soil vapour investigation is typically to provide the data needed to evaluate the potential risk to building occupants who may be exposed to vapours migrating to indoor air. Specific objectives of the soil vapour investigation may include the following:

- develop a CSM for soil vapour characterization (refer to Chapter 3 for details);
- compare measured soil vapour concentrations to applicable SVSLs;
- provide soil vapour data needed for inputs into models used for site-specific risk assessment;
- evaluate biodegradation of PHCs in soil vapour through the collection of soil vapour samples from vertical profiles or lateral transects, where available;
- evaluate cross-media transfer (chemical partitioning and attenuation through the capillary fringe) through comparison of measured concentrations in co-located groundwater and soil vapour sampling points;
- evaluate model results from soil vapour fate and transport simulations, through the collection of soil vapour samples at various points along the migration pathway and then compare the measured soil vapour concentrations to the modeled results; and,
- evaluate the influence of background chemical sources on indoor air samples through concurrent collection of external soil vapour, sub-slab vapour and indoor air samples.

The study objectives should be well defined prior to developing a soil vapour characterization program, as there may be substantive differences in sampling plans, depending on the type of data required and how that data is intended to be used.

5.3 Soil Vapour Sampling Approach and Design

This section highlights some key considerations when planning and implementing a soil vapour investigation, including selecting appropriate sampling locations and frequencies to account for spatial and temporal variability in soil vapour concentrations.

5.3.1 Overview of Sampling Strategy

Typically, a sequential phased approach is recommended when conducting a soil vapour investigation. The early phase(s) of the soil vapour investigation often focus on the characterization of soil vapour concentrations in close proximity to known or suspected sources of soil vapour, as such areas are the least likely to be influenced by spatial and temporal variability. For many contamination scenarios, the source consists of NAPL or dissolved chemicals at the water table; therefore, deeper soil vapour samples (e.g., collected above the water table) are strongly recommended to characterize the source.

If the initial characterization indicates soil vapour concentrations exceeding applicable SVSLs, a subsequent phase of soil vapour investigation may be required. Such work may include:

- further delineation of soil vapour concentrations (i.e., toward the existing and/or future buildings) through the use of lateral transects and vertical profiles; and/or,
- collection of sub-slab soil vapour samples to assess the soil vapour condition beneath existing buildings.

It is noted that this sequential phased approach may not always be appropriate or needed. Should site conditions pose an immediate concern for safety and/or adverse effects to existing building occupants, sub-slab soil vapour (or even indoor air) sampling may be considered during initial phase(s) of the assessment. This is done to help ensure that the building occupants are adequately protected early in the process, and not left unnecessarily exposed to any chemicals from soil vapour during the duration of the assessment process. Such conditions include the vapour source being located near (or beneath) a building or the presence of a potential preferential pathway that may result in enhanced (or un-attenuated) vapour migration into a building.

Effective characterization of soil vapour concentrations (e.g., from the source area to the building of potential concern) should support the design of an appropriate sampling program at each phase of the assessment. At a minimum, the planning stage of the soil vapour sampling program should consider the following:

- define clear study objectives (e.g., evaluation of the vapour intrusion pathway at existing buildings and/or future buildings);
- develop a CSM with specific consideration of factors that influence soil vapour conditions in the subsurface and vapour intrusion (e.g., geologic heterogeneity, possible temporal changes in site conditions, preferential pathways);

- define sample location and density (i.e., number and spacing of soil vapour probes);
- define timing and frequency for soil vapour sampling; and,
- prepare sampling and analysis procedures along with a QA/QC program.

Additional details on key considerations for the completion of a soil vapour sampling program are provided in Appendix III.

If the objective of the assessment is to predict exposure under planned future conditions (e.g., for brownfields redevelopment scenarios), the soil vapour sampling design should consider how land use changes and the built form of future buildings will affect soil vapour concentrations and data interpretation. Changes to surface conditions and development would generally tend to have the greatest effect on shallow vapour concentrations and the least effect on soil vapour concentrations near the contamination source. As such, it is recommended that soil vapour characterization programs meant to support future land use scenarios focus on collection of deep and near source soil vapour samples. Further guidance on selecting soil vapour sampling locations is provided in Section 5.3.3.

5.3.2 Considerations for Soil Vapour Sampling Locations

An important consideration for the design of a soil vapour characterization program is to identify representative sampling locations. While there is a continuum of possible sampling locations, it is helpful to categorize sampling locations as follows:

- deep and near source soil vapour;
- intermediate to shallow soil vapour (external to the building footprint); and,
- sub-slab vapour (immediately below the floor slab).

Some key issues and considerations with respect to each sampling location are summarized in Table 5.1. Further details are provided in Section 7.4.2 of the CCME (2016a) guidance manual.

Table 5.1. Comparison of Soil Vapour Measurement Locations

Type of Soil Vapour Data	Sampling Location	Characteristics	Use of Data and Cautions
Deep Soil Vapour *(External to Building Footprint)*	As near to water table or contamination source in vadose zone as practical, subject to considerations relating to capillary fringe and depth limitations for drilling.	Concentrations reach near-steady state conditions quickly, tend to be stable seasonally and are relatively unaffected by near-surface changes. Least affected by biodegradation. Should represent the highest concentrations of soil vapour.	If deep vapour concentrations are below target levels, the soil vapour to indoor air pathway is likely not significant. For future development scenarios, deep or near source vapour concentrations should be used.

Type of Soil Vapour Data	Sampling Location	Characteristics	Use of Data and Cautions
Intermediate to Shallow Soil Vapour *(External to Building Footprint)*	Closer to the building, but outside the building footprint. Intermediate sample depth should be mid-way between the elevation of lowest part of foundation and the vapour source. Shallow sample depth should be near to the elevation of the lowest part of the foundation	Higher spatial and temporal variability resulting from factors including geologic variability, biodegradation processes and weather and climatic factors such as precipitation, barometric pressure, temperature and wind. Greater potential for non-steady state conditions as distance from vapour source to measurement point increases.	Shallower soil vapour concentrations are expected to be lower than deep soil vapour concentrations. Shallow external soil vapour concentrations may under-predict concentrations below a building because of differences in biodegradation, soil moisture or other factors. Shallower soil vapour samples more susceptible to atmospheric short circuiting.
Sub-slab Soil Vapour *(Beneath Building Foundation)*	Immediately below foundation slab. Generally, central locations away from the foundation footings preferred.	Higher temporal and spatial variability expected as samples are affected by changes in near-surface conditions such as barometric pumping, temperature changes, HVAC systems, sub-slab utilities (e.g., drains, sewers), and variability in foundation subsoils. Greater potential for non-steady state conditions.	Logistical issues associated with sample collection. Sub-slab sample location may or may not be representative of the vapour concentrations entering the building and often require an appropriate sampling density and frequency to account for potential spatial and temporal variability.

5.3.3 Recommendations for Sampling Location

The sampling density (i.e., the number of samples and sample spacing) will vary on a site-specific basis. A soil vapour sampling plan should start with an identification of broad assessment objectives. Key considerations include whether vapour intrusion is being assessed for existing or future buildings, the location and extent of the vapour source(s) and buildings of concern, and location of any preferential pathways, if present.

Soil vapour sampling locations may be selected to characterize conditions at the contamination source (e.g., based on highest contaminant concentrations in soil and groundwater) or beneath the building to be investigated (e.g., sub-slab soil vapour). For existing buildings, sub-slab soil vapour samples from the areas of the building with the highest potential for adverse effects due to vapour intrusion are generally recommended, if practical. While proximity to the contamination source and sensitive receptors are typically the primary drivers for selecting sub-slab sampling locations, considerations should also be given to other site-specific conditions that may affect the intrusion of vapours into the buildings (refer to Section 5.3.3.2 for further information). For planned future buildings, sampling of deep and near source soil vapour is generally recommended.

Since soil vapour concentrations can exhibit considerable spatial variability (refer to Appendix IV for further information), it is generally recommended that soil vapour samples be collected at multiple locations and depth intervals between the vapour source and buildings of concern. This can provide a more comprehensive evaluation of the current and potential future risk of vapour intrusion. Lateral transects and vertical profiles can also be used to characterize spatial variability in soil vapour concentrations. Further guidance on lateral transects and vertical profiles is presented in Section 7.4.3 of the CCME (2016a) guidance manual.

Because of different factors affecting soil vapour concentrations and observed variability, additional discussion is provided below on recommended external soil vapour and sub-slab soil vapour sampling approaches.

5.3.3.1 External Soil Vapour (External to Building Footprint)

Both modeling and empirical data (CCME, 2016a; ITRC, 2007; USEPA, 2015a, 2012a, 2012b, 2012c) demonstrate that sub-slab soil vapour concentrations can be higher than external soil vapour collected outside the building footprint at comparable depths (i.e., 1 m to 3 m below the building foundation). This discrepancy may be expected at some sites, as differences in subsurface conditions outside of the building footprint, as compared to those vertically below the building foundation, can cause changes in the relative effects of various fate and transport mechanisms that affect soil vapour concentrations. For example, the potential capping effect of the foundation slab may result in greater concentrations of vapours beneath the building than at the same depth in adjacent open areas (USEPA, 2012b).

Since external soil vapour concentrations may not always be representative of conditions beneath the building foundation, the use of these data could potentially lead to non-conservative predictions of sub-slab soil vapour and/or indoor air concentrations at some sites. For this reason, caution should be exercised when external soil vapour data (particularly those collected at a shallow depth and/or near the buildings slab) are relied on as a primary line of evidence for the vapour intrusion assessment. For reference, ITRC (2007) indicates that external soil vapour samples that are collected near foundation at a depth of approximately 3 to 5 feet (or approximately 1 to 2 m) below the lowest floor may be an appropriate surrogate for sub-slab sampling.

Key considerations for selecting external soil vapour sampling locations are discussed in Section 7.4.3 of the CCME (2016a) guidance manual and are summarized as follows:

- Soil vapour samples should be collected on at least two sides of an existing building via probes located within 2 to 3 m of building (but beyond the zone of fill and disturbance surrounding the building foundation). One location should also be in the direction of the inferred highest soil vapour concentrations based on soil and groundwater data.
- When assessing a future development scenario, a minimum of two soil vapour probes are recommended at each APEC (additional probes may be warranted for delineation purposes). Deep (and near-source) soil vapour sampling is also recommended for assessing the future building scenario.
- For site screening or risk assessment purposes, deep (and near source) soil vapour data should be obtained, with a minimum recommended depth equal to half the distance between the building foundation and the vapour source.
- To minimize potential bias associated with atmospheric air leakage and variability introduced through shallow fate and transport processes, soil vapour samples should preferably be obtained from a minimum of 1 m bgs, although with appropriate precautions this depth can be reduced to 0.5 m. Some key considerations for shallow soil vapour sampling are provided in the CCME (2016b) suggested operating procedure.
- Where appropriate, vertical soil vapour profiles and lateral transects can be obtained to characterize spatial variability in soil vapour concentrations at selected locations.

5.3.3.2 Sub-slab Soil Vapour (Beneath Building Foundation)

The number and location of sub-slab soil vapour samples should be sufficient to characterize sub-slab soil vapour conditions and to address the potential for vapour entry into all parts of the building structure exposed to subsurface contamination. Field results demonstrate that there may be significant spatial variability in sub-slab soil vapour concentrations, depending on building-specific conditions. As such, it is recommended that sub-slab soil vapour samples be collected at multiple locations (refer to Appendix IV for further information).

While there are no simple solutions to obtaining representative sub-slab soil vapour data, certain measures can be undertaken to help improve the chances of collecting adequately representative samples (CCME, 2016a; McAlary et al., 2010):

- complete high density or high resolution sampling to characterize the spatial distribution of sub-slab soil vapour concentrations; and,
- utilize high purge volume soil vapour sampling to obtain spatially averaged sub-slab soil vapour concentrations.

For small to moderate sized houses, a minimum of two to three sub-slab vapour samples is generally considered reasonable for screening purposes. For larger buildings, a greater number of samples are warranted to characterize spatial variability and to delineate areas with elevated sub-slab vapour concentrations. Recommendations for the minimum number of sub-slab soil vapour samples, based on the building footprint area, are provided in Appendix 8b of the MOECC (2016a) guidance document. Such recommendations may represent an appropriate starting point. That said, the number and location of sub-slab samples should be also based on an assessment of building specific features and contamination conditions, which include, but may not be limited to, the following:

- building foundation types and conditions;
- homogeneity and composition of sub-slab material;
- building susceptibility to soil vapour entry (e.g., presence of sumps, elevator/utility pits, earthen/damaged floor);
- subsurface contamination location and distribution relative to the building foundation; and,
- areas within a building with different receptors and/or HVAC systems.

Where practical, it is generally recommended that sub-slab soil vapour samples be collected near the central portion of the building and away from locations where indoor or outdoor air could be drawn into the sub-slab samples (e.g., cracks in foundations, exterior walls, etc.). Collection of soil vapour at deeper locations beneath the building is also recommended when there is the potential for indoor air and soil vapour exchange.

For some cases (e.g., large buildings), high purge volume sub-slab sampling may be considered to reduce the number of sub-slab soil vapour samples. Fewer samples may also be considered when the extent of the soil vapour plume is expected to underlie only a portion of (or external to) a building footprint.

5.3.4 When to Sample and Sampling Frequency

Investigation of the vapour intrusion pathway will often require multiple rounds of soil vapour sampling as there can be significant temporal variability in soil vapour concentrations. Such variability is generally due to soil vapour migration, hydrogeological factors, meteorological conditions, and building and/or utility-related factors.

The vapour intrusion literature presented in Appendix IV suggests that the temporal variability in soil vapour may be one to two orders of magnitude and that this variability can be attributed to different site-specific factors. Therefore, it is important to consider key factors affecting vapour intrusion when determining the timing and frequency of soil vapour sampling. Such consideration may also improve data interpretation and the confidence in decision making regarding the vapour intrusion assessment.

Key factors affecting such variability may include, but may not be limited to, the following:

- **Temperature:** Effects on soil vapour concentrations due to changes in the vadose zone temperature are reported to be minimal (ITRC, 2007), although higher shallow soil temperatures may, in some instances, result in higher VOC volatilization rates and therefore increase the rate of vapour intrusion during the summer. Also, the difference between indoor and outdoor temperature may result in stack effects that can significantly impact the intrusion of soil vapour into a building (refer to Section 6.2.4 for further information). These stack effects include not only the winter stack effect, but also solar stack effects generally observed during summer and early fall (USEPA, 2015c).

- **Precipitation:** Soil vapour sampling results can be sensitive to weather changes, particularly for shallow samples. Soil vapour sampling should not be conducted during and immediately after heavy rainfall events, as the collection of a representative sample may be difficult under such conditions. In addition, infiltration of water into soil can result in a reduction in soil vapour concentrations due to partitioning of vapour into soil moisture and, in some cases, induce advective movement of soil vapour. The time for moisture to drain from soil pores will depend on the soil type. Coarse-grained soil (sand or gravel) will typically drain to field capacity within a few hours (from complete saturation) while fine-grained soil will generally take longer to drain (Hillel, 1982). Field capacity is the soil water content after water drainage by the force of gravity is mostly complete. Based on drainage data, it is recommended to wait at least one day after a heavy rainfall event (defined here as 0.5 cm) for coarse-grained soils (sand or gravel) prior to sampling, and several days for fine-grained soils.

- **Barometric pressure***:* The effect on soil vapour concentrations due to barometric pressure are generally insignificant at depths greater than 1-2 m bgs or under surface cover (ITRC, 2007). Routine consideration of barometric pressures in the timing of sampling programs is neither practical nor warranted in a majority of cases; however, weather data, including barometric pressure, should be obtained from the nearest meteorological station for the period when the sample was collected (e.g., for a period starting several days before the sample was collected and extending to several days after the sample was collected). Such data can be useful in data interpretation. It should be noted that barometric pressure fluctuations can cause significant effects on soil vapour concentrations when a very thick (and permeable) coarse-grained unsaturated zone is present. Under such conditions, the possible effects of barometric pressure fluctuations should be incorporated into the design of the soil vapour sampling program, and it may be appropriate to only obtain soil vapour samples when the barometric pressure is decreasing.

- **Frozen ground**: It is hypothesized that, depending on the moisture of the ground when it freezes and the properties of the snow cover, there may be reduced fluxes of vapours and oxygen through this frozen layer. This would potentially reduce vertical migration and increase lateral migration of soil vapour. However, Hers et al. (2014) examined the influence of snow and frost cover at one cold climate site and indicated little effect on seasonal soil vapour concentrations. Given that there has been limited investigation of this factor, consideration may be given to repeat sampling of soil vapour beneath the frozen layer for both frost and non-frost cover conditions on a site-specific basis.

- **Groundwater condition:** If groundwater impacts are the principal vapour source, groundwater concentrations and water table fluctuation data may be necessary for assessing the potential for vapour intrusion. For example, rising groundwater levels move the source closer to the occupied space, increasing the potential for vapour intrusion. In some situations when the groundwater level drops, soil contamination, which was previously submerged, could be exposed, thereby increasing volatilization of VOCs. Therefore, soil vapour sampling may be necessary during periods of both falling and rising groundwater levels on a site-specific basis. This includes sites where a substantial smear zone, which could be exposed by decreasing groundwater levels, is known or suspected to be present.

In general, it is recommended that soil vapour samples be collected in a manner that is likely to produce reasonably conservative predictions of vapour intrusion. Consequently, it is recommended that samples be collected when higher soil vapour concentrations representative of seasonal "worst case" conditions are expected. When there are contradictory lines of evidence for the identification of a worst-case season, several rounds of sampling during different seasons are generally recommended to characterize concentration variability.

The number of sampling events should also consider the specific objectives of the investigation and the results of initial soil vapour testing. One sampling event with sample results exceeding the respective SVSL may be sufficient to confirm the potential for the vapour intrusion pathway is of concern. However, multiple sampling events would be required to demonstrate that a vapour intrusion pathway is unlikely to be of concern.

The determination of sampling time and frequency should be based on the assessment of site-specific conditions in order to account for temporal and seasonal variability. Recommendations for sampling frequency are provided below as general guidance:

- If soil vapour concentrations are well below their respective SVSLs (e.g., 10 to 100 times lower), a minimum of two sampling events may be sufficient to demonstrate that a vapour intrusion pathway is unlikely to be of concern, unless a major change in conditions occurs at the site (e.g., elevated water table or significant seasonal change in rainfall). The sampling events should be at least three (3) months apart over two different seasons with at least one event performed during the reasonable worst-case conditions.
- When soil vapour concentrations (or LRLs) are near the SVSLs or site conditions suggest significant variations between sampling events, additional sampling events should be completed to address the seasonal and/or temporal variability. Consideration should be given to sampling soil vapour for more than one year to characterize the influence of inter year climatic variability.

5.3.5 Biodegradation Assessment

As previously discussed in Sections 4.4.2 and Appendix I, under certain environmental conditions, the vapours of some chemicals (particularly PHCs) may naturally biodegrade in the unsaturated zone. This can result in a substantial reduction of PHC concentrations in vapours over relatively short distances in the vadose zone. Thus, an evaluation of the vapour intrusion pathway may not be required if the distance between a PHC vapour source and the building foundation is sufficient to allow PHC vapours to attenuate to concentrations below the levels of concern.

Key factors affecting biodegradation below buildings include contaminant source type and concentrations, depth of the source below the building, building size, presence of surface cover (and potential capping effect), distribution of contamination below the building, and geochemical conditions able to support microbial activity (refer to Appendix I for further information). As biodegradation can be site-specific, testing of soil vapour for biodegradation indicators may be necessary to characterize the biodegradation reaction zone (e.g., evidence of sufficient oxygen for aerobic biodegradation).

The recommended approach for a biodegradation assessment, when required, includes sampling both target chemicals (e.g., PHCs and BTEX) and some key indicator parameters (e.g. O_2, CO_2 and CH_4). These indicators are useful for assessing both aerobic and anaerobic biodegradation processes. For example, depleted oxygen and elevated CO_2 levels indicate aerobic biodegradation of hydrocarbons while elevated CH_4 levels indicate anaerobic biodegradation.

Other parameters may also prove useful in assessing biodegradation and vapour intrusion. For example, testing of nitrogen is recommended for quality control purposes and as an indicator of potential soil gas advection (Jourabchi et al., 2013). Consideration should be given to the analysis of other chemicals that are potentially less biodegradable (e.g., cyclohexane, 2,2,4-trimethylpentane), if present at the site. Such chemicals may serve as useful tracers for non-degradative processes (Sanders and Hers, 2006).

5.4 Soil Vapour Probe Construction and Installation

Soil vapour probes can be constructed of a variety of materials and installed using several techniques (Atlantic PIRI, 2016; CCME, 2016a). The main options for the installation of soil vapour probes include:

- probes installed in boreholes in soil or coreholes through a concrete slab;
- probes installed and advanced using direct push drilling;
- probes driven directly into the subsurface; and,
- sub-slab soil vapour probes.

Further discussions on the installation methods for each of the above probe types and other considerations (e.g., probe materials, potential for short circuiting of atmospheric air) are included in Section 7.5 of the CCME (2016a) guidance manual.

5.5 Soil Vapour Sampling Procedures

The collection of representative soil vapour samples depends on a number of factors. Such factors include the integrity of the sampling apparatus, probe construction, sampling procedure, geologic variability and weather conditions. Different testing procedures are required to confirm if soil vapour sampling is practicable at a particular location and to ensure that the collection of soil vapour samples will yield reliable results that are representative of actual site conditions.

The following discusses some key considerations for collection of soil vapour samples. Further details and suggested operating procedures (SOPs) can be found in Section 7.6 of the CCME (2016a) guidance manual and SOP No. 5 and 6 of the CCME (2016b) guidance document:

- **Soil Vapour Probe Development and Equilibration**: This step should be done for new probes prior to sampling by:
    - Removing air entrained in the sand pack during installation, by purging a minimum of three probe volumes of air (including the probe volume, tubing volume and air-filled pore volume of the sand pack); or,
    - Allowing soil vapour within the probe to reach equilibrium, via diffusion of surrounding soil vapour. The recommended time that allows a probe to re-equilibrate is dependent on installation techniques; for example, 20 minutes for driven probes and a week for probes installed in a hydro-vac hole.
- **Flow and Vacuum (Probe Performance) Check**: This test should be performed for selected probes to ensure the flow and vacuum are within acceptable ranges and the estimated soil-air permeability is consistent with geologic materials surrounding the probe. Flow and vacuum measurements can be also helpful in identifying situations where additional care or remedial steps should be exercised. Such situations may include:
    - Probes may be plugged or within the saturated zone, if the vacuum is much higher than expected.
    - There may be short circuiting or a leak in the sampling train, if the vacuum is much lower than expected.
- **Leak Testing of Probes**: This test should be performed at all new probes and existing probes that are being re-sampled to assess whether there is an introduction of atmospheric air into probes. If the leak test is only completed for a sub-set of probes, a detailed supporting rationale for this limited testing should be provided. A probe leak test can be done by applying a tracer compound (either tracer gases, such as helium and SF6, or volatile liquid tracers, such as iso-propanol) at the base of the probe (typically within a shroud). The probe leakage is defined as the concentration of a tracer compound in soil vapour divided by that in the shroud (multiplied by 100). The leakage can be evaluated and interpreted using the following criteria:
    - Acceptable limits for leakage are less than 2%.
    - A leakage of greater than 2% indicates greater uncertainty in the sample integrity, and results should be qualified. While it is recommended that probes be fixed (or replaced) and leak check repeated, correction factors may be applied to the measured vapour concentrations, if the leakage is less than 10%.
- **Leak Testing of Sampling Train:** A leak test for each sampling train should be performed to ensure that leakage of the sampling train is within acceptable limits. This test can be done using the leak tracer test (similar to leak testing for probes) or shut-in vacuum test. If the leakage is greater than 2%, it is recommended that the sampling train be fixed and the leakage rate rechecked.
- **Probe Purging**: This step should be done for all probes to ensure a representative soil vapour sample is collected by removing stagnant air from the probe and filter pack and allow the probe to equilibrate prior to sampling. Key considerations with respect to probe purging include the following:

  - In general, a minimum of three probe volumes should be removed prior to sampling.
  - Best practices typically include collecting soil vapour samples once field indicators (e.g., organic vapours, O_2, CO_2) measured using a hand-held photoionization detector (PID) have stabilized (e.g., +/- 10% from previous sample).

- **Soil Vapour Sampling**: There are various soil vapour sampling devices (e.g., evacuated steel canisters and sorbent tubes). The selection of an appropriate device is often driven by the study objectives, site specifics (e.g. COPCs and geologic conditions), and requirements with respect to analytical methods and LRLs. Each sampling device may require different procedures for collecting, handling and storing along with sample and field quality control measures to ensure that the data quality objectives are met.

5.6 Soil Vapour Analysis

Different analytical testing methods can be used for analyzing soil vapour samples. The analytical method selected depends on the vapour intrusion assessment objectives, the applied sampling method and data quality objectives. Soil vapour programs often consist of a combination of field testing of soil vapour samples using hand-held detectors and laboratory analysis of target COPCs. Common soil vapour sampling and analytical methods are summarized in Table 7.3 of the CCME (2016a) guidance manual.

It is important to understand the various analytical procedures for soil vapour and air samples as well as their potential limitations. Further details on analytical methods for soil vapour are presented in Section 7.7 of the CCME (2016a) guidance manual. Some general guidance with respect to analysis of PHCs in soil vapour and air samples is presented in Attachment I.1 of Appendix I.

Since soil vapour and air methods are not as well defined as methods for soil and groundwater, adequate consultation with the laboratory is essential. The following should be discussed: optimal sampling flow rate and duration, detection limits, field and laboratory QA/QC requirements and considerations, and the handling and transport of samples. Communication with the laboratory during the planning stages of a program will help ensure that important analytical considerations are taken into account during the development of the sampling plan.

The laboratory should be accredited by an internationally recognized accreditation body (e.g., Standards Council of Canada or Canadian Association for Laboratory Accreditation) in accordance with the International Standard ISO/IEC17025:2005 - *General Requirements for the Competence of Testing and Calibration Laboratories*.

5.7 Ancillary Data

Ancillary datasets are essential to the effective interpretation of soil vapour results. Such data includes, but may not be limited to, the following:

- passive soil vapour samplers being deployed for longer sampling durations (e.g. days to weeks) to provide time-integrated soil vapour data;

- physical properties of soil in the vadose zone (e.g., soil moisture, bulk density, soil-air permeability, water-filled porosity and total organic carbon content) to support the vapour intrusion assessment (e.g. vapour intrusion modeling);
- hydrogeological properties and data (e.g., groundwater elevation and hydraulic conductivity) to understand the seasonal influence on volatilization of COPCs from impacted groundwater;
- meteorological data (e.g., temperature, barometric pressure, wind speed and direction, relative humidity and precipitation) to better understand the potential seasonal and temporal variability in soil vapour measurements;
- building pressure data (e.g. differential pressure between the building and outdoor air, and between building air and sub-slab soil vapour) to assess the potential for vapour intrusion occurring at the site;
- building ventilation (e.g., measured using tracer gas) to better understand the potential of indoor dilution;
- tracer test (e.g., using naturally-occurring radon) to evaluate sub-slab to indoor air attenuation or to evaluate potential preferential pathways;
- flux chamber test used to measure the emission flux rate of COPCs from surface soil to indoor air;
- larger-scale tracer and pneumatic testing to estimate soil-air permeability and to evaluate soil vapour migration pathways; and,
- tree core analysis for volatile COPCs to assess contamination distribution in the subsurface.

Ancillary data should be collected as part of the ESA work completed prior to, or during, soil vapour sampling; however, if not collected, some of the required data may be collected after the soil vapour sampling is completed. Additional details on relevant ancillary data for vapour intrusion assessments, as well as the associated interpretation of such data, are available in the CCME (2016a) guidance manual.

5.8 Data Interpretation and Analysis

The procedures for data interpretation and analysis of soil vapour data are described below. Some key considerations when reviewing or implementing soil vapour investigations and assessments are provided in Appendix III.

5.8.1 Data Organization and Reporting

The soil vapour data should be tabulated and plotted to facilitate evaluation and review of data relationships and trends. The following data organization and presentation methods are recommended:

- tabulate all data including sample location identifier, sample date, sample depth, sampling methods (including sampling duration and flow rate), chemical analysis methods, laboratory detection limits, results of chemical analysis, applicable SVSL;

- tabulate field screening and laboratory analysis data to enable side by side comparisons;
- prepare plan drawings showing soil vapour concentration data that includes pertinent structures (buildings, utilities, paved areas, vegetated areas);
- compare soil vapour with nearby groundwater concentration data and consider geologic conditions when evaluating variability; and,
- prepare vertical profiles of soil vapour concentration data that include O_2, CO_2, CH_4, and show borehole log data, where available.

5.8.2 Data Quality Analysis

Following receipt of the soil vapour analytical results, the data should be evaluated to determine whether they meet the data quality objectives outlined in the sampling plan. The data quality checks should include the following:

- Review reported detection limits relative to the data quality objectives. In some cases, sample dilution may be required, which may result in raised detection limits.
- For evacuated canister analyses, review canister pressure before start of sampling, upon completion of sampling and upon receipt by the laboratory.
  - Prior to sampling, the vacuum should be greater than 27 inches Mercury (in Hg, at sea level), and after sampling is completed, there should be a vacuum remaining in the canister (ideally between 4 and 6 in Hg, but no more than 10 in Hg).
  - As indicated in the suggested operating procedure (SOP No. 5) of the CCME (2016a) guidance manual, if there is no vacuum left in the canister after sampling, the data may be still considered valid for short duration soil vapour sampling (i.e., typically less than 2 hours); however, results should be flagged.
  - For longer duration air sampling (i.e., typically 8 or 24 hours), there should be a residual vacuum for the sample to be considered valid. Both MDEQ (2013) and NJDEP (2018) suggested that if the residual vacuum is 1.0 in Hg or less, the sample should be considered invalid.
  - The vacuum should also be measured upon receipt by the laboratory and significant differences in laboratory and field vacuum (i.e., beyond the range of accuracy of the vacuum gauge) generally indicate potential leakage during transit. The effect of temperature variation on pressures should be considered when interpreting these results.
- For sorbent tube analyses, review results of analyses of front and back sections of the tube (or two tubes in series or parallel obtained at different flow rates) to evaluate possible chemical breakthrough.
  - Breakthrough can result when the adsorptive capacity is exceeded, the air flow through the tube is too high, or by chromatographic effects caused by other chemicals.

  - If the laboratory considers the first tube saturated, then results are potentially biased and re-sampling should occur.
  - The criterion for evaluating breakthrough is method and chemical dependent but typically is a concentration in the second tube that is greater than 10 to 25 percent of the concentration in the first tube.
  - If the sample media is not saturated, the front and back concentrations of the tube should be added together when reported.
- Compare the precision for laboratory and field duplicate or co-located samples, as quantified by the relative percent difference (RPD).
  - The acceptable precision is method and chemical dependent. For USEPA TO-15, the performance criterion for relative percent difference between laboratory duplicates is generally 25%.
  - For field duplicates, the acceptable RPD is higher since there is sampling variability in addition to laboratory variability. A provisional RPD for field duplicates is 50% based on the current state of knowledge.
- Review analytical results for available blank samples (e.g., field transport blanks) to identify possible issues with the laboratory or field procedures that may have affected the results.
- Recognize that reported concentrations within five times of the quantification limit are typically more uncertain than higher concentration values.

5.8.3 Data Consistency Analysis

The results of the soil vapour sampling program should be reviewed in terms of the expected results, based on consistency with the conceptual site model and internal consistency between sampling points. These consistency checks should include the following:

- The soil vapour concentrations should be spatially consistent with the soil and groundwater concentrations. For example, the highest soil vapour concentration should be found in source contamination areas where soil and/or groundwater concentrations are also highest.
- When there is a dissolved groundwater source, measured soil vapour concentrations should be less than groundwater concentrations multiplied by the dimensionless Henry's Law constant, since there will be attenuation of chemicals through the capillary transition zone. The magnitude of the difference should increase as soil becomes finer-grained (without significant secondary porosity), and in areas of elevated recharge (e.g., due to irrigation).
- When there is a localized contamination source above the water table, diffusion in all directions from the source will occur; depending on the size and distribution of the source, a radial diffusion pattern may be observed.

- The soil vapour concentrations should generally decrease with increasing distance from a source.
- The vertical gradients of PHC vapours, O_2, CO_2, CH_4 and nitrogen, if collected, should be internally consistent.
    - Typically, an increase in PHC vapour concentrations should be associated with a decrease in oxygen and increase in carbon dioxide concentrations (refer to Section 7.10.3 of the CCME (2016a) guidance manual for further information).
    - Depleted nitrogen concentrations can indicate the potential for advective soil gas transport (Jourabchi et al., 2013).
    - As described in the American Petroleum Institute’s guidance (2005), stoichiometric relationships for aerobic biodegradation can be used to quantify the fluxes and concentration profiles expected. If this pattern is not observed, there may be additional contamination sources present or there may be data quality issues (e.g., short circuiting).
- Significant depletion in oxygen concentrations should be observed close to PHC source zones and below confining layers. Elevated oxygen concentrations close to PHC sources indicate that the soil vapour sample was compromised through short-circuiting or leakage.
- The potential influence of preferential pathways including sewers should be taken into account.
- Soil vapour concentrations should be consistent with expected temporal trends based on an analysis of available temporal data and expected variation based on potential indicators for vapour intrusion such as indoor-outdoor temperature difference or other factors.

5.9 Further Evaluation

Data quality and consistency should be evaluated to determine whether there are data gaps or quality issues that warrant additional soil vapour testing. The soil vapour concentrations will typically be compared to risk-based generic (if available) or site-specific screening levels for the vapour intrusion pathway. Depending on the results of this comparison, additional soil vapour characterization and/or indoor air testing may be warranted.

CHAPTER 6 INDOOR AIR QUALITY TESTING FOR VAPOUR INTRUSION ASSESSEMENT

This chapter was developed in parallel with the following guidance documents:

- CCME (2016a) *Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment* – Volume 1 Guidance Manual; and,
- SABCS (2011) *Guidance on Site Characterization for Evaluation of Soil Vapour Intrusion into Buildings.*

Therefore, there are text and figures common to this chapter, Chapter 8 of the CCME (2016a) guidance manual and Chapter 4 of the SABCS (2011) guidance document. Where warranted, modifications have been made to reflect the policy of the Ministry and the conditions in Ontario.

6.1 Context, Purpose and Scope

The testing of IAQ generally occurs as part of the latter phase(s) of a vapour intrusion assessment. Such testing can be useful when the results of earlier phases of the investigation indicate the potential for adverse effects from vapour migration into indoor air. IAQ testing may also occur as part of earlier phase(s), particularly when adverse impacts to indoor air are considered likely (refer to Section 4.2.2 and Section 6.3.6 for further information).

The use of IAQ measurements to evaluate potential health risk associated with vapour intrusion is an option when evaluating a current exposure scenario (i.e., occupants of an existing building). While indoor air testing can provide a direct measurement of potential inhalation exposure, there are a number of issues that can complicate a vapour intrusion investigation based solely, or primarily, on indoor air measurements. These issues include background sources of the COPC and significant variability often observed in indoor vapour concentrations due to building construction, HVAC operation, weather conditions and other factors. An IAQ testing program is also a relatively intrusive activity that, particularly for a residential or institutional setting, requires appropriate communication of program objectives and results with the building owners and occupants.

The basic steps for the design of an IAQ program are similar to those described for soil vapour characterization and consist of the following:

- define the IAQ study objectives;
- develop a CSM, with specific consideration of factors that influence IAQ based on site conditions; and,
- prepare an indoor air sampling and analysis plan.

Similar to soil vapour characterization, it is not possible to provide a standardized template for IAQ program design. Instead, key principles and factors that should be considered in developing a sampling strategy are discussed below. A detailed flowchart outlining the framework for an IAQ study is provided in Figure 6.1.

Indoor air sampling should be carried out according to an established plan, considering the study objectives and the data quality objectives; however, the plan should be flexible in that if the circumstances change, the plan can be adapted accordingly. In addition, if relevant information is obtained from activities such as the pre-sampling building survey or preliminary assessment, the program should be refined and revised to address these changes.

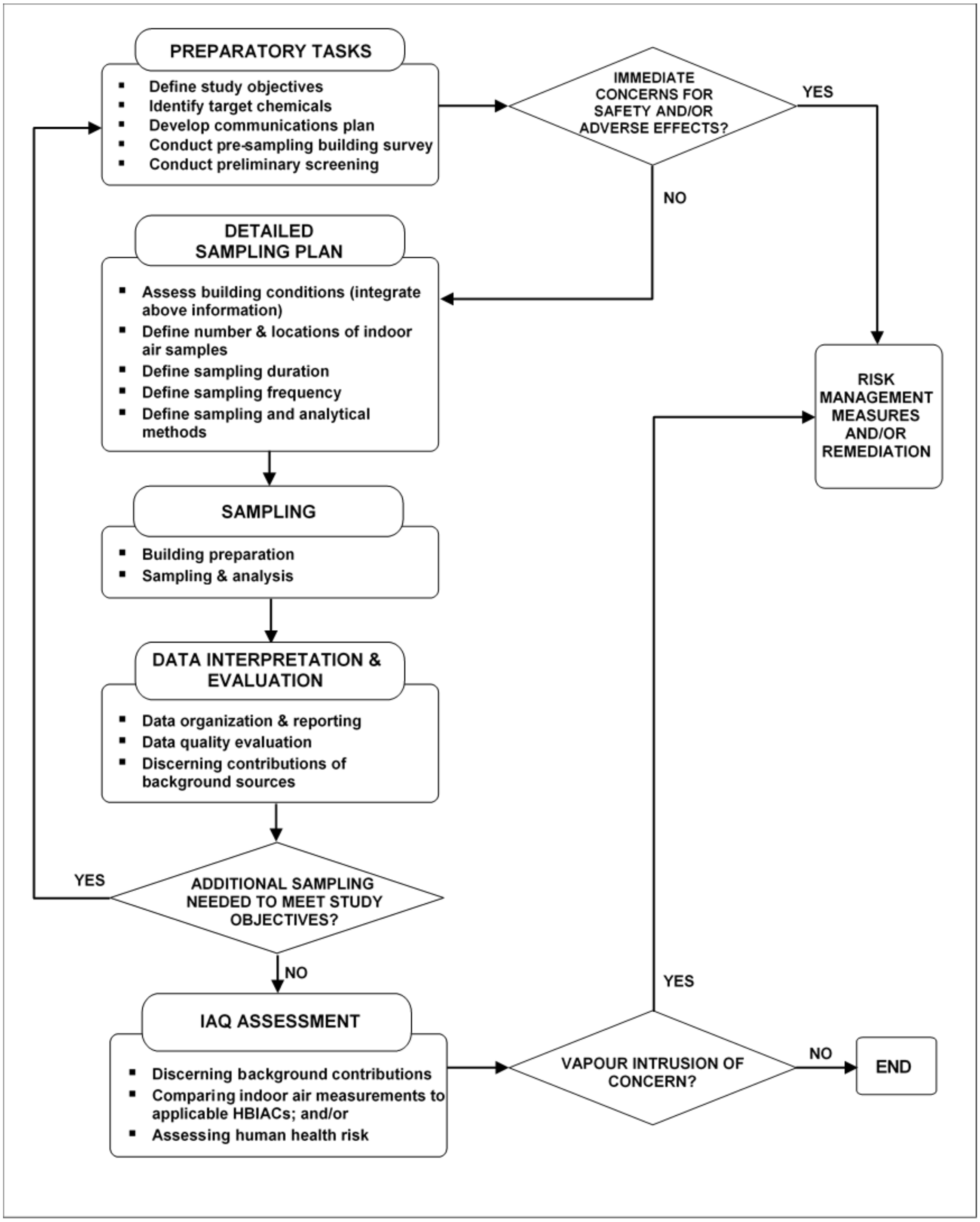

Figure 6.1. Framework for IAQ Sampling and Analysis Program

IAQ studies for assessment of vapour intrusion typically include some concurrent testing of outdoor air as well as sub-slab or near building soil vapour testing. Sub-slab or near building soil vapour samples may be used to identify chemicals that have the potential to migrate into indoor air. Similarly, outdoor air samples may provide information with respect to the influence of ambient air quality on IAQ. These types of samples may provide additional lines-of-evidence that are helpful in assessing potential vapour sources.

6.2 Conceptual Site Model for Indoor Air

The CSM for soil vapour transport and intrusion into buildings is described in Chapter 3. The purpose of this section is to describe specific aspects of the CSM that could influence IAQ (excluding subsurface factors).

6.2.1 Background Indoor Air Concentrations

When evaluating the impact of subsurface vapour sources on IAQ, it is important to note that indoor sources and outdoor sources that are unrelated to subsurface contamination (referred to as “background sources”) may also contribute to the concentration of volatile chemicals in indoor air.

Examples of common indoor background sources include:

- household products (e.g., cleaning solvents);
- off-gassing from building products (e.g., carpeting, shower curtains, building insulation, pressed wood products, fabrics);
- home heating (e.g., heating oil storage, combustion emissions);
- tobacco smoke;
- attached garages (e.g., vehicle emissions, stored products); and,
- volatilization from tap water (particularly when heated).

Examples of common outdoor background sources include:

- vehicle emissions;
- outdoor equipment emissions (e.g., gas-powered lawnmowers, paving equipment); and,
- industrial emissions (e.g., smokestacks, fugitive emissions).

Due to the presence of indoor background sources, indoor air concentrations of various chemicals are frequently higher than outdoor air concentrations (refer to Figure V.1 of Appendix V for further information). Examples of some common indoor air sources and associated volatile chemicals are provided in Table V.1 of Appendix V. Additional information on chemicals present in various consumer products is described in the following household product databases:

- U.S. National Library of Medicine (USNLM), *Household Product Database* (URL: https://www.nlm.nih.gov/toxnet/index.html), and,
- New Jersey Department of Environmental Protection (NJDEP), *Common Household Sources of Background Indoor Air Contamination (URL:* http://www.nj.gov/dep/srp/guidance/vaporintrusion/household_sources_of_contamination.pdf).

A number of studies evaluating background IAQ for Canadian residences were completed between 1990 and 2010. A summary of these studies is presented in Tables V.2 to V.4 of Appendix V. In general, these studies indicated the presence of various VOCs indoors, with considerable variation in the measured indoor air concentrations within and between the studies. This variability can be attributed to differences in sampling methods (e.g., sorbent tubes versus evacuated canisters), sampling time (e.g., winter versus summer, different study years from 1990 to 2010), geographic settings, climatic conditions, building characteristics (e.g., air exchange, building age, and products/materials used indoors), and outdoor air conditions.

Indoor air concentrations from more recent studies have tended to be lower than those from earlier studies. For example, lower indoor air concentrations were observed in the more recent (post 2000) studies than those reported in the earlier (1990s) studies for a number of chemicals (e.g., BTEX, as shown as examples in Figure V.2 of Appendix V). This observation is consistent with data reported in US studies (USEPA, 2011).

The decrease in indoor air concentrations, especially for benzene and trichloroethene (TCE), is expected to continue in the future as more environmentally friendly consumer products and building materials (e.g., low VOC or water-based products) are developed and used in homes. USEPA (2015a) also suggested that the introduction of regulations and practices that promote the use of less toxic chemicals in consumer products and industrial processes and that also reduce emissions from mobile and stationary sources are likely to result in improvements to IAQ in the future.

For these reasons, current or future indoor air concentrations for volatile chemicals in a building are expected to be lower than those observed historically. This should be taken into consideration when using historical literature data presented in Appendix V (or other references) to interpret the IAQ data collected during site-specific vapour intrusion investigations (refer to Section 6.5.3 for further information).

Due to the possible presence of multiple sources and their varying contributions to the total indoor air concentration, differentiating between sources becomes important when assessing soil vapour intrusion into buildings. Particular care must be taken in the collection, review and interpretation of IAQ data to support the vapour intrusion assessment. For instance, it is important to understand as well as to minimize the effects of indoor sources through an assessment of building conditions and proper building preparation prior to sampling (refer to Exhibit 6.1 for further information). A summary of methods to evaluate the contributions of background sources, including the comparison to literature background indoor air data, is provided in Section 6.5.3.

6.2.2 Building Foundation Construction

Building foundation construction may influence soil vapour intrusion rates into the building. For example, soil vapour can migrate through relatively small cracks or openings in the foundation or through utilities such as sewers, drains or sumps. Soil vapour intrusion rates may also vary depending on the types of foundation, which may include basement, slab-on-grade, crawlspace or earthen floor construction. That said, a study prepared for Health Canada (Golder, 2010) indicated that little difference was observed in vapour attenuation factors for different foundation structures.

For houses, there is often a perimeter edge crack between the foundation wall and the concrete floor slab. For commercial buildings, construction methods are more variable. For some buildings, measures are taken to seal concrete foundations, which may reduce vapour intrusion. Regardless of the building type, utilities represent potential entry points for soil vapour intrusion.

Building foundations may also influence the potential for aerobic biodegradation of PHCs under such buildings. This is because of the potential for reduced oxygen migration to areas below buildings. Empirical soil vapour data compiled in the USEPA (2013) technical document, however, did not indicate significant oxygen depletion below small to medium sized buildings above PHC contamination. Hers et al. (2014) also suggests that significant oxygen transport may occur both through intact concrete via diffusion and through cracks and laterally from beyond the building through advective processes driven by building depressurization, wind and barometric pressure fluctuations.

Regardless, caution should be exercised when evaluating the aerobic biodegradation of soil vapour under buildings, particularly under large buildings with competent slabs exhibiting low diffusivity and low permeability. This is because such conditions may appreciably limit oxygen migration.

6.2.3 Building Ventilation

Building ventilation (natural or mechanical) is known to be a key contributing factor to vapour intrusion and IAQ. For example, through building ventilation and exchange with fresh air, soil vapour concentrations can be diluted upon mixing with indoor air.

Building ventilation data can be expressed in different metrics which include, but may not be limited to, the following:

- air change per hour (ACH), a ratio of the outdoor air intake volume per hour to the air filled volume of a relevant space; or,
- airflow rate per person and airflow rate per unit area, the volumetric flow rate of outdoor air required for a building occupant or a unit area of occupiable space.

Minimum ventilation rates are mandated for most buildings in both Canada and the United States, with standards and codes generally implemented at the provincial or state level (Mudarri, 2010; Health Canada, 2018). Examples of common standards, to which numerous local building codes refer, include American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) Standards 62.1-2016, 62.2-2016 and CAN/Canadian Standards

Association (CAN/CSA)-F326-M91 (R2014) (ASHRAE, 2016a, 2016b; CSA, 2014). These standards require different minimum ventilation rates in accordance to the number of occupants, building size or occupant activities, etc. For example, CAN/CSA-F326-M91 (R2014) requires ventilation rates of 5 to 10 L/s of outdoor air for each house occupant which correspond to roughly a complete house air change every three hours (or ~ 0.33 ACH; Health Canada, 2018). In Ontario, the building ventilation requirements must be in compliance with those set out in the Ontario Building Code (O. Reg. 332/12 - Building Code).

Empirical data from a number of studies on air exchange rates in U.S. and Canadian homes (e.g., Aubin et al., 2010; Gilbert et al., 2008; Murray and Burmaster, 1995; Otson and Zhu, 1997; Walkinshaw, 1987) suggest a wide range of air exchange rates (but generally less than 0.5 ACH), with key factors including the type or age of the homes, weather and geographic location. Key findings of these studies are summarized in Section 8.2.3 of the CCME (2016a) guidance manual.

Air exchange rates in industrial, commercial and institutional buildings tend to be more variable, but are often expected to be higher, on average, than residential buildings. This is because such buildings may house more people per unit floor area and may house activities that require greater ventilation (e.g., commercial cooking in a restaurant, industrial applications in a factory, etc.). For example, the USEPA Building Assessment Survey and Evaluation Study of one hundred randomly selected commercial buildings found that the 25th, 50th and 75th percentile ACH values were 0.47, 0.98, and 2.62, respectively (NIST, 2009). The study noted that the selected buildings represented a wide range of buildings, both with respect to construction and usage.

When conducting a site-specific assessment, it may be instructive to obtain information on building ventilation from building HVAC engineers. Design and test information on air flow rates for return and supply air is often available and may prove useful in assessing the potential for vapour intrusion.

6.2.4 Building Pressure and Weather Condition

Building pressures can have a significant effect on the rate of soil vapour intrusion into buildings, as well as the degree of mixing and dilution within the building structure. As such, it is important to understand key factors and their resulting effects on building pressures, when assessing the potential risk for vapour intrusion and designing a soil vapour intrusion mitigation system. Examples of key factors affecting the building pressure include the following:

- Stack effect often involves the movement of air due to density differentials (primarily a function of temperature and humidity). In general, hot and/or moist air will tend to rise in a building and may exit the top of the building (e.g., through a chimney, leaky attic, exhaust vent). This can create a negative pressure in the building, which is generally a driving force for the infiltration of outdoor air and soil vapour into the building through openings within the lower regions of the building (e.g., doors, windows, cracks within the building foundation). Houses with basements were typically found to be under-pressurized 2 to 10 Pascal (Pa) (but can be as high as 15 Pa), when assessed during heating season (Figley 1997, Hers et al. 2001). While there is limited data for slab-on-grade homes, such homes would be expected to have lower pressure differentials, with under pressurizations on the order of 2 to 4 Pa (Hers et al., 2001).

- The design and operation of HVAC systems can also play an important role in building pressurization. For example, imbalanced HVAC systems (i.e., where air intake does not adequately balance air exhaust) can lead to a difference in air pressure between the inside and outside of the house (either negative or positive). The HVAC system may be designed to provide for positive pressure under most conditions (except in certain parts of the building based on code requirements, i.e., garages). That said, the stack effect occurring inside high-rise buildings may be still sufficient to maintain a negative pressure at ground level during cold weather.
- Climatic conditions can also influence building pressures. Wind force can create pressure differentials between upwind and downwind sides of the building, which may cause building depressurization. Additionally, barometric pressure changes can cause pressure differences between the building interior and exterior. These pressure differences may occur at varying temporal scales (hourly to seasonally), but in general, the most significant pressure differences occur under severe winter conditions.

6.2.5 Mixing of Vapours Inside Building

Once within the building, soil vapour will migrate as a function of advection and dispersion due to the movement of air and will also diffuse as a result of concentration gradients. In addition, the mixing of vapours inside a building may occur between building floors and this process often depends on the HVAC system and air leakage between floors.

Elevator shafts, when present, may also play an important role in the movement of soil vapour in indoor air. Elevator shafts often include a sump with a drain hole at the bottom, which may allow entry of soil vapour into a building. Elevator shafts can also represent conduits for the vertical migration of vapours between building floors.

6.2.6 Vapour Depletion Mechanisms

Chemical or physical mechanisms (e.g., adsorption on to building materials, chemical transformations due to photo-oxidation) may result in the removal of vapours from indoor air, in addition to the dilution that may occur through building ventilation. However, such mechanisms may not have significant effects on IAQ, except where specific measures are undertaken to actively treat IAQ issues (e.g., use of activated carbon filters).

Since vapour intrusion typically occurs over a timescale of months to years, the removal of volatile chemicals in air through adsorption onto building materials is unlikely to have a significant long-term effect on indoor air concentrations, as adsorption sites on building materials will likely become saturated over time. In addition, adsorption onto building materials can be reversible (i.e., desorption can occur) and thus may also need to be considered as a potential source of volatile chemicals, depending on building conditions. For example, even after vapour intrusion is mitigated (e.g., through a sub-slab venting system), there may be a period of time during which a COPC is detected in indoor air as a result of desorption from building materials.

Chemical transformations processes such as photo-oxidation are generally relatively slow when compared to air exchange rates (i.e., half-lives of days) and biodegradation is unlikely to be a relevant process in an indoor environment.

6.3 Development of Indoor Air Quality Study Approach and Design

The following sub-sections highlight some key considerations when planning and implementing an IAQ investigation program.

6.3.1 Define Study Objectives

The study objectives should be well-defined prior to developing a sampling plan, as the sampling plan could vary substantially depending on the type of data required and how that data is intended to be used. The primary goal of the IAQ study is often to provide data that could be used to evaluate exposure and potential human health risk due to the inhalation of indoor vapours (which originate from contamination located in the subsurface). To meet this objective, the building conditions and sampling locations should generally reflect typical exposure conditions, as further described below. Samples collected to meet this objective are typically referred to as “exposure point” samples.

There may be other specific objectives of the IAQ study that would result in a different sampling strategy. For example, if the goal is to evaluate potential entry points for soil vapour into a building, samples may be collected close to cracks or within utility openings. Samples collected to meet this objective are typically referred to as “pathway” samples. If the objective of the IAQ study is to evaluate the potential influence of background sources of IAQ relative to subsurface sources, several indoor air samples from different locations within a building may be required. In addition, the building environment may be artificially controlled at the same time as IAQ sampling is conducted to assist in evaluation of background sources, as described in Section 6.3.10.

The study objectives can also be broadly defined in terms of the phase or level of investigation. An initial preliminary investigation may consist of a limited number of IAQ samples. If the preliminary investigation indicates a potential IAQ concern, additional investigation may be appropriate. Finally, if vapour intrusion mitigation systems are installed, follow-up IAQ monitoring may be required for some period of time after such systems are operational.

6.3.2 Identify Target Chemicals

The target chemicals for the sampling plan are dependent upon the contamination source. Target chemicals would generally include the primary chemicals of the contamination source and potential breakdown products of these chemicals (e.g., breakdown products of PCE). For PHC impacted sites, target chemicals generally include volatile petroleum fractions such as aliphatic and aromatic hydrocarbons as well as other specific chemicals such as BTEX (refer to Appendix I for further details). Non-target chemicals that are background or injected compounds (e.g., helium) could also be sampled and used as tracers as part of the vapour intrusion assessment.

For an IAQ study designed to evaluate vapour intrusion from a sub-surface source (e.g., contaminated soil or groundwater), a screening process based on the volatility and toxicity of a COPC can be used to identify target chemicals (as presented in Appendix II). Target chemicals may also be identified based on the results of previous indoor air sampling at the site or based on the history of the site and/or neighbouring properties.

6.3.3 Develop Communications Program

An important part of the IAQ program is communication with the building occupants and owners, as well as other stakeholders. This is done to keep them informed and involved in the process. Such measures should be implemented early in the process (i.e., prior to sampling) and continue throughout the duration of IAQ program (i.e., measured indoor air results disseminated to relevant stakeholders).

Issues to address with building occupants include:

- identifying why the study is being conducted and what the study objectives are;
- scheduling the pre-sampling building survey;
- discussing the types of activities to avoid prior to the sampling events and background chemical issues;
- scheduling and discussing the sampling that will be conducted; and,
- communicating the results of the sampling program.

Consideration should be given to the development of an access agreement between parties prior to sampling.

6.3.4 Conduct Pre-Sampling Building Survey

Buildings should be inspected prior to and during IAQ testing to assess whether there are potential background sources and to describe building conditions that may influence indoor air concentrations. Building occupants may also be interviewed to obtain additional information on factors that may affect IAQ and to determine the building occupancy characteristics.

Examples of a pre-sampling building survey that could be used to direct a building inspection and occupant interviews have been published by ITRC (2007) and NJDEP (2018). A separate survey should be completed for each building being investigated.

The pre-sampling building survey may be used as a tool to refine the sampling plan and identify any building preparation activities that should be considered prior to sampling (refer to Section 6.3.10 for further information). Relevant portions of the survey should be reviewed again at the time indoor air sampling is performed.

6.3.5 Conduct Preliminary Screening

In conjunction with the pre-sampling building survey, a preliminary screening of the study building using a portable air monitoring instrument such as a photoionization detector (PID) can provide useful information on background sources in indoor air. When sensitive PIDs are used (low ppb_v range), they may also be capable of identifying entry points where vapour intrusion is potentially occurring. Although portable air monitoring instruments may be useful tools for identifying background sources or targeting sampling locations at some sites, they should not be used to rule out the presence of background chemicals in indoor air, for the following reasons:

- most direct-measuring instruments measure relative concentrations of multiple organic compounds as a group and are not capable of identifying specific chemicals; and,
- for most conventional PIDs, the sensitivity of these instruments is often insufficient to detect chemicals at levels that may be of concern for human health.

PID measurements in some environments may also be biased high. For example, condensation on the PID sensor may result in a slowly rising false positive response that may reach several hundred ppm_v (Western Australia Department of Environment 2005). Microparticles of dust and wood soot absorb moisture more readily than a clean sensor surface, exacerbating the effect of moisture; therefore, relevant conditions during sampling should be noted, and the instrument calibration should be checked frequently.

Note that there are a range of portable instruments that have been used for quantitative assessment of indoor air concentrations to detection limits of approximately 1 $\mu g/m^3$ (or lower in some cases) which is within the range needed for human health risk assessment. Such instruments include PIDs, gas chromatographs with mass spectrometers and electron capture detectors. Advantages of quantitative field analysis at low detection limits include high throughput of samples and rapid quantification allowing buildings or areas of concern to be quickly identified.

6.3.6 Identify Immediate Concerns for Safety and/or Adverse Effects

If the building survey or preliminary screening identifies immediate concerns associated with chemical odours or where occupants exhibit adverse effects potentially attributable to inhalation of volatiles in indoor air (e.g., headaches, dizziness, nausea), further actions should be taken to address the concerns as quickly as reasonably achievable. Such actions include identifying the chemical source and mitigating the hazard (e.g., increase ventilation, relocate occupants, etc.), as warranted.

There may also be instances where there are safety concerns associated with the accumulation of potentially explosive levels of methane or oxygen deficient conditions inside or near to buildings. In the case of methane gas from landfills infiltrating structures through subsurface transport, the MOECC (2016c) Procedure D-4-1 "*Assessing Methane Hazards from Landfill Sites*" should be followed.

6.3.7 Define Number and Locations of Indoor and Outdoor Air Samples

The number and locations of indoor air samples will be dictated by several factors. If a preliminary investigation of IAQ is being undertaken, a limited number of samples may be sufficient. If the study objectives require a statistical approach or analysis of results and/or to demonstrate that vapour intrusion is unlikely to be of concern, multiple samples would be required.

The building characteristics including size, construction and ventilation patterns will also influence the required number of samples. For example, if the building is a small house with reasonably good ventilation, then the indoor air concentrations within the house may be relatively uniform and one or two indoor air sample(s) may be sufficient. For a larger building, such as a commercial building or school, where indoor air concentrations may vary in different parts of the building, multiple samples may be required to adequately characterize the IAQ.

The indoor air sampling density (number and spacing) will vary on a site-specific basis. It is recommended that the determination of the required number and spacing of indoor air samples be supported by different lines of site-specific evidence. Such lines of evidence include, but may not be limited to, the following:

- exposure scenarios that exist within the building(s) (e.g., child care, office);
- characterization of subsurface vapour source(s) and the proximity of those source(s) to buildings of concern;
- presence of internal building partitions that divide building floors into separate areas or units;
- HVAC layout with different ventilations zones or systems;
- presence of potential soil vapour entry points (e.g., sumps or drains, utilities, etc.);
- any other conditions that may impact the vapour intrusion pathway; and,
- building footprint.

Recommendations for the minimum number of indoor air samples, as a function of the building footprint area, are provided in Appendix 8b of the MOECC (2016a) user guide. These recommendations may represent a starting point when determining an appropriate number of indoor air samples to collect.

For residential buildings with multiple floors, consideration should be given to collecting at least one sample per floor (per sampling event) to characterize inter-floor variability. Where minimal sampling is conducted for a preliminary assessment, it is generally preferable to target the first level of the building (e.g., basement) since vapour concentrations are expected to be highest in lower regions of the building in instances of vapour intrusion.

For multi-unit buildings, it may be necessary to sample all units. A “worst first” approach could be also considered to prioritize units for investigation, based on location of the vapour source(s) to indoor air, susceptibility of each unit to vapour intrusion (e.g., ventilation, sumps or drains, utilities), and other preferential migration pathways.

Exposure samples should be collected within the typical breathing zone at a height of approximately 1.0 to 1.5 m above the floor, near the centre of the room, as this area is generally representative of overall room conditions. When assessing the potential entry points for soil vapour into a building or the worst case conditions, samples should be collected close to visible cracks in the wall and floor, sump pits, floor drains or utility openings.

Outdoor air will influence IAQ and may also contain chemicals at concentrations that exceed HBIACs. Therefore, it is good practice to obtain outdoor air samples as part of the IAQ program. The number of samples will be site-specific, but several samples obtained from multiple locations may be needed. As part of the outdoor air program, it is also important to identify emission sources such as gasoline stations, major highways, paving operations and remediation systems. It is important to protect outdoor air samplers from the elements (rain or snow) and vandalism.

6.3.8 Define Sampling Duration

The duration of sample collection may depend on the study objectives. The selected sample duration should yield an average concentration of a COPC over the expected daily exposure duration. For a residential scenario, it is possible that residents may be present in the home 24 hours per day. Therefore, a standard 24-hour sample duration is the minimum duration recommended for a residential scenario, unless technical or time considerations require shorter time frames. CCME (2016a) guidance manual summarized different studies on indoor radon and these studies provide valuable insight on potential indoor air concentration variability due to vapour intrusion.

For a commercial scenario, a minimum sampling duration equivalent to the standard 8-hour workday (which is the expected exposure duration for a typical worker) is recommended. Ventilation systems are often designed for energy efficiency reasons to run at minimal levels outside of normal working hours, so a sample collected over longer periods to average temporal variability may be best collected in successive 8-hour increments. A longer or shorter sample duration could be selected, if warranted, based on site-specific conditions and site use.

When determining the sampling duration, potential limitations of the sampling device should be considered. Potential limitations include the following:

- For evacuated canisters, flow controller accuracy needs to be consistent over the duration of sample collection.
- For sorbent tubes, chemical breakthrough and moisture interference may be an issue for long-term samples, depending primarily on the sampling duration and flow rate.

Passive diffusive samplers are better suited to longer sampling periods than active canister or sorbent tube methods and may be deployed over one to two weeks or potentially longer. A potential advantage of longer duration samples is to provide a better indication of long-term exposure through integration of concentration variability over the sampling period.

6.3.9 Define Sampling Frequency

The sampling frequency will depend on study objectives, the nature of the contamination source and temporal variability expected due to factors such as building characteristics, weather conditions and occupancy characteristics during sampling. Field data collected from different types of buildings suggest that the temporal variation in indoor air concentrations is significant, up to two or three orders of magnitude (refer to Appendix IV for further information).

Temporal/seasonal characterization generally includes indoor air sampling during worst-case seasonal conditions when the indoor air concentrations are likely to be higher than those observed during other seasons. In a cold climate region, such as Ontario, high indoor air concentrations may occur during the winter. This is because of lower air exchange rates and greater stack effect within a building that are often observed during this season. That said, other factors such as high groundwater elevation and the solar stack effect may, in some instances, result in a high potential for vapour intrusion during other seasons. For reference, empirical data from different studies listed in Appendix IV appear to suggest that the timing of peak indoor air concentrations to be quite variable. Additional discussions on some key factors contributing to temporal/seasonal variability of soil vapour are discussed in Section 5.3.4.

Because the factors affecting when the high or highest indoor air concentration will occur are site-specific, multiple rounds of indoor air sampling across several seasons are recommended. This will help to better assess the temporal variability associated with vapour intrusion.

When indoor air samples are collected as a primary line of evidence with the objective of ruling out the vapour intrusion pathway, the following sampling frequency is recommended as a general guide. It is, however, advised that the determination of sampling time and frequency be based on an assessment of site-specific conditions to appropriately address the temporal and seasonal variability.

- If indoor air concentrations are well below their respective HBIACs (e.g., 100 to 1000 times lower), a minimum of two sampling events may be sufficient to demonstrate that the vapour intrusion pathway is unlikely to be of concern, unless a major change in conditions occurs at the site (e.g., elevated water table or significant seasonal change in rainfall). The sampling events should be at least three months apart over two different seasons with at least one event performed during the reasonable worst-case conditions.
- When indoor air concentrations are near the HBIACs or site conditions suggest significant variations in indoor air concentrations between sampling events, additional sampling events should be completed to address the seasonal and/or temporal variability. Consideration should be given to sampling indoor air for more than one year to characterize the influence of inter-year climatic variability.

6.3.10 Prepare the Building for Sampling and Conditions during Sampling

A list of measures that should be considered when performing IAQ sampling programs is provided in Exhibit 6.1. Building occupants should be informed of the required measures or sampling conditions in advance of the sampling event.

EXHIBIT 6.1. Preparation of Building for IAQ Sampling

Summary of possible measures to be considered prior to IAQ sampling:

- Remove products that are known significant sources of VOCs, such as fuel containers, paint, paint strippers or solvents (at least three days, and preferably one week, prior to sampling), as practical. Such products stored in an ordinary manner at typical volumes may not need removal but should be noted in the field notes.
- Ensure that containers of VOC-containing products are tightly sealed, as practical.
- Extinguish combustion sources (*e.g.,* candles, wood stoves, tobacco products, incense, etc.) prior to sampling (preferably 24 hours prior to sampling).
- Consider delaying sampling where recent renovation or construction work has been undertaken. This is to allow elevated VOCs associated with new construction materials, paint, furnishings or sealing work to dissipate. Note that many new interior building materials may off-gas VOCs for a long period of time (e.g., weeks or months after being installed).
- Ventilate the space to help eliminate residual contaminants, once known VOC sources are removed or controlled. This may be done through operation of the building HVAC system or opening of doors, windows, or operation of exhaust fans. It should be completed at least 24 hours prior to sampling.
- Operate electrically-powered HVAC systems (heating and cooling) under normal operating conditions for at least 24 hours prior to and during the scheduled sampling time (unless the objective is to artificially control building conditions).
- Survey potential outdoor air sources within a 300 meter radius of the site.

Measures to be avoided 24 hours prior to and during sampling:

- Storage or use of fuel products, solvents, glues or petroleum-based materials within building or attached garages.
- Operation and storage of automobiles in attached garages.
- Operation of fireplaces.

As discussed in Section 6.2.1, there are a number of potential background indoor sources. As such, reasonable efforts should be made to minimize the contribution of identified background sources prior to and during the indoor air sampling. For example, all products that are known significant sources of VOCs should be removed prior to sampling, along with any residual contamination associated with these products.

Consideration should be given to obtaining ancillary data (refer to Section 5.7 and Section 6.5.3 for further information), such as the differential pressure between the building and outdoor air and meteorological data, to aid in the interpretation of indoor air data. It may also be important to monitor the operation of fans, central vacuum cleaners, and other mechanical devices that could influence ventilation and pressure conditions during indoor air sampling.

6.4 Indoor Air Analytical Methods

The selection of the indoor air analytical method depends on a number of factors, including data quality objectives, study objectives, detection limits and the COPC. Typically, indoor air samples are obtained using either sorbent materials, canisters (e.g., Summa canisters), or passive diffusive samplers.

Further details on air analysis are provided in Section 5.6 of this guidance document and Section 8.4 of the CCME (2016a) guidance manual.

6.5 Data Interpretation and Analysis

The following sub-sections provide key considerations for data interpretation and analysis of indoor air data for the purpose of assessing impacts to IAQ resulting from vapour intrusion.

6.5.1 Data Organization and Reporting

The IAQ data should be tabulated and plotted to facilitate evaluation and review of data relationships and trends. The following data organization and presentation is recommended:

- tabulate all data including sample location identifier, sample date, sample height, sample location within room, sampling methods, chemical analysis methods, laboratory detection limits and results of chemical analysis, applicable HBIACs, and background indoor and outdoor air concentrations, where available.
- calculate constituent ratios and evaluate trends with respect to:
  - indoor air to soil vapour or sub-slab vapour samples;
  - first building level to higher level air samples; and,
  - indoor air to outdoor air samples.
- note building size, foundation conditions, utility penetrations through floor, sumps and drains, attached garages, and stains on floor;
- note preferential pathways such as sewers;
- note building HVAC conditions during indoor air sampling and qualitatively describe opening of windows and doors, operation of fireplace, furnace and fans; and,
- note potential significant indoor sources of VOCs present during sampling.

6.5.2 Data Quality Evaluation

Following receipt of indoor air testing results, the data should be evaluated to determine whether data quality objectives outlined in the sampling plan are met. The data quality analysis for indoor air is similar to that for soil vapour (see Section 5.8.2 for further information).

6.5.3 Discerning Background Contributions

As indicated in Section 6.1, the main purpose of completing an IAQ investigation under this guidance is to evaluate the potential impacts to indoor air resulting from vapour intrusion. Therefore, careful consideration must be given to determining which chemicals are derived from background sources and which are likely related to the sub-surface contamination.

To the extent possible, multiple lines-of-evidence should be considered when evaluating IAQ data. The relative importance of various lines of evidence should be based on professional judgment and should consider data quality and site conditions, as well as factors affecting vapour intrusion and IAQ.

Examples of key methods for discerning background contributions to the potential adverse effect on IAQ include the following:

- **Building Survey and Occupant Use**: A visual building inspection together with compilation of information on occupant use and indoor sources may be completed to evaluate potential background sources for a given chemical. Additional discussions pertaining to different background sources are provided in Section 6.2.1.
- **Sub-slab Soil Vapour Data**: The ratio of the sub-slab soil vapour to indoor air concentrations may be used as a line of evidence for vapour intrusion. For example, a low ratio (i.e., a ratio of less than 10) may suggest that the potential indoor air impact be mainly attributable to background sources.
- **Comparison of Indoor and Outdoor Air Concentrations**: Chemicals from outdoor sources may enter the building through ventilation intakes, doors and other openings. The ratio of indoor to outdoor air concentrations may be used to evaluate the potential impact of outdoor sources on the IAQ. For example, if the ratio is high (i.e., appreciably greater than one), this may indicate that the potential indoor air impact is not attributable to outdoor sources. Note that this step alone is not sufficient to rule out the vapour intrusion pathway.
- **Constituent Ratios**: The ratios between chemical concentrations in different media (e.g., groundwater, soil vapour, indoor air and outdoor air) for concurrent data and chemicals with similar fate and transport properties can be evaluated to differentiate background and sub-surface sources. For example, if the ratios are significantly different, there may be background contributions for some or all COPCs.
- **Marker Chemicals**: These chemicals are generally associated with the subsurface contamination, but not background indoor air sources. An example of a possible marker chemical is 1,1 dichloroethene (1,1-DCE). This chemical may be found in the subsurface as a breakdown product of TCE, but it is not a common background chemical in indoor air. If detected in indoor air (and the presence of an alternative

background source for 1,1-DCE is ruled out), it is likely that vapour intrusion is occurring. Marker chemicals, if present, are also useful compounds when evaluating constituent ratios using the method described above.

- **Spatial Trends**: Spatial variability in VOC concentrations within the building may be used to evaluate the potential impacts to indoor air attributable to background or sub-surface vapour sources. For example, higher VOC concentrations in a basement, as compared to those in upper floors, may indicate the presence of a subsurface vapour source. That said, consideration should be also given to the possible contributions of background sources, as it is not uncommon for solvents and other possible background sources to be stored in basements.
- **Comparison of Indoor Air Data to Literature Background Concentrations**: Indoor air data may be compared to a historical range of background data compiled from literature (e.g. studies listed in Appendix V). If indoor air measurements reported at a given site significantly exceed the historically reported range of background concentrations, it may be that vapour intrusion is contributing to the indoor air concentrations. This is because current or future indoor air concentrations for different VOCs in a building are expected to be lower than those observed historically (refer to Section 6.2.1 for further information). For the same reason, comparison to historical background data alone should not be relied upon to conclude that background sources are primarily responsible for indoor air concentrations and that vapour intrusion is not of concern. Instead, multiple line(s) of site-specific evidence (e.g., sub-slab soil vapour, indoor air, ambient air and building survey, if available) should be considered when evaluating the potential influence and contribution from both background and sub-surface sources.
- **Modification of Building Pressurization**: Indoor air concentrations may vary significantly with changes in building pressure, since soil gas advection induced by building depressurization is often the main driver for vapour intrusion. IAQ testing under positive and negative building pressurization can be used to assess vapour intrusion under near worst case conditions and to evaluate the possible influence of background sources on indoor air quality.
- **Comparison of Indoor Air Measurements to Empirical Data and/or Modeling Results**: The measured indoor air concentrations may be compared to predicted concentrations from empirical relations or mathematical models (e.g. using the J&E model). When there is good quality input data, the modeled and measured values can be expected to agree within about an order-of-magnitude. Note however that the comparisons using the J&E model may not be meaningful if there are site conditions that fall outside of the processes accounted for in this model such as the presence of preferential pathways.
- **Emerging Methods**: Examples include the use of carbon stable isotope analysis to measure the isotope ratios of a chemical for identifying potential vapour sources. For example, if the carbon isotope ratios from a chemical (e.g., TCE) in indoor air are similar to those measured in a variety of consumer products but different from sub-surface sources (e.g. groundwater), it is likely that indoor sources are responsible for the indoor air impact. Another example is using naturally-occurring radon as a

tracer to evaluate sub-slab to indoor air attenuation for target chemicals. This can be done through the simultaneous measurement of these target chemicals and radon in indoor air, outdoor air and sub-slab soil vapour.

Further details related to aforementioned methods for identifying background sources are also available in Section 8.5.3 of the CCME (2016a) guidance manual.

6.5.4 Comparison of Indoor Air Measurements to Health-based Indoor Air Concentrations

Comparison of the measured indoor air concentrations to applicable HBIACs is often considered an important part of the vapour intrusion assessment. HBIACs are set at concentrations at (or below) which no adverse effects are expected. The derivation of HBIACs is based on the approach and inputs presented in Section 2 of the MOE (2011) rationale document and it is important to remember that HBIACs were developed for use in a brownfield scenario under O. Reg. 153/04.

When a HBIAC is exceeded, it does not necessarily mean that an adverse effect will occur. However, the risk of adverse effects is expected to increase as a measured concentration increases above the HBIAC. Exceedance of the HBIAC indicates that further work is warranted to investigate the potential for adverse effects. This could include consideration of how the HBIAC was developed, supplementary environmental sampling and/or a human health risk assessment.

CHAPTER 7 REPORTING AND DOCUMENTATION

A soil vapour and/or indoor air investigation and assessment report is often prepared as a stand-alone document, although in some cases it may be included as a separate section or appendix in a larger investigation report (e.g., Phase Two ESA) or risk assessment.

The soil vapour and/or indoor air investigation report should include a description of the project-specific objectives, the conceptual site model, deviations from the initial/proposed work plan (if any), all field notes and data results (including any data inconsistencies or laboratory analytical issues). An analysis and interpretation of the data collected, and conclusions and recommendations should also be included. Some key considerations for a soil vapour investigation and assessment program are listed in Appendix III, which can be also modified to fit an indoor air investigation and assessment program. Generally, the following details, if available, should be provided in the report:

- field investigation scope, methods and QA/QC procedures;
- hydrogeological information (e.g., groundwater levels);
- description of unsaturated soil lithology and grain size;
- general description of building (type, size, number of stories, units) for current land use scenario and proposed building design for future use scenario (if applicable);
- information on subsurface utilities near building;
- description of land use and conditions surrounding building (e.g., paved area, landscaped areas);
- probe construction details;
- field data including leak test, field screening results, flow rates and pressure readings (from a vacuum gauge) during sample collection;
- contamination characterization including quality control/quality assurance data;
- description of soil vapour transport modeling inputs and rationale for selected values (if modeling of soil vapour transport was conducted); and,
- all data, including results of chemical analysis (along with certificates of analysis), applicable VICVs and QA/QC performance.

The following additional information on the building can provide added perspective in terms of the potential for vapour intrusion:

- description of building foundation (e.g., slab-on-grade, basement, crawlspace, general condition of foundation);
- description of building (e.g., approximate age, footprint area, height of each storey, number of stories, general information on construction); and,
- description of building HVAC systems.

The soil vapour or indoor air investigation reports should include site plans and maps identifying soil vapour and/or indoor air sampling locations. The relative location of soil and groundwater contamination with respect to the locations of vapour probes and current or future buildings should also be depicted on these figures (or separate figures). When soil vapour measurements have been collected, it is generally recommended that cross-sections depicting subsurface conditions also be included. The cross-sections should be based on data obtained from well logs, indicating the location of underground utilities and soil vapour probes (showing the screen intervals), extent of soil and groundwater contamination, depth to the water table, and known or anticipated location and depth of building foundations (refer to Section 5.8 for further information).

The soil vapour and/or indoor air analytical data should be summarized and presented on tables that facilitate a review of the spatial and temporal trends as well as the relationships between lateral and vertical sampling locations. Data interpretation and analysis should follow the recommendations outlined in Sections 5.8 and 6.5.

The uncertainties in the predicted or measured exposures should be discussed. These include site characterization data, vapour attenuation factors and any risk estimates. Sources of variability in the site characterization data, including factors influencing spatial and temporal variability, should also be discussed.

Finally, note that in addition to the above, any environmental site assessment and/or risk assessment reports submitted under O. Reg. 153/04 that includes a soil vapour and/or indoor air investigation and assessment report must also meet the requirements outlined in O. Reg. 153/04.

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APPENDIX I:
VAPOUR INTRUSION ASSESSMENT FOR PETROLEUM HYDROCARBONS

I.1. Background

Petroleum hydrocarbons (PHCs) are diverse mixtures of hydrocarbons that are composed of hundreds of aliphatics (e.g., hexane, octane, and cyclohexane) and aromatics (e.g., benzene, toluene, ethylbenzene, and xylenes (BTEX)). Many PHC compounds (and also non-PHC additives in petroleum products) are volatile and can migrate through the subsurface into overlying buildings. This process, referred to as petroleum vapour intrusion (PVI), potentially poses explosive hazards (safety hazards) and/or adverse effects to building occupants as a result of the inhalation of PHC vapours. The quantification of PHCs in soil vapour and indoor air can often be an essential component when evaluating and addressing vapour intrusion concerns.

Recent research and publications including databases of empirical evidences (Lahvis et al., 2013; USEPA, 2015; Wright, 2012) and modeling simulations (Abreu et al., 2009) have provided an improved framework to quantify the effects of biodegradation on PHCs in the subsurface. It has been recognized that PHCs can aerobically degrade and that significant attenuation of PHC vapours can occur over relatively short distances, under specific environmental conditions (refer to Section I.2 and I.3 for further details). As such, the vapour intrusion process can be significantly different when comparing PHCs (or aerobically biodegradable compounds) to recalcitrant compounds (e.g. chlorinated hydrocarbons (CHCs)), under the same environmental settings. Some key differences between the vapour intrusion processes for PHCs and CHCs are discussed in detail in the USEPA (2015, 2013, 2012a) technical documents.

I.1.1 Biodegradation of Petroleum Hydrocarbons

PHC biodegradation is typically conceptualized as the complete degradation of PHCs into carbon dioxide and water and/or transformation of complex PHCs to other simpler (generally less toxic) compounds by microbial communities (Das and Chandran, 2011; Varjani, 2017). Recent research suggests that intermediate compounds, consisting of polar metabolites such as ketones, aldehydes and alcohols, may be formed during this process (Zemo et al., 2013). These intermediate compounds, generally less volatile and more soluble than the parent PHC compounds, are unlikely to represent a concern for vapour intrusion; however, further research is needed in this area.

Biodegradation plays a major role in degrading or removing PHCs from the subsurface; and thereby reducing the potential for PVI (DeVaull et al., 2002; Fischer et al., 1996; Hers et al., 2000; Johnson et al., 1998; Laubacher et al., 1997; Ostendorf and Kampbell, 1991). USEPA (2015) introduces the concept of a biologically active vadose zone, in which appropriate conditions are available over an extensive area which allow for persistent and significant biodegradation of PHC vapours to occur. Such conditions include adequate nutrients, moisture and oxygen levels necessary to sustain the needed habitat of microorganisms capable of degrading PHC vapours.

Conceptually, when the biologically active soil is of sufficient thickness, the biodegradation rate of PHCs may exceed the diffusion rate of these compounds. This often results in a substantial attenuation of PHC vapours in the vadose zone over a relatively short time and distance (DeVaull, 2007; USEPA, 2013).

I.1.2 Recent Studies on Petroleum Vapour Intrusion

Recent evaluations of different sub-surface media measurements (primarily soil vapour and groundwater) have provided an improved understanding of PHC attenuation in the sub-surface and the associated potential for PVI (Davis, 2009; Lahvis et al., 2013; USEPA, 2013). Both empirical and modeling study results have demonstrated that biodegradation can limit the migration of PHC vapours from a subsurface source, thus minimizing the flux of PHC vapours from the subsurface to overlying buildings. Numerous reviewed case studies (USEPA, 2013) appear to suggest that the distance from the vapour source to the building of concern beyond which PVI is unlikely to occur is approximately 30 feet (or 9 to 10 m) and that this distance depends on site-specific conditions, such as type of vapour source, subsurface conditions (e.g., moisture content, oxygen availability), and building characteristics. A number of jurisdictions (e.g., British Columbia, New Jersey, Massachusetts, Kansas, Pennsylvania) have used a 30-foot (or 10 m) threshold distance (in both vertical and horizontal directions) as a preliminary screening step for PHC-impacted sites (BCMoECCS, 2017a; MassDEP, 2016; NJDEP, 2018; KansasDHE, 2016; PADEP 2017). Some of these jurisdictions have also allowed this distance to be further refined with the consideration of site-specific conditions.

Both ITRC (2014) and USEPA (2015) guidance documents present an investigative approach that uses vertical inclusion distances as part of an alternative screening approach for evaluating the potential of PVI. These vertical inclusion distances are determined from an analysis of empirically observed data on the vertical thickness of biologically active (and clean) soil present between a PHC source and building foundation, which is required for PHC vapour concentrations to effectively attenuate to levels that are below those of concern for PVI. Depending on the vapour source type, the recommended distances are from 5-6 feet (for a dissolved PHC source) to 15-18 feet (for a LNAPL source).

A number of jurisdictions (KansasDHE, 2016; MDEQ, 2013; MassDEP, 2016; NJDEP, 2018; PADEP, 2017) have recently incorporated this vertical inclusion distance approach as an alternative step for evaluating the PVI pathway. However, it is noted that the approach only applies to sites with stable, discrete petroleum sources that are properly characterized. It is also recognized that there is limited knowledge of PHC vapour behavior and attenuation under a number of specific site conditions, which could justify the need to use a greater vertical distance (refer to Section I.6 for further information). If such conditions are suspected or known to exist at a site, then further PVI investigation (e.g., through indoor air and/or soil vapour sampling) is generally warranted.

I.2. Target PHC Compounds for PVI

In Ontario’s brownfields program, PHCs are addressed (and regulated) both as a mixture and by using specific indicator compounds. As a mixture, Ontario generally relies on the

CCME fractionation approach, which is largely based on the work by Total Petroleum Hydrocarbon Criteria Working Group (TPHCWG). Specific indicator compounds (e.g., BTEX, naphthalene) are also included in an effort to address more toxic compounds (which may not have been accounted for in the mixture approach).

I.2.1. Background

As part of the CCME fractionation approach, total PHCs are grouped into four (4) fractions with specified ranges of equivalent carbon number: PHC F1 (C_6 to C_{10}), PHC F2 ($C_{>10}$ to C_{16}), PHC F3 ($C_{>16}$ to C_{34}) and PHC F4 ($C_{>34}$). PHC F1 and F2 are composed of aliphatic and aromatic sub-fractions that are both soluble and volatile; and are therefore relevant when assessing the vapour intrusion pathway. PHC F1 and F2 fractions are described in more detail below:

- PHC F1 represents the sum of following non-specific aliphatic and aromatic hydrocarbon compounds:
  - aliphatic C_6-C_8;
  - aliphatic $C_{>8}$-C_{10};
  - aromatic $C_{>8}$-C_{10}; and,
  - BTEX.
- PHC F2 represents the sum of following non-specific aliphatic and aromatic hydrocarbon compounds:
  - aliphatic $C_{>10}$-C_{12};
  - aliphatic $C_{>12}$-C_{16};
  - aromatic $C_{>10}$-C_{12}; and,
  - aromatic $C_{>12}$-C_{16}.

Note that some individual indicator compounds, such as BTEX and naphthalene, can be subtracted from the content of total PHCs. This subtraction, if completed, should be clearly documented in a certificate of analysis (if done by the laboratory) and in the assessment report.

I.2.2. Recommended Target PHC Compounds for Petroleum Vapour Intrusion Assessment

An evaluation of both total PHCs (with fractionation) and specific indicator compounds is required as part of the vapour intrusion assessment.

Soil and groundwater samples should be collected and analyzed for the following minimum list:

- PHC F1 or PHC F1 minus BTEX (PHC $F1_{\text{-BTEX}}$);
- PHC F2 or PHC F2 minus Naphthalene (PHC $F2_{\text{-napthelene}}$);
- BTEX; and,
- naphthalene, if subtracted from PHC F2 or if PHC residuals remain at the site (e.g., when measured concentrations of PHC F2 exceed its free product threshold in soil or half-solubility in water). See below for further details.

Indoor air and soil vapour samples should be collected and analyzed for PHC F1 and F2; however, individual aliphatic and aromatic sub-fractions should also be reported. Sub-fraction data allows for a more accurate evaluation of the composition and potential risk of PHCs in indoor air and subsurface vapors (refer to Section I.4 for further details). It is also important to note that (1) there is no standardized analytical method currently available in Ontario for quantifying PHCs in air and soil vapour samples and (2) current analytical methods (e.g., using Gas Chromatography/Mass Spectrometry (GC/MS) for air samples) demonstrate a low recovery of $C_{>12}$ compounds and therefore do not produce a reliable result for this group. In addition, empirical data (e.g., HDOH, 2012) suggests that the contribution of $C_{>12}$ aliphatic and aromatic compounds to the total PHC vapour is relatively small, due to their lower volatility. As such, excluding this group of compounds from the laboratory analysis is unlikely to affect the overall conclusion with respect to the vapour intrusion risk. This approach is consistent with those suggested by other jurisdictions (BCMOE, 2015; CRC CARE, 2013 and HIDOH, 2012; MassDEP, 2009). In general, it is recommended that PHC vapours be analyzed for the following groups of aliphatic and aromatic sub-factions and indicator compounds, at a minimum:

- aliphatic C_6-C_8;
- aliphatic $C_{>8}$-C_{10};
- aliphatic $C_{>10}$-C_{12};
- aromatic $C_{>8}$-C_{10};
- aromatic $C_{>10}$-C_{12};
- BTEX and,
- naphthalene, if subtracted from PHC F2 or if PHC residuals remain at the site (e.g., measured concentrations of PHC F2 exceeding its free product threshold in soil or half-solubility in water). Limited field soil vapour data suggest that naphthalene might drive the vapour intrusion risk in some cases, due to its higher toxicity. For example, the HDOH (2012) study indicated naphthalene was not detected above laboratory reporting limits in the majority of the vapour samples, however, naphthalene was reported to exceed the vapor intrusion action level at some locations where the reported level of PHC was low. Also, given that the inhalation toxicity reference value (TRV) currently selected for naphthalene is well below that for Aromatic $C_{>8}$-C_{12}, naphthalene may become a vapour intrusion risk driver if it makes up more than 1% of Aromatic $C_{>8}$-C_{12}.

Note that additional compounds (e.g., n-hexane, specific fuel additives) may also need to be analyzed in indoor air and soil vapour, depending on site use history (e.g., potentially contaminating activities), known or suspected formulation of the PHC product(s) being investigated and weathering of PHCs to further refine the PVI assessment.

Attachment I.1 provides some key analytical considerations when analyzing and quantifying PHC vapours based on aliphatic and aromatic sub-fractions.

I.3. Screening Sites for Petroleum Vapour Intrusion

The step-wise assessment process that is described in Chapter 4 of this guidance document can be applied when screening PHC impacted sites for the potential of vapour intrusion. This process often includes the comparison of concentrations of PHC compounds measured in different media (e.g., soil, groundwater, and soil vapour) to applicable standards and related risk-based concentrations (e.g., site conditions standards (SCSs) and vapour intrusion component values (VICVs)). The derivation approach of VICVs for PHC fractions is generally presented in other documents (MOECC 2016; MOE 2011) and summarized in Section I.5.

Under the preliminary screening process, considerations often include determination of the inclusion zone, which is defined as the area surrounding a vapour source through which VOCs can travel laterally or vertically in the sub-surface and migrate into overlying buildings. In general, an evaluation of the PVI pathway is triggered if PHC compounds are at levels exceeding applicable VICVs (e.g., soil to indoor air (S-IA) or groundwater to indoor air (GW2) component values) and present within 10 m (laterally or vertically) of the foundation of existing (or future) buildings.

As part of the screening process, the qualified person/site assessor will also need to determine whether any precluding conditions are present at the site. The presence of a precluding condition may require the use of a greater inclusion distance and/or warrant additional lines of evidence (e.g., soil vapour and indoor air data) to evaluate the potential vapour intrusion pathway. Examples of precluding conditions that can be encountered at PHC impacted sites include the following:

- preferential transport pathways present within the inclusion zone, consisting of a direct connection between contamination and the building (e.g., fractured bedrock, sewers or utility tunnel/conduits, clay-type soils that may be prone to fracturing);
- ongoing releases of PHC products that may potentially result in expanding plumes and inability to appropriately define the lateral inclusion distance;
- soil vapour under pressure (e.g., sites with significant biogenic gas generation); and,
- extensive low permeability cover between the contamination source and building (e.g., large building footprint, paved areas, permafrost or near frozen conditions that exist for most of the year). For example, Davis et.al. (2009) and USEPA (2015, 2013) suggest that large building footprint may limit atmospheric oxygen transport beneath the center area of a building and that if the overlying building has sides greater than 15-20 m in length, then additional investigation may be warranted.

Note that there may be other conditions (e.g., the presence of highly organic or excessively dry soils, and PHC fuel types with high ethanol content) present at the site that may limit the bio-attenuation of PHC vapours in the subsurface. It is expected that the qualified person/site assessor rely on their knowledge of the site and a well-developed conceptual site model (CSM) when considering the potential presence of precluding conditions and their possible implications on the PVI assessment (refer to ITRC (2014) and USEPA (2015) guidance documents for further information).

I.4. Derivation of Vapour Intrusion Component Values for Petroleum Hydrocarbon Fractions

Under Ontario’s brownfields program, S-IA and GW2 component values were derived to support the development of soil and groundwater standards (refer to MOE (2011) rationale document for further details). Details regarding how these component values were derived for the PHC F1 and F2 fractions are summarized below.

Representative physical and chemical parameters and toxicity reference values (TRVs) are assigned to each aliphatic and aromatic sub-fraction (MOECC 2016), which allows for VICVs to then be developed for those sub-fractions in the same manner as done for individual chemicals. For soil and groundwater, S-IA and GW2 component values are derived for each individual aromatic and aliphatic sub-fraction (listed in Table I.1) and then combined to determine the final values for PHC F1 and F2 using their mass proportion in the medium of interest (i.e., soil and groundwater) and the inverse mass-weighted average calculation, as detailed below:

$$VICV_{Fraction\_i} = (\sum(MP_{sub\text{-}fraction\_j} / VICV_{sub\text{-}fraction\_j}))^{-1} \quad \text{(Equation I.1)}$$

Where:

$VICV_{Fraction\_i}$ = vapour intrusion component value (e.g., GW2) derived for fraction "i"

$VICV_{sub\text{-}fraction\_j}$ = vapour intrusion component value (e.g., GW2) for sub-fraction "j" within fraction "i"

$MP_{sub\text{-}fraction\_j}$ = mass proportion of sub-fraction "j" within fraction "i" (unitless)

Table I.1 presents the mass proportion of each sub-fraction in soil and groundwater which are used to derive the generic SCSs and component values. The soil mass fractions are based on the typical petroleum product composition (CCME, 2008) and the groundwater mass fractions are calculated based on their corresponding soil mass proportion and equilibrium partitioning relationship. Generic S-IA and GW2 component values derived for PHC F1 and F2 fractions (and for all aliphatic and aromatic sub-fractions) are listed in the (MOECC, 2016) Approved Model. Note that the Approved Model (and all component values included therein) may be updated from time to time, the reader is encouraged to use the most up-to-date version of the Approved Model.

Table I.1. Mass Proportion of Each Sub-fraction within PHC F1 and PHC F2

Sub-Fractions	**Mass Fraction in Soil**	**Mass Fraction in Groundwater**
PHC F1 - Aliphatic C_6-C_8	0.55	0.605
PHC F1 - Aliphatic $C_{>8}$-C_{10}	0.36	0.063
PHC F1 - Aromatic $C_{>8}$-C_{10}	0.09	0.332
PHC F2 - Aliphatic $C_{>10}$-C_{12}	0.36	0.024
PHC F2 - Aliphatic $C_{>12}$-C_{16}	0.44	0.002
PHC F2 - Aromatic $C_{>10}$-C_{12}	0.09	0.603
PHC F2 - Aromatic $C_{>12}$-C_{16}	0.11	0.371

Source: MOECC (2016) Approved Model

For soil vapour and indoor air, the theoretical mass proportion of each sub-fraction can be also determined based on a corresponding soil value (as presented in Table I.1) and theoretical equilibrium partitioning components. However, empirical data suggest that the use of these theoretical values may not always conservatively represent the actual composition of PHCs in the vapour phase at a site, which could lead to an underestimation of the potential risk. In addition, the composition of PHC vapours can change significantly over time (e.g., due to the effects of weathering) and can also vary spatially away from the source. For these reasons, it is recommended that when analyzing soil vapour and indoor air samples, the concentrations of each individual aliphatic and aromatic sub-fraction be analyzed and used in the PVI assessment, rather than only using PHC F1 and F2 concentrations. This approach is expected to provide a better representation of both the composition of the petroleum product and environmental conditions at the release sites and lead to better decisions when assessing PVI at these sites.

Note that for some sub-fractions, the same TRV is used when deriving VICVs. In these cases, it is recommended that when assessing soil vapour and indoor air data, the analytical results for those sub-fractions (where the same TRV in used) be summed and compared to the applicable soil vapour screening levels (SVSLs) or health-based indoor air concentrations (HBIACs). For example, as the $C_{>8}$-C_{10} aliphatic and $C_{>10}$-C_{12} aliphatic sub-fractions were both derived using the same TRV, the total reported concentration of $C_{>8}$ to C_{12} aliphatic compounds should be compared to the SVSL or HBIAC derived for either $C_{>8}$-C_{10} aliphatic or $C_{>10}$-C_{12} aliphatic.

I.5. Alternative Screening Assessment: Vertical Inclusion Distance

The vertical inclusion distance approach, which is based on similar approaches described in ITRC (2014) and USEPA (2015) guidance documents, allows for the use of alternative vertical inclusion distances to screen sites out from any further PVI assessment. This approach is intended only for PHC impacted sites with stable and well characterized sources. The full extent and nature of contamination needs to be adequately established as part of the site characterization and CSM development. Note that additional site characterization is typically needed under this approach to fully delineate PHC contamination (both laterally and vertically) and to confirm the existence of a biologically active clean zone.

The completion of the following steps, at a minimum, is required when using vertical inclusion distances to screen a site out from any further PVI assessment. All site data obtained from each step should also be incorporated into the CSM to ensure that all possible sources, site conditions that could influence PHC vapour migration into buildings of concern are properly considered and assessed.

i) **Classification of vapour source:** Under the alternative screening approach, each vapour source is first grouped either as a light non-aqueous phase liquid (LNAPL) source (free phase and/or residual-phase) or a non-LNAPL source (i.e., dissolved phase source).

The presence of LNAPL can be determined from direct evidence, including measurable accumulations of free product in monitoring wells, visible PHC film or sheen (in the groundwater) or staining (in soil). The identification of residual-phase sources is more challenging but is generally completed through the analysis of key parameters. Both ITRC (2014) and USEPA (2015) guidance documents list some key indicator criteria that can be used for LNAPL identification in support of screening PVI sites, as summarized in Table I.2.

Table I.2. Key Indicators for Identifying the presence of LNAPL in Support of Screening Sites for PVI Assessment

Groundwater	Soil
- Benzene > 1 mg/L - TPH* > 30 mg/L - BTEX > 20 mg/L - Current or historical presence of LNAPL (including sheens)	- Benzene >10 mg/kg - TPH* >100 mg/kg (for fresh gasoline) and >250 mg/kg (for weather gasoline and diesel) - PID or FID readings >500 ppm - UV or LIF response in NAPL range - Current or historical presence of LNAPL (including sheens)

<u>Notes:</u> BTEX: Benzene, toluene, ethylbenzene and xylenes; FID: Flame Ionization Detector;LIF: Laser Induced Fluorescence; PID: Photoionization Detector; TPH: Total Petroleum Hydrocarbons; UV: Ultraviolet; *: TPH is a measure of the concentration or mass of PHC constituents present in a given amount of air, soil, or water, as defined in USEPA (2013).

The indicator criteria described in Table I.2 are based on those used to group sites when the empirical assessments of vertical inclusion distances were being completed, therefore they are appropriate for assessing the presence of LNAPL in order to select the applicable vertical inclusion distance for a petroleum impacted site. The indicators for groundwater assume that the site is impacted with gasoline and should be adjusted when investigating sites with other petroleum types. Note that these LNAPL indicators apply only to the alternative screening for PVI assessment and that the free product threshold and half-solubility (i.e., 50% of a chemical's solubility limit) remain important triggers for assessing the potential for the presence of free product and when developing site condition standards for soil and groundwater (MOE, 2011).

ii) **Confirmation that site conditions support biodegradation**: The minimum thickness of soil (listed in Step v), below) between a PHC vapour source and the base of existing (or future) buildings (e.g., lowest part of building foundation) must be sufficient to provide effective bio-attenuation of PHC vapours. As previously discussed, there are a number of conditions which may reduce the potential for PHC biodegradation in the subsurface and, the presence of one or several of these conditions may invalidate the use of the vertical inclusion approach at some sites.

In addition to the precluding conditions listed in Section I.3 (above), the following conditions are also known to limit bio-degradation:

- PHC fuel types containing greater than 10% vol/vol ethanol and the presence of compounds (e.g., methane) that can increase the oxygen demand and in turn limit the biodegradation rate of PHC vapours in the subsurface (Jourabchi et al., 2013);

- historical leaded gasoline containing detectable concentrations of lead scavengers (1,2-dichloroethane or ethylene dibromide) in soil vapour. Additional details are presented in Step iii) below;
- soils that are excessively dry (less than 2% by volume or 1.2% by weight moisture);
- soils with a naturally high content of organic matter (greater than 4%, e.g., peat, bay muds, wetlands and delta soils); and,
- certain geologic material that may not support biodegradation. Examples of such material include coarse sand and gravel with a low content of silt, clay, and organic matter (USEPA 2015).

If one or more of the previously identified precluding conditions are present at a site, additional investigation (e.g., collection of soil vapour and indoor air data) should be considered to determine whether the use of screening using a vertical inclusion distance is appropriate. For example, determination of vertical profiles of PHC vapours and fixed gas (e.g., oxygen, carbon dioxide and methane) concentrations can be helpful for characterizing the biodegradation reaction zone, including evidence of sufficient oxygen for biodegradation to occur.

iii) **Additional Considerations for non-PHC compounds**: Petroleum fuels often contain additives other than PHCs which are intended to improve certain performance properties of the fuel. The presence of non-PHC additives will generally require additional assessment (e.g., soil vapour and indoor air data) to determine if the use of a vertical inclusion distance approach is appropriate to screen sites. Examples of non-PHC additives include ethers (e.g., MTBE) and lead scavengers (e.g., ethylene dibromide [EDB] and 1,2-dichloroethane [1,2-DCA]). For fuels with lead scavengers, there is a lack of soil vapour data available and the biodegradation rate of those fuels has not been rigorously quantified. For this reason, the vertical inclusion distance approach is not recommended for cases where soil vapour concentrations include detectable levels of lead scavengers.

Sources of non-PHC compounds (e.g., CHCs) may be also present and the non-PHC contamination may be comingled with PHC sources. In such conditions, it is recommended that screening using vertical inclusion distances not be applied and that more standard lines of evidence (e.g., soil vapour and indoor air data) be collected.

iv) **Determination of the lateral inclusion zone:** This step establishes the lateral inclusion zone, which includes the full lateral extent of PHC contamination (e.g., in soil and/or groundwater) with the addition of a lateral inclusion distance of 10 m. Buildings located within the lateral inclusion zone should be assessed for foundation type (e.g., slab-on-grade, crawlspace, presence of a gravel crush layer and basement), depth to the bottom of the foundation slab, and the size of the building footprint. Some key considerations for developing site-specific lateral and vertical inclusion distances for PVI are provide in the USEPA (2012b) technical paper.

v) **Determination of vertical inclusion distance**: This inclusion distance is the vertical distance from the lowest point of the gravel crush layer present beneath the building foundation to the shallowest area of PHC contamination (i.e., vapour source). When there is LNAPL contamination present, the top of the residual LNAPL smear zone must be used to determine the vertical distance. When contamination is limited to dissolved phase chemicals in groundwater, the shallowest area must include the top of the capillary fringe, associated with the highest observed water level (once annual and seasonal variations in water level have been reasonably determined). Establishing the distance to the shallowest area of the PHC contamination is a critical component to this approach and is typically only possible following the development of a detailed CSM that accounts for possibly changing site conditions over time.

Once the above steps have been completed, an evaluation of the PVI pathway is then only triggered if the vertical inclusion distance (i.e., distance between the base of the gravel crush layer and the vapour source) is within:

- 2 m for non-LNAPL sources; or,
- 6 m for LNAPL sources.

Note that the use of the vertical inclusion distance approach may not be appropriate for cases where the site will be undergoing changes or redevelopment that may result in conditions that potentially limit the biodegradation of PHC at the site (e.g., new construction that may lead to the creation of new precluding conditions). And depending on the regulatory context, the use of the vertical inclusion distance approach may also need to be documented in a risk management plan (e.g., the separation distance maintained as a property use restriction or risk management measure).

I.6. References

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Quantified as TPHd/DRO at Biodegrading Fuel Release Sites.” *Groundwater Monitoring and Remediation*, 33(4): 44–56.

Attachment I.1 Guidance on Analysis of Petroleum Hydrocarbon in Vapour and Air Samples

A standardized analytical method does not currently exist in Ontario for petroleum hydrocarbons (PHCs) in vapour and air samples, specifically when trying to quantify PHCs within the F1 and F2 fraction ranges. There is a concern that lack of standardization could lead to variations in analytical procedures between laboratories, which may create biases with respect to reporting PHC vapour and air data. As such, there is a need to develop a streamlined qualitative method, which would allow laboratories to better quantify PHC vapour and air samples and the qualified person/site assessor to evaluate potential vapor intrusion risks posed by PHC contaminated soil and groundwater with greater confidence.

The following guidance was developed for laboratories in an attempt to promote greater consistency when quantifying and interpreting PHC vapour and air data (within the PHC F1 and F2 fraction ranges) across different contaminated sites in Ontario. The guidance is not intended to be exhaustive but aims to provide some key analytical requirements with respect to calibration and quantification. Note that this guidance is applicable for quantification of volatile hydrocarbons with a boiling point range of approximately 68°C (n-hexane) to 218°C (naphthalene). Therefore, it may not be suitable for quantification of petroleum products that contains a significant proportion of hydrocarbons with boiling points outside this identified range.

The guidance was developed in consultation with several laboratories in Ontario and was based on the review of the following references:

- British Columbia Ministry of Environment. 2015. British Columbia Environmental Laboratory Manual*.* Section H: Air and Vapour Constituents – Organic.
- Massachusetts Department of Environmental Protection. 2009. Method for the Determination of Air-Phase Petroleum Hydrocarbons (APH). Final Revision 1.

Analytical Method:

Sampling by thermal desorption tube (using appropriate sorbent media), or canister with Analysis by Gas Chromatography/Mass Spectrometry (GC/MS).

Matrix:

Air and soil vapour.

Instrument Configuration:

The reference gas chromatographic column for this method is a coating of 100% dimethyl siloxane (e.g. DB-1, HP-1, RTX-1 or equivalent) or 5% phenyl siloxane phase (e.g. DB-5, HP-5, RTX-5 or equivalent). Chromatographic column may have a significant impact on the retention time order of aliphatic and aromatic compounds within the collective hydrocarbon ranges specified in the method. The stationary phase type may not be modified.

GC/MS must be run in scan mode with a minimum of 35-260 amu scan range.

GC Analysis and Calibration Procedures

Calibration Overview:

Total ion chromatography (TIC) or extracted GC/MS areas are integrated in their appropriate ranges (refer to Table I.1.1). Calculations are based on linear response factors that are determined from a minimum of 3-point calibration curves that must span at least 2 orders of magnitude and must use internal standard calibration. Samples where the maximum peak height exceeds the highest peak height of the upper calibration level must be diluted or appropriate qualifier must be used. Refer to Table I.1.1 below for applicable calibration standards.

Calibration Standards:

See Table I.1.1 and Table I.1.2 with guidance related to which standard compounds are required for each petroleum fractions

Retention Time Window Standard:

The retention time window standard must contain a minimum of the following: n-hexane (nC_6), n-Octane (nC_8), n-decane (nC_{10}) and n-dodecane (nC_{12}).

Target Chemicals:

The following target chemicals are to be included, as a minimum, and are to be reported separately. Quantitation for these chemicals should be done using authentic standard with internal standard correction. Note that these target chemicals must be reported in addition to the aromatic and aliphatic sub-fractions within nC_6 to nC_{12} ranges (collectively quantified using the method presented in Table I.1.1).

Benzene	Total Xylenes$^{\Delta}$
Toluene	Naphthalene$^{\#}$
Ethylbenzene	N-Hexane

$^{\Delta}$ Individual xylene isomers concentrations can also be reported.

$^{\#}$ Indicate in the final report if this compound elutes prior to n-dodecane or after.

Daily Calibration Check

At a minimum, run a daily calibration check much include the lowest calibration standard and the midpoint calibration standard to confirm stability of the calibration curve. Rerun the calibration curve if the low standard deviates by more than 30% from the curve or if the midpoint calibration standard deviates by more than 20% from the curve.

Interferences from Non-petrogenic Compounds

Certain organic compounds that are not associated with the release of petroleum products may be detected using MS detectors and can therefore lead to a high bias in the analytical PHC result. These compounds, if quantified, can be subtracted from the PHC quantification. In this case, the following should be considered:

- At a minimum semi-quantitation of these unknown may be estimated using the response factor of the internal standard; and,
- The certificate of analysis should report both the total concentration and the estimated concentration of non-petrogenic compounds.

Table I.1.1: Summary of PHC Fraction and Quantitation

Hydrocarbon Range	Retention Time Range for Integration	Quantitation Ions	Quantitation Compound to be used	Calculation Approach
PHC F1-Aliphatic C_6-C_8	Beginning of n-hexane to apex of n-octane	TIC	Average response of a minimum of three aliphatic compounds eluting in C_6 - C_8 range#	(Total PHC F1-Aliphatic C_6-C_8 concentration as determined by the TIC) minus (applicable targeted aromatics) *
PHC F1-Aromatic $C_{>8}$-C_{10}	Apex of n-octane to apex of n-decane	Extracted ions 91+120	Average response of a minimum of three aromatic compounds eluting in $C_{>8}$ - C_{10} range#	Total as determined using sum of extracted ions (91+120)
PHC F1-Aliphatic $C_{>8}$-C_{10}	Apex of n-octane to apex of n-decane	TIC	Average response of a minimum of three aliphatic compounds eluting in $C_{>8}$ - C_{10} range#	(Total F1-Aliphatic $C_{>8}$-C_{10} as determined by the TIC) minus (Total F1-Aromatic $C_{>8}$-C_{10})
PHC F2-Aromatic $C_{>10}$-C_{12}	Apex of n-decane to end of n-dodecane	Extracted ions 120+134	Average response of a minimum of three aromatic compounds (must include at least one C_4-benzene or C_5-benzene) eluting in $C_{>10}$ - C_{12} range#	Total as determined using sum of extracted ions (120+134)
PHC F2-Aliphatic $C_{>10}$-C_{12}	Apex of n-decane to end of n-dodecane	TIC	Average response of a minimum of three aliphatic compounds eluting in $C_{>10}$ - C_{12} range#	(Total PHC F2-$C_{>10}$-C_{12} as determined by the TIC) minus (Total PHC F2-Aromatic $C_{>10}$-C_{12}) minus (applicable targeted aromatics)*

Notes: #: Example of suggested standard compounds presented in Table I.1.2.

*: Aromatics include benzene, toluene, ethylbenzene, xylenes & naphthalene (these should be subtracted from appropriate subfractions based on the individuals chromatographic set up).

Table I.1.2: Example of Suggested Standard Compounds to be Used for Each PHC Fraction and Quantitation

Hydrocarbon Range	Quantitation Ions	Suggested Compounds
PHC F1 - Aliphatic C_6-C_8	TIC	n-hexane cyclohexane n-octane
PHC F1 – Aromatic $C_{>8}$-C_{10}	Extracted ions 91 + 120	ethylbenzene isopropyl benzene 1-methyl-3-ethylbenzene
PHC F1 – Aliphatic $C_{>8}$-C_{10}	TIC	n-octane n-nonane n-decane
PHC F2 – Aromatic $C_{>10}$-C_{12}	Extracted ions 120+134	1,2,3-trimethylbenzene isopropyl toluene 1,2,4,5-trimethylbenzene
PHC F2 – Aliphatic $C_{>10}$-C_{12}	TIC	n-decane butylcyclohexane n-dodecane

APPENDIX II:
CONSIDERATIONS TO IDENTIFY CHEMICALS OF POTENTIAL CONCERN FOR VAPOUR INTRUSION

II.1. Toxicity and Volatility Considerations

The screening process used to determine whether or not a chemical is of potential concern for vapour intrusion includes an evaluation of both volatility and toxicity, using the following steps:

- **Step 1**: If either one of the following conditions is met, then the chemical is considered sufficiently volatile and screened in, to be further assessed as part of Step 2:
  - Henry's Law constant is greater than $1x10^{-5}$ atm-m^3/mol; or,
  - Vapour pressure is greater than 1.0 millimeter of mercury (equivalent to 1.0 Torr).
- **Step 2**: If the maximum theoretical indoor air concentration based on conservative assumptions (C_{air}) exceeds applicable health based indoor air concentration (HBIAC) or odour thresholds (if available), then the chemical should be retained in the vapour intrusion assessment, as follows:
  - If C_{air} > HBIAC (or odour thresholds), then the chemical is considered a chemical of potential concern (COPC) for the vapour intrusion assessment; or,
  - If C_{air} ≤ HBIAC (or odour thresholds), then the chemical is not considered a COPC for the vapour intrusion assessment.

Detailed calculations for this screening approach are presented in Exhibit II.1.

II.2. Mobility Considerations

Organic chemicals that are near neutral (e.g., relatively non-polar) such as polycyclic aromatic hydrocarbon (PAH) compounds can adsorb into native organic carbon present in subsurface soils and thus, the rate of soil vapour transport will be retarded through this sorption process until all the adsorptive sites are occupied. Although eventually soil vapour profiles will theoretically reach a steady state profile as sorption sites are filled, this process can be relatively slow. Equilibrium conditions may never be reached if there is an insufficient mass of chemicals or biodegradation is occurring.

The rate at which chemicals move in the subsurface is dependent on their chemical and physical properties, such as organic carbon-water (K_{oc}) partitioning coefficient, organic carbon content in soil (f_{oc}), soil moisture and transport distance. For one-dimensional transient soil vapour transport by diffusion and sorption, the approximate time to reach steady state conditions for vapour transport within a soil column, where the initial boundary condition is a step change increase in concentration at time zero can be approximated using the equations below (Johnson et al., 1999).

$$\tau_{ss} = R_v * \Theta_a * L^2 / D^{eff} \quad \text{(Equation II.1)}$$

$$R_v = 1 + \rho_{b*} K_d / (\Theta_{a*} H') + \Theta_w / (\Theta_{a*} H') \quad \text{(Equation II.2)}$$

$$K_d = K_{oc} * f_{oc} \quad \text{(Equation II.3)}$$

$$D^{eff} = D_a * \Theta_a^{3.33}/\Theta^2 + D_w/H' * \Theta_w^{3.33}/\Theta^2 \qquad \text{(Equation II.4)}$$

Where:

τ_{ss} = time to steady state (seconds);

L = transport distance (cm);

R_v = retardation coefficient (unitless);

Θ_a = air-filled porosity (unitless);

D^{eff} = effective diffusion coefficient (cm^2/sec);

D_a = free air diffusion coefficient (cm^2/sec);

D_w = water diffusion coefficient (cm^2/sec);

Θ_w = water-filled porosity (unitless);

Θ = total porosity (unitless)

K_d = soil-water partitioning coefficient (cm^3/g);

K_{oc} = organic carbon-water partitioning coefficient (cm^3/g);

H' = Henry's Law constant (unitless); and,

ρ_b = bulk dry density (g/cm^3).

II.3 References

Johnson, P.C., M.W. Kemblowski, and R.L. Johnson. 1999. "Assessing the Significance of Subsurface Contaminant Vapor Migration to Enclosed Spaces: Site-specific Alternatives to Generic Estimates." *Soil and Sediment Contamination*, *8*(3): 389-421.

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Exhibit II.1. Determination of A Chemical of Potential Concern for Vapour Intrusion

1. *Estimate Maximum Vapour Concentration*

NAPL Present: $C_v^{NAPL} = UCF_1 * MW*P/(R*T)$

No NAPL Present: $C_v^{NO\ NAPL} = UCF_2 * S * H'$

Maximum Vapour Concentration: $C_v = \mathrm{Max}\,(C_v^{NAPL}, C_v^{NO\ NAPL})$

Parameter	**Default**
C_v^{NAPL} = Vapour concentration, NAPL present (mg/m^3)	Calculated
$C_v^{NO\ NAPL}$ = Vapour concentration, NAPL not present (mg/m^3)	Calculated
MW = Molecular weight (g/mole)	Chemical specific
P = Pure chemical vapour pressure (atm)	Chemical specific
R = Gas constant (m^3-atm/K-mole)	8.21×10^{-5}
T = Absolute temperature (K, 273 + T(^{o}C))	288[#]
H' = Dimensionless Henry's Law Constant	Chemical specific
S = Pure chemical aqueous solubility (mg/L)	Chemical specific
UCF_1 = Unit conversion factor (mg/g)	1,000
UCF_2 = Unit conversion factor (L/m^3)	1,000

[#]: A temperature of 15 degrees Celsius (or 288 degrees Kelvin) is used to derive generic site condition standards (including the S-IA and GW2 component values).

2. *Calculate Maximum Theoretical Indoor Air Concentration*

$C_{air} = C_v * \alpha$

Parameter	**Default**
C_{air} = Concentration in air (mg/m^3)	Calculated
α = attenuation factor (unitless)[Δ]	0.02

[Δ]: for the purpose of identifying COPCs for vapour intrusion, $\alpha = 0.02$ is recommended for all property uses.

3. *Calculate Health-Based Indoor Air Concentration*

Detailed approach and inputs are presented in the MOE (2011) rationale document and MOECC (2016) Approved Model. Briefly, the health-based indoor air concentration (HBIAC) can be determined as follows*:*

Carcinogen : $C_{airc}^T = CRL*UCF/IUR/CIAP$

Non-carcinogen: $C_{airnc}^T = TC*SAF*UCF/NCIAP$

Health-based indoor air concentration: $HBIAC = \mathrm{Min}\,(C_{airc}^T, C_{airnc}^T)$

Parameter	**Default**
C_{airc}^T = Carcinogenic indoor air concentration (µg/m^3)	Calculated

C_{airnc}^{T} = Non-carcinogenic indoor air concentration ($\mu g/m^3$)	Calculated
TC = Tolerable concentration (mg/m^3)	Chemical specific
IUR = Inhalation unit risk ($(mg/m^3)^{-1}$)	Chemical specific
SAF = Source allocation factor (unitless)	Chemical specific
CRL = Cancer risk level (unitless)	10^{-6}
UCF = Unit conversion factor (µg/mg)	1,000
CIAP = Cancer indoor air prorating (unitless)	Refer to MOE (2011)
NCIAP = Non-cancer indoor air prorating (unitless)	Refer to MOE (2011)

APPENDIX III:
KEY CONSIDERATIONS FOR SOIL VAPOUR INVESTIGATION AND ASSESSMENT

The following list is intended to provide some key aspects that should be considered when reviewing or implementing soil vapour investigation and assessment reports. Please be advised that it is not meant as a comprehensive list for determining whether (or not) the soil vapour investigation and assessment report can be accepted by the Ministry. Further details on soil vapour characterization are provided in Chapter 5.

III.1. Site Characterization

Details pertaining to addressing conceptual site model (CSM) development for vapour intrusion studies are provided in Chapter 3 of this document and Section 4.5 of CCME (2016a) *Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment – Volume 1: Guidance Manual*, as summarized below:

- Were geologic and hydrogeological characteristics (e.g., soil properties, depth to groundwater level, groundwater flow direction) provided in support of defining potential vapour flow and transport?
- Were areas (e.g., locations and depths) with the highest concentration of volatile contaminants in soil and groundwater and/or free product identified and discussed?
- Were the extent and areas of known and inferred releases/sources of volatile contaminants identified and discussed?
- Were areas where vapour intrusion (VI) related exposure may be of potential concern (referred to as *potential VI impacted areas*) identified and discussed?
- Were all (existing & future) buildings located within each potential VI impacted area (referred to as *buildings of concern*) identified and discussed?
    - Were relevant construction features of buildings of concern (e.g., foundation structures, basements) & building ventilation (e.g. HVAC systems) discussed?
    - Were areas of known/anticipated sub-surface utilities/structures located and discussed?
- Were known/anticipated preferential pathways that intersect vapour sources and buildings of concern identified and discussed?
    - If present, whether and how they may affect vapour intrusion into buildings of concern?

III.2. Soil Vapour Sampling Program Design

Soil vapour should be adequately characterized at each potential VI impacted area. Rationales for the selection of the soil vapour sampling locations and spacing should be clearly documented, along with sufficient description and assessment of the following:

- Were objectives of the soil vapour sampling program identified and discussed?
- Were chemicals of potential concern (COPCs) identified and discussed?

- Were rationales for selecting the location and depth of each soil vapour probe provided (e.g. near vapour sources)?
    - Were lateral transects needed?
    - Were vertical profiles needed?
    - Was biodegradation assessment needed?
- Was seasonal/temporal variability considered in the sampling program?
- Were figures illustrating (1) location of existing (and if known, future) buildings; (2) areas of soil and groundwater contamination, (3) groundwater flow direction, (4) soil vapour sampling points, (5) paved/vegetated areas and preferential pathways (if any) provided?

III.3. Soil Vapour Probe Construction and Installation

Suggested operating procedures (SOPs) for soil vapour probe installation should be provided, along with borehole logs and field notes. The following should also be addressed:

- Were soil vapour probe types (e.g., probes installed in boreholes, driven probes, sub-slab) identified and discussed?
- Were appropriate drilling methods used to minimize disturbance to surrounding soil?
- Were appropriate materials used for probes and were they properly stored and handled before use?
- Were probes constructed with an appropriate seal (e.g., annular and surface)?
    - For shallow probes, were appropriate precautions taken to minimize atmospheric short-circuiting?
- Were finalized field logs provided, along with details of the soil vapour probe construction, including probe materials, geologic conditions, length of the screen interval, depth from ground surface to the top of the screen interval, sand pack, seal location and thickness, soil vapour probe diameter and screen slot size?

III.4. Soil Vapour Probe Development and Performance Testing

SOPs for soil vapour probe development and performance testing should be provided. The following should also be addressed:

- Were soil vapour probes adequately developed by: removing air (e.g., minimum of three probe volume of air, including probe pipe or tubing, pore volume of sand pack)?
    - Was sufficient equilibrium time allowed for soil vapour to stabilize/equilibrate prior to sampling?
- Was a flow and vacuum check implemented to verify an acceptable gas flow rate and vacuum?
    - Was sufficient time allowed for the vacuum generated to dissipate before sampling?

III.5. Leak Testing

SOPs for leak testing should be provided. The following should also be addressed clearly:

- Was a leak test completed to confirm a competent seal of probes with respect to:
  - annular leaks; and,
  - short circuiting through surface.
- Was a leak test (pressure shut-in test or tracer test) performed to verify that no significant leakage occurred in the sampling train?

III.6. Soil Vapour Purging and Sampling

SOPs for purging and sampling should be provided, along with a sampling train diagram and field notes. The following should also be addressed:

- Were probes purged (e.g., minimum three probe and filter pack volume)?
  - Was sufficient time allowed for equilibrium conditions to re-establish prior to sampling?
  - For sub-slab sampling, was purged soil vapour vented outdoors?
- For sub-slab and near-building sampling, was the building operating under a normal condition (e.g., ventilation, HVAC system operating) during sampling?
- Were meteorological data (e.g., precipitation) recorded prior to and during sampling & was this data considered when discussing soil vapour sampling results?
- Were appropriate sample handling and storage methods used? For sampling using sorbent tubes, were the following obtained/discussed?
  - appropriate selection of sample tubes and sorbent materials;
  - safe sampling volume (sufficient time and sampling flow rate) to provide the required detection limit and minimize breakthrough; and,
  - description of the quality assurance and quality control (QA/QC) measures performed and reasonable QA/QC performance objectives, including the following:
    - cleaning and proofing of sampling train materials and sampling device;
    - field duplicates, field transport blank, and equipment blank, where appropriate;
    - tests for breakthrough; and,
    - sampling flow rate and time (should be recorded before, during and after sampling).
- For sampling using evacuated canisters, were the following obtained/discussed?
  - appropriate selection of volume of canister and sampling flow rate; and,
  - description of the QA/QC measures performed and reasonable QA/QC performance objectives proposed for:
    - cleaning and proofing of sampling train materials and sampling device;
    - field duplicates, field transport blank, and equipment blank, where appropriate; and,
    - vacuum measurements (before and after sampling and upon lab receipt).

III.7. Soil Vapour Sampling Analysis

A description of the soil vapour analytical method, and data quality objectives should be provided. The following should also be addressed:

- Were samples analyzed within the appropriate holding time?
- Were detection limits acceptable with respect to project objectives?
- Were field trip blanks/field duplicates analyzed?
- Were laboratory duplicates/blanks analyzed?
- For canisters, was the vacuum measured and within acceptable limits prior to sampling, after sampling and upon receipt by the lab?
- For sorbent tubes, were fronts and backs of tubes (or two tubes in series) analyzed to evaluate possible breakthrough or were safe sampling volumes used in the field evaluated and confirmed?

III.8. Soil Vapour Analytical Results

A discussion on soil vapour analytical results should be provided, along with all certificates of analysis or analytical reports for all soil vapour samples. The following should also be addressed:

- Were soil vapour field data, including leak test data, purge volumes and sample rates clearly presented (e.g. tabular format)?
- Were QA/QC performances evaluated and did they meet the proposed objectives?
- Were the reported soil vapour analytical results representative of the site condition in respect to:
  - seasonal/temporal variability?
  - spatial variability (vertical and lateral)?
- If site-specific soil vapour screening levels (SVSLs) were proposed/derived for COPCs, were the following provided?
  - details on the proposed derivation approach;
  - details on assumptions/input parameters used in the derivation approach and whether they are appropriate based on site-specific conditions; and,
  - information on preferential pathways, if identified, and how they are accounted for in the derivation approach.
- Was the data consistency (i.e., in respect to other lines of evidence) evaluated to determine whether there are data gaps that warrant additional soil vapour sampling?

APPENDIX IV:
LITERATURE REVIEW ON TEMPORAL AND SPATIAL VARIATON IN SOIL VAPOUR AND INDOOR AIR

The following table (Table IV.1) provides a summary of six different field studies on temporal and spatial variation of soil vapour and indoor air concentrations associated with the vapour intrusion pathway. The results of these studies are presented here for reference purposes only and may not be representative of results at a given vapour intrusion site.

References

Brenner, D. 2010. “Results of A Long-term Study of Vapour Intrusion at Four Large Buildings at the NASA Ames Research Center.” *Journal of the Air and Waste Management Association,* 60(6): 747-758.

Folkes, D., W. Wertz, J. Kurtz, and T. Kuehster. 2009. “Observed Spatial and Temporal Distributions of CVOCs at Colorado and New York Vapour Intrusion Sites*.” Groundwater Monitoring & Remediation*, 29 (1): 70-80.

Johnson, P., C. Holton, Y. Guo, P. Dahlen, H. Luo. 2016. “Integrated Field-Scale, Lab-Scale, and Modeling Studies for Improving the Ability to Assess the Groundwater to Indoor Air Pathway at Chlorinated Solvent-Impacted Groundwater Sites.” SERDP ER-1686.

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US EPA (United States Environmental Protection Agency). 2015. “Simple, Efficient, and Rapid Methods to Determine the Potential for Vapour Intrusion into the Home: Temporal Trends, Vapour Intrusion Forecasting, Sampling Strategies, and Contaminant Migration Routes.” EPA/600/R-15/070, 2015. Prepared by B. Schumacher and J.H. Zimmerman.

US EPA. 2012. “Fluctuation of Indoor Radon and VOC Concentrations Due to Seasonal Variations.”

US EPA. 2009. “Vertical Distribution of VOCs in Soils from Groundwater to the Surface/Sub-slab.” EPA/600/R-09/0.

Table IV.1. Studies on Temporal and Spatial Variation of Soil Vapour and Indoor Air Concentrations

Location	Study Description	Media	Spatial Variation	Temporal Variation	Key Notes from Study
Indianapolis, IN [USEPA, 2015, 2012; Lutes et al. 2014]	• *Building structure(s)*: a vacant residential duplex (wood frame on a brick foundation with a poured concrete floor); one side heated in the winter & the other not. • *Contamination source*: groundwater (gw) impacted with various hydrocarbons (e.g. PHCs and CHCs); depth to gw 10-18ft (~ 3- 5 m), rapidly fluctuates with nearby creek. • *Vadose Zone*: Topsoil or fill overlying sand or silty sand with varying amounts of clay or sandy clay with trace gravel. • *Monitoring*: daily, weekly & monthly sampling of IA, sub-slab, internal/external SV and GW (Aug 2010 - Jun 2014) .	Indoor air (IA) Soil vapour (SV)	-	>100x 20x to 40x (for sub-slab SV) 10x (for external shallow and deep soil vapour)	• A strong seasonal cycle was observed for PCE and chloroform indoors, which appears to be correlated to the strength of the stack effect. The study also indicated that these stack effects included not only the winter stack effect but also solar stack effects during summer and early fall. • There were other variables that affected IA levels, thus sampling approaches that were based on assumption that near-worst-case conditions can be determined from a single variable, e.g., indoor/outdoor temperature differential, were unlikely to lead to accurate predictions. • Current IA sampling guidance on collecting samples at any time in any winter as a reasonable prediction of near-worst-case vapour intrusion should be reconsidered. IA results from the study showed peak IA concentrations in late fall/early winter or a significant, steady rise in SV concentrations over the course of a winter. • Suggestion, based on the study, for similar sites, would be to collect 2 samples in winter, 1 in early - mid winter and another in winter months. • It will be necessary to consider year-to-year variations in meteorological conditions because it is possible to observe IA levels continuously for several months during a winter but miss by a factor of approximately 5 peak concentrations observed in prior and subsequent winters.

Location	Study Description	Media	Spatial Variation	Temporal Variation	Key Notes from Study
Layton, UT [Johnson. 2014; Johnson et al., 2016; Holton, 2015]	• *Building structure(s)*: a residential two-storey home (915 ft^{2,} or 85 m^2). • *Contamination source*: a regional dilute GW plume impacted with CHCs, depth to water at about 3.3 m. • *Vadose Zone*: fine sandy silt with fine sand stringers • *Monitoring*: indoor air (at 2 hour and 4 hour intervals), sub-slab and SV and GW. monitoring (16 events over 24 months) under natural conditions (Feb 2010 and Aug2012; 2.5 years).	Indoor air	-	100x to 1000x	• Near source data were more consistent spatially and temporally than near slab data. • There were active vapour intrusion periods, which occurred in late fall, winter, sometimes early spring (highest observed in both December 2010 and 2011). • Analysis of the study data indicated that typical indoor air sampling plans (e.g., sample quarterly for four seasons, or two samples in winter and summer or in two winters) would likely mischaracterize the occurrence and magnitude of short- and long-term VI exposure at houses like the study house.
		Soil vapour	10x to 100x (for sub-slab) 10x for 3 ft (or 1 m) below slab SV 50% (about mean) for 6 ft (or 2 m) below slab SV	10 X (for sub-slab) 2x for 3 ft (or 1 m) below slab SV 50% (about mean) for 6 ft (or 2 m) below slab SV	

Location	Study Description	Media	Spatial Variation	Temporal Variation	Key Notes from Study
Denver, Colorado (Folkes et al., 2009)	• *Building structure(s)*: 45 single-family residential with different slab structures. • *Contamination source*: GW impacted with CHCs; gw depths ranging from ~30 - 50 feet (or 9 -15 m) • *Vadose Zone*: sandy to clayey silt. • *Monitoring*: IA quarterly or semi-annually for 2 -10 years.	Indoor air	-	~ 100x	• Seasonal trends suggested median winter concentrations (Dec to Feb) were 15% higher than the annual average.
Queens, New York (Folkes et al., 2009)	• *Building structure(s)*: 2 houses with a shared wall. • *Contamination source*: GW impacted with CHCs; gw depth at ~65 ft (or 20 m). • *Vadose Zone*: silty glacial sands & gravels • *Monitoring*: sub-slab SV (monthly) (Nov 2006 - Mar 2008).	Soil vapour	-	4x to 5x (for sub-slab SV)	• No clear trend in pattern of SV concentrations over time.

Location	Study Description	Media	Spatial Variation	Temporal Variation	Key Notes from Study
Moffett Field, CA (Brenner, 2010)	• *Building structure(s)*: 4 large commercial buildings at the NASA Ames Research Center • *Contamination source*: GW impacted with VOCs • *Vadose Zone*: Unknown • *Monitoring*: IA from Jun 2003 - Oct 2004 (3 sampling periods).	Indoor air	-	10x	• Monthly seasonal variability analysis showed that the IA concentration was highest in December to February and lowest from June to August
Lemoore, CA (US EPA, 2009)	• *Building structure(s)*: Maintenance buildings (slab-on-grade) and airpark parking areas. • *Contamination source*: dissolved CHC plume; gw depth: 10 - 14 ft (or 3-4 m) • *Vadose Zone*: Clay &silt. • *Monitoring*: SV beneath slab and under covered area.	Soil vapour	100x to 1000x shallow SV below a slab	<4x (for SV beneath slab) 4x-30x (for SV at under covered area)	• No obvious seasonal trend but it would appear that highest concentrations observed in late December and June to October. • Variability in the SV concentrations was not strongly linked to changes in GW concentration, suggesting that other factors have a greater effect on SV concentration. • Concentration gradient in SV collected in the immediate vicinity of the slab does not appear to be the result of a short-term effect.

<u>Notes:</u> -: no information

APPENDIX V:
LITERATURE REVIEW ON BACKGROUND INDOOR AIR CONCENTRATIONS OF VOLATILE ORGANIC COMPOUNDS IN CANADIAN HOMES

Key indoor sources for some common volatile organic compounds (VOCs) are summarized in Table V.1. A compilation of background VOC concentrations in indoor air collected at Canadian residences is also include in Tables V.2, V.3 and V.4. Note that the background concentrations are presented in this appendix for reference purposes only and may not be representative of the indoor air quality at a given site.

Background indoor air concentrations at U.S homes are also compiled in different reports, listed below for reference:

- United States Environmental Protection Agency (US EPA): *Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990 – 2005): A Compilation of Statistics for Assessing Vapor Intrusion*. (URL:https://www.epa.gov/vaporintrusion/background-indoor-air-concentrations-volatile-organic-compounds-north-american)
- Massachusetts Department of Environmental Protection (MassDEP): *Residential Typical Indoor Air Concentrations.* (URL: https://www.mass.gov/files/documents/2016/08/xi/iatu.pdf)
- New Jersey Department of Environmental Protection (NJDEP): *Background Levels of Volatile Organic Chemicals in Homes: A Review of Recent Literature*. (URL: https://www.nj.gov/dep/srp/guidance/vaporintrusion/vig_background_levels_of_vos.pdf)

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Table V.1. Example of Common Background Indoor Air Sources in Residences

Chemicals	Sources
Benzene	Automobile exhaust, gasoline, cigarette smoke, scented candles, rugs, carpet glue, paints, varnishes, lacquer thinners
Chloroform	Chlorinated water, adhesive remover
Chloroethane	Refrigerant
Chlorobenzene	Scented candles, plastic foam insulation, paint products, glued carpet
Dichlorodifluoromethane	Refrigerant, cleaning products
Dichloroethane- 1,1	Plastic products, flame retardant fabrics
Dichloroethane-1,2	Polyresin molded decorations, plastic products, adhesives, flame retardant fabrics
Dichlorobenzene-1,4	Moth balls, insecticide, air deodorant, toilet disinfectant
Dichloropropene-1,3	Fungicides
Ethylbenzene	Gasoline, fuel oil, paint, paint thinner, floor polish, insecticides, tub and cleaning solvents, cigarette smoke
n-Hexane	Gasoline, rubber cement, typing correction fluid, perfume aerosols
Methylene chloride	Hairspray, paint stripper, rug cleaners, insecticides, furniture polish
Naphthalene	Cigarette smoke, automobile exhaust, wood burning, insecticides, moth balls, air freshener
Styrene	Cigarette smoke, automobile exhaust, fiberglass, rubber and epoxy adhesives, wood burning
Trichloroethane-1,1,1	Spot cleaner, glues, insecticides, drain cleaners, shoe polish, paint, vanish remover
Trichloroethene (TCE)	Paint, vanish removers, metal cleaner, carpet, typewriter correction fluid, automotive cleaning, degreaser
Trimethylbenzene	Gasoline, paint, varnish, auto exhaust, wood floor wax, insecticides, carpet
Tetrachloroethene (PCE)	Dry cleaning, metal degreasing, scented candles, insecticides, rug & upholstery cleaners, auto products, paint, vanish remover.
Tetrachloroethane-1,1,2,2	Solvent, paint, rust removers, varnishes, lacquers

Chemicals	Sources
Toluene	Paint, carpets, paint thinner, adhesives, wood burning, gasoline, automobile exhaust, polishes, nail polish, scented candle, cigarette smoke, printing products
Xylenes	Gasoline, fuel oil, paint, inks, dye, paint thinner, degreasers, lubricating oils, water proofing materials, pesticides, pruning paint, flea medicine, wood burning, cigarette smoke
Vinyl chloride	Pipe sealant, breakdown products of TCE and PCE

Sources: Holmberg and Lundberg, 1985; Heroux et al., 2008; Hers et al., 2001; Ilgen et al., 2001; NJDEP, 2018; Sarigiannisa et al., 2011.

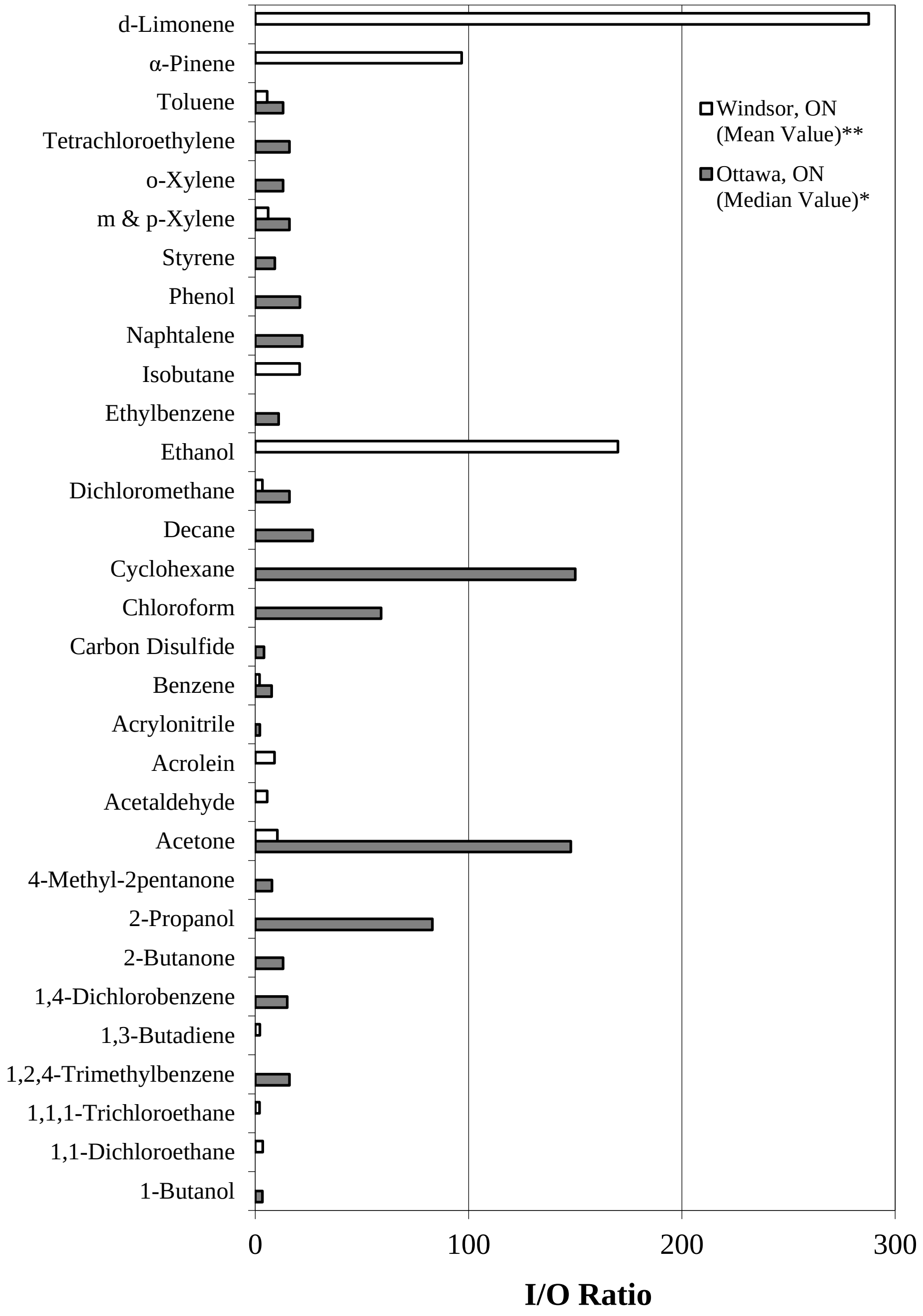
Table V.2. Summary of Studies on Background Indoor Air Concentrations

Locations	Study Summary
Edmonton, Alberta (Health Canada, 2013)	• Number of houses/buildings: 50 homes during the winter and summer (with 26 homes participating in both seasons) • Timeframe sampled: 2010 (Winter and Summer) • COPCs: 193 VOCs • Sample size: 1321 in total for both winter (n=652) and summer (n=669) • Collection device/Period/Analytical Method: 6.0L Summa^{TM} canister)/ 24 hours/GC-MS. • Data available: Min/Max, Geometric mean/Arithmetic mean, Percentiles (5th, 25th, 50th, 75th, 90th, 95th); for indoor & outdoor air
Halifax, Nova Scotia (Health Canada, 2012)	• Number of houses/buildings: 50 homes during the winter and summer (with 42 homes participating in both seasons) • Timeframe sampled: 2009 (Winter and Summer) • COPCs: 193 VOCs • Sample size: 1255 in total for both winter (n=599) and summer (n=656) • Collection device/Period/Analytical Method: 6.0L Summa^{TM} canister)/ 24 hours/ GC-MS. • Data available: Min/Max, Geometric mean/Arithmetic mean, Percentiles (5th, 25th, 50th, 75th, 90th, 95th); for indoor & outdoor air
Regina, Saskatchewan (Heroux et al, 2010; Health Canada, 2010a)	• Number of houses/buildings: 146 homes during the winter and summer (with 71 homes participating in both seasons) • Timeframe sampled: 2007 (Winter and Summer) • COPCs: 194 VOCs • Sample size: 412 (for 24-hr data only) • Collection device/Period/Analytical Method: 6.0L Summa^{TM} canister)/ 24 hours (5-day data also available, but not reported in this appendix)/GC-MS • Data available: Min/Max, Geometric mean/Arithmetic mean, Percentiles (5th, 25th, 50th, 75th, 90th, 95th); for indoor & outdoor air
Windsor, Ontario (Health Canada, 2010b; Stocco et al., 2008)	• Number of houses/buildings: 45 to 48 homes (each sampling event) • Timeframe sampled: 2005- 2006 (Winter and Summer) • COPCs: 188 VOCs • Sample size: 1294 in 2005 and 872 in 2006

Locations	Study Summary
	• Collection device/Period/Analytical Method: 6.0L Summa^{TM} canister/24 hours (5-day data also available, but not reported in this appendix)/GC-MS • Data available: Min/Max, Geometric mean/Arithmetic mean, Arithmetic, Percentiles (5th, 25th, 50th, 75th, 90th, 95th); for indoor & outdoor air
Quebec City, Quebec (Heroux et al., 2008; Gilbert et al., 2008)	• Number of houses/buildings: 96 residences • Timeframe sampled: 2005 (January-April) • COPCs: 26 VOCs • Sample size: 96 • Collection device/Period/Analytical Method: 3M organic vapour monitors/7days/GC-MS (for VOCs) and 2,4-DNPH cartridges/24 hours/HPLC (for formaldehyde) • Data available: Min/Max, Geometric mean/Geometric standard derivation, Median; for indoor air
Ottawa, Ontario (Zhu et al., 2005)	• Number of houses/buildings: 75 residential houses • Timeframe Sampled: 2002/2003 (November to March) • COPCs: 37 VOCs monitored • Sample size: 75 • Collection device/Period/Analytical Method: sorbent tube (active sampling)/100 minutes/GC-MS • Data available: Arithmetic mean, Percentiles (50th, 75th, 90th); for indoor & outdoor air
Greater Toronto Area, Ontario (CCME, 2016; Otson & Zhu, 1997)	• Number of houses/buildings: 44 homes • Timeframe Sampled: 1996 (February- April) • COPCs: 30 VOCs • Sample size: unknown • Collection device/Period/Analytical Method: OVM 3500 passive sampler/24 hours/GC-MSD-SIM • Data available: Mean, Max; for indoor & outdoor air
Hamilton, Ontario (Hamilton Indoor Air (1993) Statistics; CCME, 2016)	• Number of houses/buildings: unknown • Timeframe Sampled: 1993 • COPCs: 28 VOCs • Sample size: unknown • Collection device/Period/Analytical Method: unknown • Data available: Min/Max, Geometric mean/Arithmetic mean/Percentiles (50th, 95th); for indoor air

Locations	Study Summary
Canada-wide (10 Provinces) (CCME, 2016; Fellin & Otson, 1994; Otson et al., 1994)	• Number of houses/buildings: 754 residences • Timeframe sampled:1991-1992 • COPCs: 26 VOCs • Sample size: 185 (Winter), 178 (Spring), 197 (Summer) and 194 (Fall) • Collection device/Period/Analytical Method: 3M OVM 3500 passive sampler/24 hours/GC-MS-SIM • Data available: Mean, Max; for indoor air

Notes: COPCs = chemicals of potential concern; VOCs = volatile organic compounds; GC = gas chromatography; MS = mass spectroscopy; SIM = selective ion monitoring; HPLC = high performance liquid chromatography.



Sources: ** Zhu et al., 2005, ** Stocco et al. 2008*

Figure V.1. Indoor Air/Outdoor Air Ratio of VOCs in Homes in Ontario

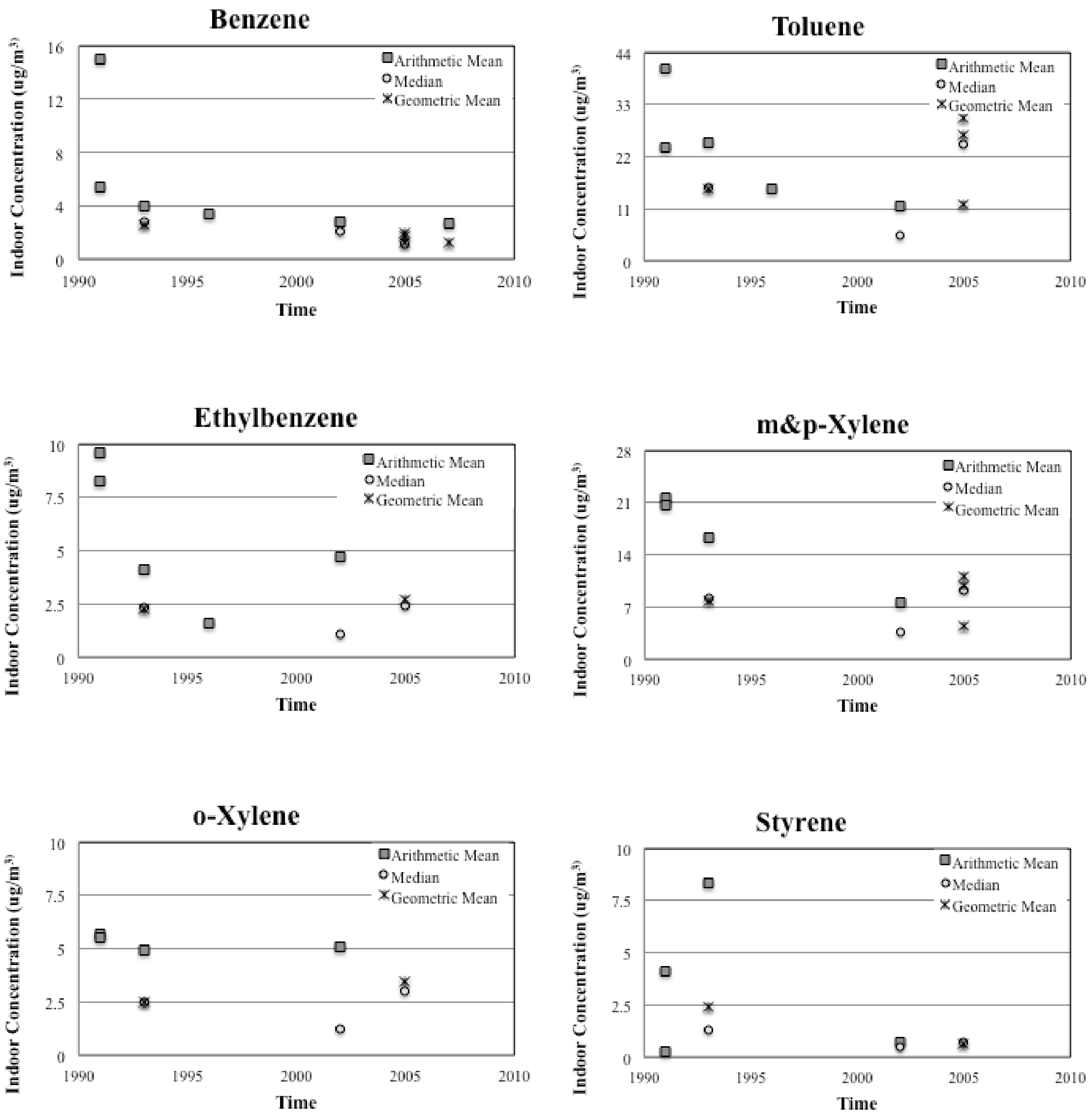


Figure V.2. Summary Central Tendency for Background Indoor Air Levels of Selected Aromatic Hydrocarbons in Canadian Homes from 1990 to 2010

Table V.3. Compilation of Indoor Air Quality Data in Canadian Homes from 1991 to 1999

Unit in μg/m^3

Chemicals	**Canada-wide (1991)**	**Canada-wide (1991)**	**Hamilton ON (1993)**	**Hamilton ON (1993)**	**GTA ON (1996)**	**GTA ON (1996)**	**SK & ON (1991 & 1999)**	**SK & ON (1991 &1999)**
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
1,1-Dichloroethylene	-	-	0.15	2.02	-	-	-	-
1,1,1-Trichloroethane	-	-	9.94	115.79	-	-	-	-
1,2,4-Trichlorobenzene	NV	-	0.23	2.30	-	-	-	-
1,2,4-Trimethylbenzene	11.5	-	10.05	123.20	-	-	-	-
1,4-Dichlorobenzene	18.9	-	8.67	236.47	53.4	1600	-	-
1,3,5-Trimethylbenzene	2.7	640	3.99	148.32	0.53	1.47	5.1	15
1,4-Dioxane	-	-	-	-	0.42	0.68	-	-
Benzene	5.4	67.9	3.99	54.61	3.42	45.8	15	42.3
Bromodichloromethane	-	-	0.28	1.32	-	-	-	-
Carbon Tetrachloride	-	-	0.57	4.51	-	-	-	-
Chloroform	1.46	-	-	-	1.77	3.71	-	-
Ethylbenzene	8.2	540	4.16	53.21	1.58	20.9	9.6	32.9
Hexane	NV	5.24	7.94	114.86	5.24	108	99.4	-
Naphthalene	4.0	-	5.09	73.35	4.81	83.4	7.2	30
Styrene	0.3	130	8.37	176.61	-	-	4.1	11.3
m & p-Xylene	20.6	1470	16.33	317.19	-	-	21.6	74.2
o-Xylene	5.5	320	4.95	70.17	-	-	5.7	20.3
Tetrachloroethylene	2.7	313	3.06	33.61	1.59	9.55	8.2	30
Toluene	40.8	5730	25.04	156.43	15.2	186	23.9	110.5
Trichloroethylene	0.5	165	0.30	3.53	-	-	2.3	6.5
Vinyl Chloride	-	-	-	1	-	-	-	-

Notes: -: not reported; NV: no value; *: non detect (reported at half of method detection limit); ON: Ontario, SK: Saskatchewan, GTA: Greater Toronto Area.

Table V.4. Compilation of Indoor Air Data in Canadian Homes from 2002 to 2010

(a) Edmonton (Alberta) – Summer 2010

Unit in µg/m^3

Chemical	**Min**	**Max**	**AM**	**50th**	**75th**	**95th**
1,1-Dichloroethane	<	<	<	<	<	<
1,1-Dichloroethylene	<	0.05	<	<	<	<
1,1,1-Trichloroethane	<	2.315	0.221	<	0.248	1.053
1,2-Dichlorobenzene	<	0.099	<	<	<	<
1,2-Dichloroethane	0.044	8.904	0.738	0.184	0.607	3.483
1,2-Dichloropropane	<	0.203	<	<	<	<
1,2,4-Trichlorobenzene	<	0.221	<	<	<	0.111
1,2,4-Trimethylbenzene	<	86.8	2.997	0.626	1.494	12.59
1,4-Dichlorobenzene	<	0.805	0.14	0.052	0.12	0.461
1,3,5-Trimethylbenzene	<	22.97	0.802	0.168	0.373	3.469
1,3-Dichlorobenzene	<	<	<	<	<	<
Benzene	0.155	7.189	1.037	0.63	1.061	4.12
Bromodichloromethane	<	<	<	<	<	<
Bromoform	<	0.184	<	<	<	<
Bromomethane	<	<	<	<	<	<
Carbon Disulfide	0.147	2.375	0.318	0.284	0.363	0.553
Carbon Tetrachloride	0.408	1.355	0.55	0.523	0.565	0.793
Chlorobenzene	<	0.098	<	<	<	<
Chloroform	0.083	8.045	1.348	0.915	1.853	4.214
Chloromethane	1.02	2.627	1.317	1.272	1.402	1.702
Cis-1,2-Dichloroethylene	<	<	<	<	<	<
Dibromochloromethane	<	<	<	<	<	<
Ethylbenzene	0.102	25.76	1.986	0.889	2.018	7.867
Ethylene Dibromide	<	<	<	<	<	<
Hexane	0.158	20.44	1.751	0.734	1.492	7.697
Methyl Ethyl Ketone	1.001	46.41	5.21	3.245	4.824	15.38
Methyl Isobutyl Ketone	<	10.92	0.605	0.266	0.65	1.406
Methyl Tert-butyl Ether	<	<	<	<	<	<
Naphthalene	<	10.65	0.506	0.256	0.39	1.662
Styrene	<	9.383	0.708	0.481	0.85	2.067
m & p-Xylene	0.295	78.7	6.575	2.426	6.655	29.66
o-Xylene	0.112	27.97	2.094	0.767	1.864	10.87
Tetrachloroethylene	<	721.38	4.502	0.253	0.679	7.027
Toluene	0.497	82.25	9.723	6.14	11.47	30.04
Trichloroethylene	<	1.654	<	<	<	0.298
Trichlorofluoroethane	0.4463	1.047	0.565	0.547	0.695	0.693
Vinyl Chloride	<	0.055	<	<	<	0.021

Notes: <: less than method detection limit; AM: arithmetic mean.

(b) Edmonton (Alberta) – Winter 2010 Unit in µg/m^3

Chemicals	**Min**	**Max**	**AM**	**50th**	**75th**	**95th**
1,1-Dichloroethane	<	0.66	<	<	<	<
1,1-Dichloroethylene	<	0.093	<	<	<	0.02
1,1,1-Trichloroethane	0.032	4.2	0.317	0.067	0.247	1.7
1,2-Dichlorobenzene	<	25.52	<	<	<	0.047
1,2-Dichloroethane	0.067	6.547	0.711	9.24	0.7	4.167
1,2-Dichloropropane	<	4.487	0.089	<	<	0.427
1,2,4-Trichlorobenzene	<	0.228	<	<	<	<
1,2,4-Trimethylbenzene	0.153	327.07	5.579	1.427	2.72	9.807
1,4-Dichlorobenzene	0.483	95	0.086	0.056	0.087	0.34
1,3,5-Trimethylbenzene	0.047	90.27	1.493	0.408	0.753	3.12
1,3-Dichlorobenzene	0.048	<	<	<	<	<
Benzene	0.408	9.66	1.682	1.2	2.152	4.032
Bromodichloromethane	<	0.08	<	<	<	<
Bromoform	0.28	<	<	<	<	<
Bromomethane	<	0.127	0.053	0.053	0.056	0.067
Carbon Disulfide	0.08	4.308	0.397	0.293	0.427	0.84
Carbon Tetrachloride	0.24	1.673	0.521	0.512	0.547	0.707
Chlorobenzene	<	0.916	<	<	<	<
Chloroform	0.044	14.29	1.158	0.647	1.007	3.627
Chloromethane	1.113	8.624	1.476	1.373	1.516	1.912
Cis-1,2-Dichloroethylene	<	2.86	<	<	<	<
Dibromochloromethane	<	0.272	<	<	<	<
Ethylbenzene	0.18	551.92	10.45	1.493	2.9	17.42
Ethylene Dibromide	<	0.208	<	<	<	<
Hexane	0.147	22.33	2.334	1.732	2.856	6.904
Methyl Ethyl Ketone	0.707	550.8	13.31	4.14	7.947	47.27
Methyl Isobutyl Ketone	<	127.3	0.941	0.22	0.427	0.92
Methyl Tert-butyl Ether	<	2.26	<	<	<	<
Naphthalene	<	57.25	1.349	0.487	0.793	2.933
Styrene	<	770.39	3.44	0.553	0.916	3.044
m & p-Xylene	<	1355.6	33	4.56	9.693	65.22
o-Xylene	0.2	211.11	5.568	1.493	2.793	17.91
Tetrachloroethylene	<	30.79	1.343	0.42	1.276	5.547
Toluene	0.388	383.29	18.05	7.587	11.06	45.89
Trichloroethylene	<	3.593	0.225	0.136	0.2	0.52
Trichlorofluoroethane	0.312	0.652	0.556	0.564	0.587	0.62
Vinyl Chloride	<	0.964	<	<	<	<

Notes: <: less than method detection limit; AM: arithmetic mean.

(c) Halifax (Nova Scotia) – Summer 2009 Unit in µg/m^3

Chemicals	Min	Max	AM	50th	75th	95th
1,1-Dichloroethane	<	0.307	0.015	<	<	0.064
1,1-Dichloroethylene	<	0.096	<	<	<	<
1,1,1-Trichloroethane	0.044	40.46	0.615	0.067	0.172	3.432
1,2-Dichlorobenzene	<	2.516	0.037	<	<	0.072
1,2-Dichloroethane	0.032	22.99	1.164	0.292	0.988	5.492
1,2-Dichloropropane	<	1.96	0.047	<	0.032	0.104
1,2,4-Trichlorobenzene	<	0.28	0.058	0.04	0.068	0.16
1,2,4-Trimethylbenzene	0.024	89.99	3.827	1.052	2.912	17.87
1,4-Dichlorobenzene	0.016	1.064	0.112	0.056	0.092	0.5
1,3,5-Trimethylbenzene	<	28.35	1.11	0.308	0.828	5.616
1,3-Dichlorobenzene	<	0.052	<	<	<	0.028
Benzene	0.148	85.17	2.435	0.52	1.408	9.02
Bromodichloromethane	<	1.188	0.114	0.064	0.16	0.424
Bromoform	<	0.224	0.068	0.064	0.084	0.128
Bromomethane	<	0.12	<	<	<	0.072
Carbon Disulfide	<	5.808	0.517	0.428	0.596	1.176
Carbon Tetrachloride	0.38	1.348	0.545	0.52	0.568	0.768
Chlorobenzene	<	0.052	<	0.012	0.016	0.024
Chloroform	0.116	17.18	2.453	1.384	2.956	9.716
Chloromethane	1.012	2.513	1.302	1.284	1.376	1.601
Cis-1,2-Dichloroethylene	<	<	<	<	<	<
Dibromochloromethane	<	0.064	0.012	0.012	0.016	0.024
Ethylbenzene	0.068	210.4	6.917	1.108	3.948	23.05
Ethylene Dibromide	<	<	<	<	<	<
Hexane	<	92.41	3.692	0.716	3.556	15.46
Methyl Ethyl Ketone	0.204	582.8	12.59	2.172	3.536	10.35
Methyl Isobutyl Ketone	<	5.58	0.391	0.256	0.464	1.132
Methyl Tert-butyl Ether	<	26.07	0.323	<	<	<
Naphthalene	0.036	27.76	1.7	0.528	1.124	5.104
Styrene	0.012	29.28	0.809	0.372	0.692	1.324
m & p-Xylene	0.172	653.2	22.42	2.328	12.98	87.24
o-Xylene	0.06	155	5.154	0.812	3.132	22.8
Tetrachloroethylene	0.028	312.6	2.947	0.2	0.548	2.448
Toluene	0.376	700.8	23.28	5.906	12.45	104.2
Trichloroethylene	<	6.176	0.199	0.028	0.068	1.668
Trichlorofluoroethane	1.304	21.91	2.218	1.748	2.2	4.856
Vinyl Chloride	<	0.068	<	<	<	<

Notes: <: less than method detection limit; AM: arithmetic mean.

(d) Halifax (Nova Scotia) – Winter 2009 Unit in µg/m^3

Chemicals	Min	Max	AM	50th	75th	95th
1,1-Dichloroethane	<	0.6	<	<	<	<
1,1-Dichloroethylene	<	1.11	<	<	<	0.05
1,1,1-Trichloroethane	<	12.52	0.574	0.067	0.214	2.103
1,2-Dichlorobenzene	<	0.037	<	<	<	<
1,2-Dichloroethane	<	4.557	0.484	0.21	0.552	1.593
1,2-Dichloropropane	<	0.204	0.028	<	0.027	0.06
1,2,4-Trichlorobenzene	<	0.45	0.037	0.023	0.033	0.1
1,2,4-Trimethylbenzene	0.163	65.77	3.937	1.163	2.34	17.48
1,4-Dichlorobenzene	<	0.77	0.071	0.04	0.085	0.19
1,3,5-Trimethylbenzene	0.037	18.89	1.121	0.335	0.69	4.963
1,3-Dichlorobenzene	<	0.033	<	<	<	<
Benzene	0.307	89.69	3.219	0.83	1.795	8.173
Bromodichloromethane	<	0.843	0.093	0.07	0.14	0.337
Bromoform	<	0.697	0.032	<	<	0.04
Bromomethane	<	0.107	<	<	<	0.073
Carbon Disulfide	0.14	3.533	0.443	0.333	0.5	1.067
Carbon Tetrachloride	0.13	2.577	0.517	0.483	0.543	0.737
Chlorobenzene	<	0.22	<	<	0.013	0.02
Chloroform	<	26.42	1.986	1.388	2.289	6.03
Chloromethane	0.743	2.42	1.259	1.242	1.379	1.62
Cis-1,2-Dichloroethylene	<	<	<	<	<	<
Dibromochloromethane	<	0.033	0.011	<	0.013	0.02
Ethylbenzene	0.137	107.1	4.16	1.073	2.163	11.04
Ethylene Dibromide	<	<	<	<	<	<
Hexane	0.12	140.6	4.84	0.769	3.335	14.1
Methyl Ethyl Ketone	0.367	26.87	3.395	1.9	3.3	9.9
Methyl Isobutyl Ketone	<	4.82	0.378	0.2	0.333	1.2
Methyl Tert-butyl Ether	<	9.687	0.169	<	<	<
Naphthalene	<	9.923	0.91	0.373	0.687	4.337
Styrene	0.007	16.89	0.747	0.3	0.487	1.132
m & p-Xylene	0.337	327.8	13.06	3.108	7.5	37.06
o-Xylene	0.133	101.3	4084	0.915	2.129	12.63
Tetrachloroethylene	0.04	34.16	0.765	0.205	0.583	3.203
Toluene	0.677	420.9	20	5.199	13.51	64.04
Trichloroethylene	<	3.763	0.177	0.03	0.047	0.96
Trichlorofluoroethane	1.117	1137	11.1	1.712	2.227	4.547
Vinyl Chloride	<	0.033	<	<	<	<

Notes: <: less than method detection limit; AM: arithmetic mean.

(e) Regina (Saskatchewan) – Summer 2007 Unit in μg/m^3

Chemicals	Min	Max	AM	50th	75th	95th
1,1-Dichloroethane	0.016*	0.055	0.017	0.016*	0.016*	0.016*
1,1-Dichloroethylene	0.006*	0.035	0.006*	0.006	0.006*	0.006*
1,1,1-Trichloroethane	0.07	23.905	1.324	0.157	0.64	6.155
1,2-Dichlorobenzene	0.023*	3.085	0.085	0.023*	0.023*	0.27
1,2-Dichloroethane	0.04	9.675	0.491	0.13	0.35	2.29
1,2-Dichloropropane	0.027*	3.855	0.074	0.027*	0.027*	0.1
1,2,4-Trichlorobenzene	0.034*	1.047	0.066	0.034*	0.07	0.155
1,2,4-Trimethylbenzene	0.08	46.44	3.657	1.6	3.32	13.97
1,4-Dichlorobenzene	0.014*	9.935	0.335	0.125	0.217	0.525
1,3,5-Trimethylbenzene	0.017*	14.285	1.007	0.38	0.87	4.4145
1,3-Dichlorobenzene	0.029*	0.029*	0.029*	0.029*	0.029*	0.029*
Benzene	0.18	32.225	2.723	0.997	2.265	13.313
Bromodichloromethane	0.048*	6.91	0.615	0.33	0.765	2.01
Bromoform	0.057*	0.9	0.071	0.057*	0.057*	0.115
Bromomethane	0.033*	0.145	0.054	0.033	0.073	0.09
Carbon Disulfide	0.18	8.565	0.512	0.38	0.495	0.86
Carbon Tetrachloride	0.43	2.24	0.681	0.59	0.795	1.105
Chlorobenzene	0.021*	0.29	0.028	0.021*	0.021*	0.055
Chloroform	0.127	34.93	3.24	1.565	3.865	11.64
Chloromethane	0.945	16.2	1.64	1.195	1.45	3.8
Cis-1,2-Dichloroethylene	0.017*	0.017*	0.017*	0.017*	0.017*	0.017*
Dibromochloromethane	0.039*	1.6	0.164	0.095	0.2	0.455
Ethylbenzene	0.103	33.595	3.637	1.535	3.73	15.44
Ethylene Dibromide	0.027*	0.027*	0.027*	0.027*	0.027*	0.027*
Hexane	0.233	29.65	2.917	1.445	2.725	13.86
Methyl Ethyl Ketone	1.19	86.005	7.488	4.045	7.935	23.785
Methyl Isobutyl Ketone	0.065	2.585	0.616	0.395	0.86	1.67
Methyl Tert-butyl Ether	0	0.023	0.001	0	0	0.005
Naphthalene	0.018	10.79	1.45	0.93	1.67	5.385
Styrene	0.011*	413.605	5.029	0.68	1.505	3.545
m & p-Xylene	-	-	-	-	-	-
o-Xylene	0.11	34.47	3.63	1.413	3.79	15.435
Tetrachloroethylene	0.037	137.56	3.778	0.487	1.76	10.57
Toluene	0.77	314.755	23.539	10.727	19.17	104.23
Trichloroethylene	0.051*	1.7	0.153	0.051*	0.15	0.61
Trichlorofluoroethane	1.4	68.96	3.727	2.4	3.425	6.845
Vinyl Chloride	0.013*	0.32	0.021	0.013*	0.013*	0.04

Notes: *: non detect (reported at 1/2 method detection limit); -: not reported; AM: arithmetic mean.

(f) Regina (Saskatchewan) – Winter 2007 Unit in µg/m^3

Chemicals	Min	Max	AM	50th	75th	95th
1,1-Dichloroethane	0.016*	0.613	0.021	0.016*	0.016*	0.016*
1,1-Dichloroethylene	0.006*	0.103	0.007	0.016	0.016	0.13
1,1,1-Trichloroethane	0.057	18.483	0.846	0.117	0.453	2.913
1,2-Dichlorobenzene	0.023*	13.243	0.184	0.023*	0.023*	0.08
1,2-Dichloroethane	0.043	6.407	0.29	0.103	0.203	1.217
1,2-Dichloropropane	0.027*	0.22	0.033	0.027*	0.027*	0.027*
1,2,4-Trichlorobenzene	0.034*	0.153	0.049	0.034*	0.034*	1.27
1,2,4-Trimethylbenzene	0.197	14.17	1.806	0.973	1.763	5.667
1,4-Dichlorobenzene	0.014	1111.62	11.87	0.207	0.602	6.477
1,3,5-Trimethylbenzene	0.017*	4.137	0.503	0.28	0.487	1.717
1,3-Dichlorobenzene	0.029*	17.55	0.196	0.029*	0.029*	0.029*
Benzene	0.533	17.873	2.062	1.15	1.967	5.513
Bromodichloromethane	0.048*	2.577	0.889	0.763	1.133	2.16
Bromoform	0.057*	8.413	0.137	0.057*	0.057*	0.057*
Bromomethane	0.033*	0.12	0.04	0.033	0.033	0.08
Carbon Disulfide	0.127	1.995	0.327	0.248	0.323	0.645
Carbon Tetrachloride	0.107	0.767	0.455	0.443	0.507	0.683
Chlorobenzene	0.021*	1.053	0.042	0.021*	0.021*	0.127
Chloroform	0.307	7.087	2.166	1.9	2.65	4.897
Chloromethane	0.847	12.513	1.756	1.333	1.54	4.297
Cis-1,2-Dichloroethylene	0.017*	0.017*	0.017*	0.017*	0.017*	0.017*
Dibromochloromethane	0.039*	0.587	0.184	0.153	0.23	0.507
Ethylbenzene	0.227	14.27	1.902	1.083	1.937	5.77
Ethylene Dibromide	0.027*	0.027*	0.027*	0.027*	0.027*	0.027*
Hexane	0.337	54.445	2.235	1.037	1.623	4.64
Methyl Ethyl Ketone	0.615	837.48	18.796	3.092	6.995	30.755
Methyl Isobutyl Ketone	0.003*	2.42	0.305	0.188	0.33	1.175
Methyl Tert-butyl Ether	0	0.067	0	0	0	0
Naphthalene	0.018	37.083	0.983	0.492	0.71	1.597
Styrene	0.011*	25.343	1.053	0.453	0.697	2.3
m & p-Xylene	-	-	-	-	-	-
o-Xylene	0.223	13.463	1.825	0.98	1.747	5.99
Tetrachloroethylene	0.037	58.013	1.568	0.297	1.25	4.063
Toluene	0.023	625.225	21.329	7.823	13.957	34.293
Trichloroethylene	0.051*	13.157	0.212	0.051	0.051	0.233
Trichlorofluoroethane	1.137	49.137	3.223	2.07	2.947	6.133
Vinyl Chloride	0.013*	0.11	0..015	0.013	0.013	0.013

Notes: *: non detect (reported at 1/2 method detection limit); -: not reported; AM: arithmetic mean.

(g) Winsor (Ontario) – Summer 2005 & 2006 Unit in µg/m^3

Chemicals	Min	Max	AM	50th	75th	95th
1,1-Dichloroethane	0.043*	0.24	0.051	0.043*	0.043*	0.11
1,1-Dichloroethylene	0.076*	1.38	0.085	0.076*	0.076*	0.076*
1,1,1-Trichloroethane	0.05*	4.125	0.609	0.203	0.735	2.675
1,2-Dichlorobenzene	0.046*	0.26	0.049	0.046*	0.046*	0.046*
1,2-Dichloroethane	0.045*	23.43	0.491	0.16	0.34	1.535
1,2-Dichloropropane	0.043*	0.275	0.06	0.043	0.043	0.13
1,2,4-Trichlorobenzene	0.056*	0.35	0.095	0.056	0.13	0.26
1,2,4-Trimethylbenzene	0.27	177.28	8.81	2.36	7.12	43.095
1,4-Dichlorobenzene	-	-	-	-	-	-
1,3,5-Trimethylbenzene	0.08	95.953	2.992	0.64	2.135	14.065
1,3-Dichlorobenzene	0.05*	0.05*	0.05*	0.05*	0.05*	0.05*
Benzene	0.525	16.485	3.076	1.475	2.87	11.07
Bromodichloromethane	0.077*	8.35	0.785	0.64	1.04	1.83
Bromoform	0.053*	0.41	0.07	0.053	0.053	0.2
Bromomethane	0.089*	0.31	0.09	0.089*	0.089*	0.089*
Carbon Disulfide	0.08	4.92	0.725	0.57	0.9	1.82
Carbon Tetrachloride	0.24	7.295	0.715	0.57	0.64	1.115
Chlorobenzene	0.039*	0.235	0.042	0.039*	0.039*	0.039*
Chloroform	0.1	59.885	4.023	2.675	4.995	11.23
Chloromethane	0.06*	3.38	1.709	1.68	1.98	2.43
Cis-1,2-Dichloroethylene	-	-	-	-	-	-
Dibromochloromethane	0.083*	1.415	0.272	0.23	0.35	0.71
Ethylbenzene	0.41	912.78	15.331	2.927	7.085	39.665
Ethylene Dibromide	0.062*	0.062*	0.062*	0.062*	0.062*	0.062*
Hexane	0.385	48.2	7.315	2.41	7.51	30.24
Methyl Ethyl Ketone	0.004	1040.21	17.369	8.4	13.57	31.76
Methyl Isobutyl Ketone	0.003*	282.44	4.457	1.13	2.525	13.82
Methyl Tert-butyl Ether	0.016*	0.16	0.02	0.016*	0.016*	0.016*
Naphthalene	0.021	18.875	1.502	0.91	1.53	3.28
Styrene	0.024*	7.135	1.76	1.43	2.385	4.61
m & p-Xylene	1.065	2342.12	44.704	8.653	20.655	118.445
o-Xylene	0.345	751.12	14.316	2.687	6.015	40.78
Tetrachloroethylene	0.06*	56.915	2.473	0.56	1.61	11.183
Toluene	2.745	1466.28	55.318	23.5	52.895	160.867
Trichloroethylene	0.095*	5.79	0.44	0.29	0.47	1.45
Trichlorofluoroethane	1.405	130.88	5.757	2.97	4.2	20.29
Vinyl Chloride	0.024*	0.185	0.029	0.024*	0.024*	0.06

Notes: *: non detect (reported at 1/2 method detection limit); -: not reported; AM: arithmetic mean.

(h) Winsor (Ontario) – Winter 2005 & 2006 Unit in µg/m^3

Chemicals	Min	Max	AM	50th	75th	95th
1,1-Dichloroethane	0.043*	0.088	0.043*	0.043*	0.043*	0.043*
1,1-Dichloroethylene	0.076	0.185	0.076*	0.076*	0.076*	0.076*
1,1,1-Trichloroethane	0.05	5.2	0.398	0.13	0.352	1.484
1,2-Dichlorobenzene	0.046*	0.046*	0.046*	0.046*	0.046*	0.046*
1,2-Dichloroethane	0.045*	0.59	0.118	0.045*	0.127	0.452
1,2-Dichloropropane	0.043*	0.092	0.044	0.043*	0.043*	0.043*
1,2,4-Trichlorobenzene	0.056*	0.2533	0.068	0.056*	0.056*	0.152
1,2,4-Trimethylbenzene	0.045	14.56	2.06	1.121	2.689	7.476
1,4-Dichlorobenzene	-	-	-	-	-	-
1,3,5-Trimethylbenzene	0.023*	4.42	0.562	0.316	0.772	1.776
1,3-Dichlorobenzene	0.05*	0.05*	0.05*	0.05*	0.05*	0.05*
Benzene	0.596	13.936	2.094	1.541	2.36	5.26
Bromodichloromethane	0.077*	3.144	0.428	0.36	0.537	0.927
Bromoform	0.053*	0.95	0.064	0.053*	0.053*	0.115
Bromomethane	0.089*	0.805	0.092	0.089	0.089*	0.089*
Carbon Disulfide	0.003*	1.693	0.211	0.155	0.247	0.55
Carbon Tetrachloride	0.348	3.31	0.603	0.533	0.595	0.78
Chlorobenzene	0.039*	0.48	0.043	0.039*	0.039*	0.039*
Chloroform	0.165	47.93	1.678	1.097	1.87	3.945
Chloromethane	0.76	2.22	1.324	1.3	1.418	1.64
Cis-1,2-Dichloroethylene	-	-	-	-	-	-
Dibromochloromethane	0.083*	0.45	0.129	0.083*	0.18	0.31
Ethylbenzene	0.224	609.93	7.668	1.123	2.469	11.3
Ethylene Dibromide	0.062*	0.062*	0.062*	0.062*	0.062*	0.062*
Hexane	0.324	26.564	3.59	1.817	4.688	11.26
Methyl Ethyl Ketone	0.74	31.024	3.824	2.95	4.245	10.267
Methyl Isobutyl Ketone	0.003*	3.823	0.334	0.25	0.408	0.832
Methyl Tert-butyl Ether	0.016*	0.112	0.017	0.016*	0.016*	0.016*
Naphthalene	0.048	18.612	0.989	0.466	0.803	2.205
Styrene	0.024	1.9	0.457	0.331	0.537	1.173
m & p-Xylene	0.046	1359.31	20.307	3.03	6.807	34.84
o-Xylene	0.184	520.5	7.123	1.031	2.336	11.195
Tetrachloroethylene	0.06	12.345	1.242	0.3	0.75	7.34
Toluene	2.2	145.636	18.227	8.397	22.336	79.248
Trichloroethylene	0.095*	4.098	0.234	0.095*	0.282	0.553
Trichlorofluoroethane	1.39	81.25	3.618	1.972	2.62	6.907
Vinyl Chloride	0.024*	0.024*	0.024*	0.024*	0.024*	0.024*

Notes: *: non detect (reported at 1/2 method detection limit); -: not reported; AM: arithmetic mean;.

(i) Quebec City (Quebec) - 2005

Unit in µg/m^3

Chemicals	Min	Max	GM	50th
1,1-Dichloroethane	-	-	-	-
1,1-Dichloroethylene	-	-	-	-
1,1,1-Trichloroethane	-	-	-	-
1,2-Dichlorobenzene	-	-	-	-
1,2-Dichloroethane	0.1	2.63	-	-
1,2-Dichloropropane	-	-	-	-
1,2,4-Trichlorobenzene	0.1	0.1	-	-
1,2,4-Trimethylbenzene	0.64	68.09	3.45	2.61
1,4-Dichlorobenzene	0.1	286.57	0.58	0.36
1,3,5-Trimethylbenzene	0.26	22.38	1.26	0.92
1,3-Dichlorobenzene	0.1	15.61	-	-
Benzene	0.1	22.37	1.22	1.18
Bromodichloromethane	-	-	-	-
Bromoform	-	-	-	-
Bromomethane	-	-	-	-
Carbon Disulfide	-	-	-	-
Carbon Tetrachloride	-	-	-	-
Chlorobenzene	-	-	-	-
Chloroform	0.37	18.59	3.18	3.15
Chloromethane	-	-	-	-
Cis-1,2-Dichloroethylene	-	-	-	-
Dibromochloromethane	-	-	-	-
Ethylbenzene	0.4	19.5	2.69	2.45
Ethylene Dibromide	-	-	-	-
Hexane	0.23	38.55	2.35	2.17
Methyl Ethyl Ketone	-	-	-	-
Methyl Isobutyl Ketone	-	-	-	-
Methyl Tert-butyl Ether	-	-	-	-
Naphthalene	0.41	23.02	1.45	1.12
Styrene	0.1	14.03	0.65	0.69
m & p-Xylene	1.64	77.08	9.85	9.17
o-Xylene	0.53	26.43	3.43	3.03
Tetrachloroethylene	0.1	179.3	0.92	0.69
Toluene	3.75	436.33	26.47	24.72
Trichloroethylene	0.1	4.68	0.37	0.35
Trichlorofluoroethane	-	-	-	-
Vinyl Chloride	-	-	-	-

Notes: - :not reported; AM: arithmetic mean.

(j) Ottawa (Ontario) - 2005 Unit in µg/m^3

Chemicals	Min	Max	AM	50th	75th	90th
1,1-Dichloroethane	-	-	-	-	-	-
1,1-Dichloroethylene	0.005	4.05	0.27	0.005	0.37	0.83
1,1,1-Trichloroethane	-	-	-	-	-	-
1,2-Dichlorobenzene	0.01	0.11	0.01	0.01	0.01	0.01
1,2-Dichloroethane	0.01	0.71	0.03	0.01	0.01	0.01
1,2-Dichloropropane	0.02	0.02	0.02	0.02	0.02	0.02
1,2,4-Trichlorobenzene	-	-	-	-	-	-
1,2,4-Trimethylbenzene	0.015	56.6	3.97	2.21	3.38	6.73
1,4-Dichlorobenzene	-	-	-	-	-	-
1,3,5-Trimethylbenzene	-	-	-	-	-	-
1,3-Dichlorobenzene	0.005	16.19	0.077	0.15	0.29	1.05
Benzene	0.025	20.99	2.85	2.15	3.43	5.21
Bromodichloromethane	-	-	-	-	-	-
Bromoform	-	-	-	-	-	-
Bromomethane	-	-	-	-	-	-
Carbon Disulfide	0.015	3.29	0.34	0.13	0.46	0.86
Carbon Tetrachloride	-	-	-	-	-	-
Chlorobenzene	0.005	0.04	0.006	0.005	0.005	0.005
Chloroform	0.01	8.23	1.72	1.19	2.49	4.39
Chloromethane	-	-	-	-	-	-
Cis-1,2-Dichloroethylene	-	-	-	-	-	-
Dibromochloromethane	-	-	-	-	-	-
Ethylbenzene	0.005	201.41	4.71	1.05	1.98	4.76
Ethylene Dibromide	0.1	0.01	0.01	0.01	0.01	0.01
Hexane	-	-	-	-	-	-
Methyl Ethyl Ketone	-	-	-	-	-	-
Methyl Isobutyl Ketone	-	-	-	-	-	-
Methyl Tert-butyl Ether	-	-	-	-	-	-
Naphthalene	0.01	144.44	3.87	0.39	1.1	4.75
Styrene	0.025	6.53	0.69	0.46	0.87	1.49
m & p-Xylene	0.02	138.97	7.5	3.59	6.93	16.35
o-Xylene	0.01	205.11	5.08	1.22	3.37	6.48
Tetrachloroethylene	0.015	9.23	1.15	0.47	1.4	3.25
Toluene	0.015	112.93	11.54	5.53	12.25	25.47
Trichloroethylene	0.01	0.87	0.06	0.01	0.08	0.19
Trichlorofluoroethane	-	-	-	-	-	-
Vinyl Chloride	-	-	-	-	-	-

Notes: -: not reported; AM: arithmetic mean.