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CSAP Guidance for Assessment of Soil Vapour and Ambient Air – Update

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NOTE TO READER

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CSAP has recommended that Approved Professionals use their professional judgement[1] in applying any guidance, including this document. As the science upon which contaminated sites remediation is based is relatively young and because no two sites that involve the natural environment are the same, the need to exercise professional judgement within the regulatory process is recognized.

Ultimately, submissions for *Environmental Management Act* instruments need to meet regulatory requirements. The onus is on qualified professionals and Approved Professionals to document the evidence upon which their recommendations depend.

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The conclusions and recommendations of this document are based upon applicable legislation and policy existing at the time the document was prepared. Changes to legislation and policy may alter conclusions and recommendations.

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

Glossary

BAAD	biodegradation attenuation adjustment divisor
BPC	building pressure control
PCOC	potential contaminant of concern
CSIA	compound specific isotope analysis
CSM	conceptual site model
DNAPL	dense non-aqueous phase liquid
ECD	electron capture detector
FID	flame ionization detector
GC	gas chromatography
HPC	high purge volume
HVAC	heating ventilation and air conditioning
J&E	Johnson & Ettinger
IA	indoor air
LAAD	lateral attenuation adjustment divisor
LNAPL	light non-aqueous phase liquid
MLE	multiple lines of evidence
MTBE	methyl tertiary-butyl ether
NAPL	non-aqueous phase liquid
QA/QC	quality assurance / quality control
PHC	petroleum hydrocarbon
PID	photoionization detector
PCE	tetrachloroethylene
PVI	petroleum vapour intrusion
PFAS	poly- and per-fluoroalkyl substances
TBA	tertiary-butyl alcohol
TCE	trichloroethylene
TMB	trimethylbenzene
TPH	total petroleum hydrocarbon
SOP	suggested operating procedure
SSD	sub-slab depressurization
SSV	sub-slab ventilation
VI	vapour intrusion
VOC	volatile organic compound
VPH	volatile petroleum hydrocarbon

Table of Contents

List of Tables

List of Figures

List of Appendices

1.0 INTRODUCTION

Millennium EMS Solutions Ltd. (MEMS) and Hers Environmental Consulting Inc. were retained by the BC Contaminated Sites Approved Professional (CSAP) to prepare this report on "Assessment of Soil Vapour and Ambient Air – Update". The purpose of this project is to complete the update of the 2009 CSAP Soil Vapour Advice and Practice Guidelines (hereinafter referred to as "2009 Soil Vapour Guidelines"), which will assist contaminated sites practitioners with the investigation of soil vapour and ambient air quality in BC.

A first set of topics identified by CSAP were addressed in the report prepared by Golder Associates Ltd. and ARIS Environmental Ltd., titled "Assessment of the Soil Vapour to Air Pathway" dated August 2020 (Aris and Golder 2020). This project addresses six additional topics identified by CSAP for completion of the soil vapour guidance, as follows:

- **Assessment of future conditions**: Guidance is provided on how to obtain vapour samples representative of future buildings with various scenarios; how to delineate the vapour plume; and what are the options for collecting vapour samples at the source.
- **Vapour sampling methods and procedures**: A literature review of vapour sampling guidance and research is conducted, and recommended methods are provided including detailed procedures and measures to avoid false positive or false negative vapour concentrations. Additionally, tools for detailed assessment of the vapour intrusion pathway are described.
- **Waste oil handling and storage vapour potential contaminants of concern (PCOCs)**: A literature review on the characteristics of waste oil is conducted and a recommended generic list of waste oil PCOCs is developed.
- **Implementation of vapour attenuation from biodegradation**: A literature review of guidance and research on aerobic biodegradation of petroleum hydrocarbon (PHC) vapours is conducted. Methods for applying the BC biodegradation attenuation adjustment divisor (BAAD) in BC ENV Protocol 22 are described. Approaches that could be followed as part of detailed risk assessment are described and the vertical screening distance approach for assessment of petroleum vapour intrusion is reviewed.
- **Utility vapour intrusion**: A literature review of guidance and research is conducted on vapour intrusion into buildings through utilities. From this review, the conceptual site model and important pathways are identified. A recommended tiered approach for a screening and detailed assessment of the vapour intrusion into buildings is developed that focusses on sewers, a key preferential pathway.
- **Implementation of lateral vapour attenuation**: Methods for improving the application of the lateral attenuation adjustment divisor (LAAD) in Protocol 22 are addressed and new

approaches for implementation of lateral vapour attenuation that could be followed as part of detailed risk assessment are described.

The topics addressed in the three CSAP sponsored documents on vapours are summarized in Table 1.1. The topics have evolved based on practitioner needs in BC and new science.

This guidance document describes approaches, methods and best practices, in the main report, with additional details including review of scientific literature and guidance, in appendices. Most topics addressed are applicable within the current BC regulatory framework and recommendations provided may be adopted by practitioners. In a few instances, recent science has suggested that future review of regulatory guidance and protocols may be beneficial. Note, under a generic standards approach, vapour investigations must follow applicable BC CSR regulatory standards and existing BC ENV protocols (*e.g.,* Protocol 22), and should follow applicable guidance (*e.g.,* Technical Guidance 4). As part of a detailed risk assessment, the recent science described in this report could be considered where there is supporting rationale. In these instances, approved professionals or qualified persons should consider seeking concurrence from BC ENV before implementing a detailed risk assessment approach including obtaining a pre-approval under Protocol 6 where warranted.

The principal co-investigators and co-authors of the guidance were Dr. Ian Hers of Hers Environmental Consulting, Inc., and Dr. David Williams and Mr. Ian Mitchell of MEMS. The work was conducted under the direction of a steering committee consisting of members of the CSAP Technical Review Committee (TRC) led by Dr. Gary Lin of McElhanney. The TRC received comments from three external reviewers, Eva Gerencher and Lindsay Paterson of SLR Consulting (Canada) Ltd., Tara Siemens Kennedy of SNC-Lavalin Inc. The BC Ministry of Environment and Climate Change Strategy (BC ENV) provided review comments. The contributions of the steering committee, reviewers and BC ENV are all gratefully acknowledged.

Table 1.1 Summary of CSAP Sponsored Guidance on Vapour Intrusion in BC

Document	Main Topics Addressed
2009 Vapour Guideline	**Selection of vapour potential contaminants of concern (PCOCs) for analyses** - gasoline, diesel and dry-cleaning sites
	Measurement of shallow soil vapours – how to obtain shallow samples (to minimize ambient air leakage) and obtain samples representative of future building condition
	Attenuation factors – site conditions considered included building foundation types, shallow contamination and preferential pathways

Table 1.1 Summary of CSAP Sponsored Guidance on Vapour Intrusion in BC

Document	Main Topics Addressed
2020 Vapour Guidance	**Review of guidance** – comprehensive review of existing vapour intrusion guidance
	Conceptual site model – key site conditions and factors are described; pathway spatial and temporal variability
	Investigation of vapour pathways – approaches to vapour characterization; vapour stability; vapour sampling locations and frequency (with consideration of “worst-case” conditions); and shallow soil vapour[1], indoor air and outdoor sampling design
	Future guidance topics – identified gaps and issues
2022 Vapour Guidance Update (this document)	**Assessment of future conditions** – when to assess future condition and how to obtain samples for future condition and delineate vapour contamination
	Vapour sampling methods and procedures – methods and new investigation tools
	Selection of vapour PCOCs for waste oil handling and storage – recommended generic list of PCOCs
	Implementation of vapour attenuation from biodegradation – review of aerobic biodegradation of PHC vapours and considerations and recommendations on implementation of BAAD and risk-based approaches
	Utility vapour intrusion – approaches and methods for assessing preferential pathways including sewers are described. Risk-based approaches for establishing vapour attenuation factors are addressed
	Lateral vapour attenuation – review of lateral vapour attenuation and considerations and recommendations on implementation of LAAD and risk-based approaches

[1] The 2020 Guidance on shallow soil vapour sampling replaced the 2009 Guideline section on measurement of shallow soil vapours for assessment of future building condition.

2.0 FUTURE CONDITIONS

At some sites where indoor vapour intrusion is a potential concern, future site conditions may change in a way that affects this pathway. In particular, site redevelopment may alter a site in ways that increase the potential exposure to PCOCs *via* indoor vapour intrusion. The scope requested by CSAP on this topic was to address a) how to obtain vapour samples representative of future buildings with various scenarios; b) how to delineate the vapour plume; and c) what are the options for collecting vapour samples at the source?

CSAP (2009) suggested the use of a temporary surface soil cap when assessing shallow soil vapour at sites that are vacant or have bare ground at surface. Collection of time-series soil gas data over 6-8 months was recommended in CSAP (2009) to determine whether the surface seal was effective and mimicking future subsurface conditions. Given the typical impracticality of this approach, ARIS and Golder (2020) described alternative approaches including collection of source soil vapour samples, which would be less or minimally effected by future changes, trend analysis of time-series vapour data and modeling of transient soil vapour transport to assess future conditions.

The following section describes when consideration of future site conditions is important as well as how to assess soil vapour in a manner that is protective of these future site conditions.

2.1 When to Assess Future Conditions

An assessment of vapour intrusion under future conditions should be undertaken when it is anticipated that site conditions will change. This determination would consider the land use zoning, building code requirements, and known future site use plans. The California Environmental Protection Agency (CalEPA, 2020 draft) has identified several factors that may influence future vapour intrusion. These factors include:

- Changes to the physical or subsurface characteristics of the site, such as:
  - Changes in depth to water table depth (*e.g.*, changes to groundwater conditions resulting in shallower groundwater);
  - Changes in surface grade or removal of soil resulting in a shallower depth to impacts; and
  - Changes to surface cover such as pavement or landscaping that affect vapour migration.
- Changes to building conditions, such as:
  - Construction of new buildings, particularly buildings closer to impacts or with deeper basements (within lateral inclusion distance of VOC impacts – *e.g.*, 30 m for non-PHC);
  - Modifications to building structure (*e.g.*, additions, changes in foundation, damage);
  - Changes in land or building use (*e.g.*, a change from commercial to residential use); and
  - Changes to building operation (*e.g.*, HVAC system modifications, changes in occupancy patterns).

An additional consideration to the above factors is where concentrations of PCOCs at soil vapour monitoring points are expected to increase over time. For example, when a vapour plume has not yet achieved stability (see Section 2.4 and Aris and Golder (2020)) concentrations away from the source may continue to increase.

One of the major challenges is that future use of a property may not be known at the time of a vapour investigation. For example, the current property owner may be planning on selling the property, but the buyer and future development plans are unknown. Therefore, the investigation should typically consider a reasonable range of likely potential future conditions and/or potential land uses in the foreseeable future.

Where future use of the site is known, this information can be considered in the development of the vapour investigation. Where it is not, land use zoning combined with the Official Community Plan and development trends in the area of the site can be used as a guide to establish potential future use.

The determination of when to assess future land use can be made following the process in Figure 1 below; Table 2.1 provides guidance on site changes that may increase sensitivity to vapour intrusion.

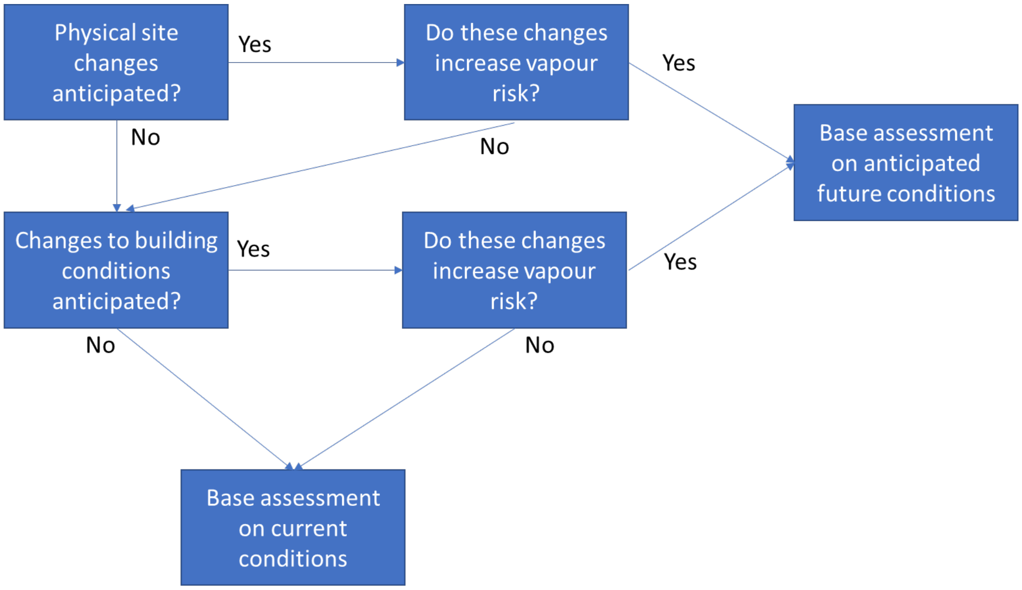

Figure 1 Decision Process for Assessing Future Site Conditions

Table 2.1 Effects of Site Changes on Vapour Intrusion Risk for Future Use Scenarios

Site Change	Sensitivity Increased By:
Physical/Subsurface Changes	
Water table depth	Smaller distance between groundwater contamination and building foundation or when greater distance (*i.e.*, water table depression) causes NAPL to be exposed to soil gas
Grade change/soil removal	Smaller distance between contaminant source and building foundation
Changes to paving/landscaping	Shallow vapour concentrations may be higher beneath impermeable surface and consequently there may be lateral vapour migration to below buildings

Table 2.1 Effects of Site Changes on Vapour Intrusion Risk for Future Use Scenarios

Site Change	Sensitivity Increased By:
Changes to Building Conditions	
New buildings	Buildings closer to contamination source than existing buildings (lateral location or slab/foundation depth)
Modifications to building structure	Building extension/addition closer to contaminant source; reduced foundation integrity, utility installation into existing slab
Changes in land/building use	Increased occupancy duration (increased hours/day or days/week)
Changes to HVAC system	Reduced ventilation and/or increased depressurization of building airspace

Where sensitivity to vapour intrusion is increased by anticipated land use or building changes, the vapour intrusion assessment should include consideration of those land use or building changes. Where the sensitivity is not increased, then an assessment based on the current land use is expected to be protective of future land uses.

2.2 How to Obtain Vapour Samples for Future Use Scenarios

The technical requirements for collecting vapour samples are similar whether investigating for a current use of the site or a future use. Fundamentally, development of a sound conceptual site model including characterization of the source is always required. However, when assessing a future use the potential changes described in Section 2.1 above should be considered. ARIS and Golder (2020) and CSAP (2009) summarizes guidance prepared by various US agencies, which includes sampling at multiple depths (including at the source depth and depth of future building foundations), and sampling at every potential future building location or on a grid spacing in the absence of a development plan. Similarly, Cal EPA (2020) recommends the collection of near-source samples to manage future risks. With a strong conceptual site model, a more focused investigation can be undertaken.

Key considerations for developing a sampling strategy for future buildings include the depth of sub-grade structures such as basements (considering land use, building code) and potential future paving. There may be higher future soil gas concentrations below a building slab compared to shallow soil gas concentrations measured at the same elevation below open ground. A modeling study of vapour intrusion for difference conceptual scenarios conducted by US EPA (2012) demonstrated this potential effect for non-degrading VOCs (*i.e.,* no decay term was included). The potential bias may also depend on whether the substance aerobically biodegrades as described in Section 5.0 of this report where the so-called "oxygen shadow effect" resulting from building foundations is evaluated in detail. Several researchers, including Abreu and Johnson (2005) and others referenced in Section 5.0 showed that, at sites with high source PHC vapour concentrations (*e.g.,* gasoline), shallow vapour concentrations may be higher beneath a building than outside the building footprint because of oxygen limitations. Therefore, shallow soil vapour concentrations of PHCs in samples from outside a building footprint may not be representative of concentrations beneath a future building at the same location. Samples should therefore be collected either close to the source or sufficiently deep as to not be influenced by a potential future building foundation.

The minimum target sampling depth should be sufficiently deep that the future building foundation does not result in a low bias when soil vapour samples used to predict future conditions are obtained in open ground areas. Based on the US EPA (2012) modeling study simulating vapour intrusion for a non-degrading substance, when the building-contamination source distance is less than about 5 m, there is the potential for open ground soil vapour samples to underpredict concentrations below a building, unless the soil vapour sample is obtained near to the source. Consequently, it is recommended that when this distance is less than 5 m, soil vapour samples should be obtained as close to the source as practically possible, which is considered within 1 m of the source. At sites where the source-building separation distance is greater than 5 m, it is acceptable to obtain a sample at 5 m distance, and then use the appropriate vertical attenuation factor for that distance (*i.e.,* deeper samples are not required). For substances that biodegrade, this rule of thumb should also hold because empirical evidence for vapour attenuation indicates aerobically biodegrading substances attenuate to below concentrations of concern within about 5 m for dissolved and LNAPL sources (see Section 5.0). Therefore, while there could be different behaviour between substances that degrade and not degrade, this would not be a concern with respect to sampling locations for biodegradable substances so long as soil gas samples are either obtained near the source or at least 5 m below the future building foundation.

If the vapour source has been well characterized, then the investigation locations can be focused based on the conceptual site model rather than assessing potential locations on a grid. For example, if the likely worst-case vapour concentrations at the site are not above applicable standards or do not pose a risk, then it follows that lower concentrations would also not be of potential concern. In general, vapour sampling for potential future development should include the locations of highest soil/groundwater concentrations. Depending on the source, the vapour investigation may either generally follow a bottom up or top-down approach as described in ARIS and Golder (2020).

Additional considerations may include:

- In the case where a potential future building foundation may extend deeper than the water table and soil vapour from directly above the water table is not representative, then groundwater data will be needed to assess potential vapour intrusion risks through estimates of soil vapour concentrations from partitioning models (*e.g.*, BC TG 4, Health Canada 2010). Soil data may also be used but is generally not recommended when specific gravity of the substance is greater than one.

- Where onsite remediation is being conducted but a vapour source will remain outside of the remedial footprint (*e.g.*, offsite or beneath infrastructure) then vapours associated with the remaining source need to be assessed.
- Where samples are being collected at shallow depths (less than 1 m below ground surface) and the ground surface is bare/unsealed, the approach in Aris and Golder (2020) should be followed to demonstrate that soil vapour concentrations are representative estimates of concentrations under potential future hard surfaces/buildings.

2.3 Vapour Intrusion Investigation when Shallow Groundwater is in Contact with Buildings

When there is shallow groundwater in contact with buildings, the site conceptual site model should be reviewed to determine if soil vapour measurement data are representative of vapour contamination and appropriate for use in assessing vapour intrusion. A soil vapour sample from directly above capillary fringe will represent an attenuated concentration in vapour and correspondingly lower pore-water concentration if in equilibrium with soil vapour. A potential concern is whether this lower attenuated concentration in soil vapour is representative of contamination that is contact with the building foundation. If the building foundation extends below the groundwater table and there are increasing concentrations with depth below the water table (*e.g.*, DNAPL), then soil vapour data clearly would not be representative.

When groundwater is potentially in contact with the building, soil and groundwater data are commonly used with partitioning models to assess vapour intrusion. However, theoretical equilibrium partitioning models result in high estimates of soil vapour concentrations for low soil and groundwater concentrations. Additionally, no attenuation (*i.e.*, attenuation factor of 1.0) is allowed except for underground parking garages (parkades) built to 2012 or later BC Building Codes. The implications include sites being identified as high risk under BC regulatory framework and risk management measures being implemented because it is not possible to verify actual soil vapour conditions until after the building is constructed. Delineation of vapour contamination is also practically challenging when no attenuation is allowed.

Research on chemical partitioning between soil or groundwater and soil vapour concentrations has been used to derive empirical adjustments to partitioning models. For example, paired soil and soil vapour data that showed measured soil vapour concentrations that were at least one order of magnitude lower than predicted vapour concentrations from the Henry's Law constant were used to establish a 10X reduction factor used in the derivation of the CCME PHC Canada-wide Standards. The US EPA PVIScreen model, used for prediction of vapour intrusion of petroleum hydrocarbon compounds, includes an attenuation factor of 0.1, which is used to reduce the predicted theoretical soil vapour concentration from groundwater. There is also research on laboratory column and field studies of chlorinated solvent transport that indicate there is a range of contaminant attenuation across the capillary fringe (*e.g.*, McCarthy and Johnson 1993; Rivett 1995; Ronen *et al*. 2005). Factors affecting attenuation across the capillary fringe include contaminant type, soil texture, water table fluctuation and biodegradation. There is also research on chemical transport through concrete that could be used to assess attenuation through foundations where contamination is near to or in contact with the foundation (Appendix B).

There has been limited assessment of how to investigate vapour intrusion at sites where buildings are in contact with groundwater with low or dilute concentrations. The use and accuracy of partitioning and attenuation models is considered a significant knowledge gap that warrants further evaluation. An assessment of empirical data including concentrations in soil, groundwater, subslab vapour and building air combined with a review of published literature on partitioning and fundamental properties of foundations could serve to improve models and refine existing approaches and guidance.

Note, under a generic standards approach, the partitioning models in TG4, and attenuation factors in Protocol 22 must be used. Under a detailed risk assessment approach, the use of adjusted partitioning or alternative attenuation models may be considered where there is supporting rationale. In these instances, approved professionals or qualified persons should consider seeking concurrence from BC ENV before implementing a detailed risk-based approach, including pre-approval under Protocol 6 when required.

2.4 Delineation and Consideration of Vapour Plume Movement

In principle, delineation is similar whether assessing existing buildings or future buildings. However, when developing the conceptual site model, vapour plume migration to locations of potential future development should be considered.

Soil vapour can migrate from sources in any direction due to diffusion along chemical concentration gradients, although it would be expected to preferentially migrate along more permeable units (*i.e.*, units with higher effective diffusion coefficients), as well as through soil gas advection in the direction of pressure gradients (*e.g.*, towards a depressurized building). As a first step of assessing future conditions and potential risks, assessment of concentrations near the source based on soil and groundwater concentrations should be considered, and as necessary further sampling along transects or grid sampling to better characterize the plume being assessed. Soil vapour delineation can potentially be optimized through indirect methods including soil gas sampling using field detectors, passive soil vapour surveys that provide estimates of mass or semi-quantitative concentrations

(McAlary *et al*. TBD; CCME 2016), or potentially approaches such as phyto-forensic methods that use sampling of vegetation to identify shallow contaminants that are drawn into plant roots (*e.g.*, Vroblesky *et al*. 1999; USGS 2017).

ARIS and Golder (2020) provide guidance on assessing the stability of vapour plumes. Much like a groundwater plume, a soil vapour plume will initially expand, but over time will achieve a stable footprint, and then contract or shrink as the source is depleted. If the contamination source (*e.g.*, NAPL or groundwater) is not stable, then this will also affect the soil vapour plume stability. The first step in the assessment process is to determine whether the contamination source and soil vapour plume are likely stable. Once a plume has been determined to be stable, a vapour investigation can be conducted that is focussed on addressing sources of shorter-term variability related to seasonal factors such as water table fluctuations and building conditions (and other factors) and not longer-term changes associated with continued vapour plume migration.

3.0 VAPOUR SAMPLING METHODOLOGY AND PROCEDURES

The measurement of soil vapour concentrations generally provides a more direct indication of potential exposure *via* vapour inhalation than partitioning from soil or groundwater data and is a common component of investigations conducted at contaminated sites in BC. Because methods and procedures continue to evolve, there is a need for updated guidance on soil vapour sampling and analysis. The scope requested by CSAP on this topic was to conduct a literature search of recent guidance on sampling methodology that includes a summary of sampling train considerations, flow rates, purge volumes and other relevant factors. Additionally, identification of factors that could lead to false positive or false negative vapour concentrations was required.

The 2009 CSAP Soil Vapour Practice Guidelines include guidance on shallow soil vapour sampling and frequency of leak testing, while the 2020 CSAP Soil Vapour Guidance (ARIS and Golder 2020) includes a literature review of multiple guidance documents on sampling and analysis methods. BC ENV TG4 indicates the references that should be followed, are specifically CCME's "Guidance Manual for Environmental Characterisation in Support of Human Health Risk Assessment" (Chapter 7, 8, appended checklists) (CCME 2016) and SABCS's "Guidance on Site Characterization for Evaluation of Soil Vapour Intrusion into Buildings" (SABCS 2011). The BC ENV "BC Field Sampling Manual" (Part D) updated in July 2020 includes detailed guidance on soil vapour sampling and analysis (Chapter 4 and Standard Operating Procedure for Soil Vapour / Gas Sampling). These guidance documents are considered the key reference documents for conducting soil vapour sampling and analysis in BC.

The approach adopted in this study was not to recreate the above guidance but instead summarize key aspects of the guidance and select additional literature to assist the reader in locating sources of relevant information (Table A1, Appendix A). From this review, a concise, tabular summary on soil vapour sampling and analysis methods is provided (Table A2, Appendix A). Where warranted, improvements to existing methods are identified.

Prior to conducting a soil vapour sampling and analysis program, a project-specific health and safety plan and project work plan should be prepared. Health and safety and utility clearance are critical components of all work and the reader is strongly encouraged to consult applicable legislation, practices and guidance and to undertake required measures (recommendations on health and safety and utility clearance are beyond the scope of this report). The work plan should describe:

- the objectives of the program;
- relevant background information including site contamination and the conceptual site model;
- the areas of potential environmental concern (APECs) and potential contaminants of concern (PCOCs) for the soil vapour investigation;
- the soil vapour sampling locations and frequency of sampling;
- the soil vapour sampling and analysis methods and quality assurance/quality control (QA/QC) procedures; and
- data interpretation.

This report addresses sampling and analysis methods and QA/QC procedures, while other aspects are addressed in CSAP (2009), ARIS and Golder (2020) and other guidance. The organization of this section of the report is divided into three parts:

1. Review and summary of recommended soil gas sampling and analysis methods.
2. Scenarios leading to false positive and false negative vapour concentrations.
3. Supplementary methods for vapour investigation (“expanded toolbox”).

3.1 Soil Vapour Sampling and Analysis

The primary guidance documents reviewed for the literature search on recent guidance for sampling methodology were BC ENV (2020b), CCME (2016), CA DTSC (2015) and ITRC (2014) with details provided in Appendix A. The topics covered in each guidance and select additional literature are listed in Table A1 and methods for soil vapour sampling and analysis are reviewed in Table A2. Select additional guidance with information on soil vapour sampling include the following: ARIS and Golder (2020), NJDEP (2018), ASTM D7663-12 (2018), Hawaii DOH (2017), and CCME (2008). Based on this review, recommended methods are provided in Table 3.1 below.

Table 3.1 Soil Gas Sampling Recommendations

	Topic	Summary
		1. Active soil gas sampling
a.	**Drilling methods for probe installation**	Geoprobe or auger drilling methods are preferred for installation of soil gas probes Minimize use of fluids (water or air) when drilling where possible to reduce disturbance Installing probes in hydro-vac holes is not preferred but may be unavoidable and required for protection of health and safety and infrastructure Do not install vapour probes in mud rotary holes
b.	**Probe and sampling train design and materials**	Temporary driven probes or permanent soil gas probes installed in a borehole are acceptable, although permanent probes are preferred because they are constructed with a seal and can be re-sampled **Materials** Acceptable probe materials are PVC or stainless steel. Wrap PVC pipe joints with Teflon tape except when sampling for PFAS vapours. Acceptable sampling train materials are Teflon or nylon. An experimental study showed significant sorption of naphthalene occurred on nylon (Hayes *et al.* 2006). Therefore, Teflon is preferred when sampling for naphthalene.[1] Nylon is less costly than Teflon and is widely used in the industry for soil vapour sampling. Sorption effects can be minimizing by reducing the length of the sampling train as practical and conditioning the tubing through purging. Do not use Tygon, silicon or polyethylene. Do not use construction materials (glues, tapes) that could emit volatiles Connections for tubing should consist of Swagelok or air-tight barbed fittings. Avoid slip fittings. Probe should be completed with an air-tight valve **Construction** Permanent probes should be installed with filter pack consisting of clean silica sand that extends a minimum of 10 cm above and below the probe. Extending the granular filter pack deeper below the base of probe to create a small sump may reduce the potential for soil water to collect near the base of the probe and affect the sampling process. Granular bentonite or slurry grout seal should be placed above the filter sand to just below ground surface. To avoid migration of grout into the filter sand, a granular bentonite seal of typically 0.3 m minimum thickness should be placed above the sand. The first lift of granular bentonite may be placed dry or with minimal hydration to avoid impacting the filter sand. A thin fine sand layer can also be placed between the filter sand and bentonite. Multiple soil gas probes may be installed in a single borehole provided that appropriate pre-cautions and testing is conducted including pressure communication testing of adjacent probes (CCME 2016)

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[1] CCME (2016) recommended that nylon not be used when sampling soil vapour for naphthalene based on an experimental study by Hayes et al. (2006) indicating naphthalene recovery of 31% in tubing.

Table 3.1 Soil Gas Sampling Recommendations

Topic		Summary
		Surface seal of subslab probes can consist of sculpting clay, swelling ("hydrating") concrete, bentonite, wax, Teflon tape (except when sampling for PFOS) and VOC-free epoxy **Sampling from Groundwater Monitoring Wells** Soil gas samples may be obtained from groundwater wells provided that the same procedures and quality control checks for soil gas probes are followed. Depending on well screen length, wells may not provide desired spatial resolution in soil vapour concentrations. Specific requirements for purging groundwater wells should be followed (see Topic 1g in this table).
c.	**Shallow probe pre-cautions**	Generally, the method described in CSAP (2009) should be followed Minimum depth for soil gas probe is 0.45 m below ground surface Place a surface seal such as an inert plastic sheet of approximate dimensions 1.5 m by 1.5 m for samples collected from probes within 1 m of ground surface The CSAP (2009) requirement for placing a surface seal 24 hours prior to purging and sampling is not considered warranted as the goal is to prevent short circuiting of air. A seal placed a few minutes prior to start of purging is considered acceptable so long the edges of plastic are sealed with soil. Minimize purge volumes through a shallow probe design that minimizes borehole and filter pack size and dead volume of probe and sampling train An approximate breakthrough volume of air-filled pores in soil corresponding to the volume when atmospheric air could be drawn into a probe can be estimated from the volume of a cone (assuming a cone approximates the air flow pattern to probe) and air-filled porosity $V = 1/3\ h\ \pi\ r^2\ \theta a$, where h = probe depth, r = radius of cone at ground surface and θa = air-filled porosity (a 45 degree cone may be reasonable)
d.	**Probe equilibrium**	Equilibration times are dependent on drilling method, as follows: • Temporary driven probes or Geoprobe PRT system: 30 minutes • Probes installed in holes advanced by direct push or auger, or rotosonic where no fluids (air or water) are used: 2 days • Probes installed in holes advanced by rotosonic where fluids are used, air rotary, or hydro-vac: Conduct time-series testing of CO_2 and O_2 using landfill gas type field meter and VOCs using PID and/or combustible gas detector to assess when concentrations stabilize • Subslab: 2 hours Equilibration times for probes installed in rotosonic (with fluids), air rotary or hydro-vac holes may be several days to weeks depending on disturbance. While there are few empirical studies available on this topic, there are modeling studies available (*e.g.,* Wong *et al*. (2003); DiGiulio *et al*. (2006) that enable prediction of the time for equilibration by diffusion for borehole filter packs (or impacted zones) of varying radii. These studies can be used to optimize the equilibration process recognizing that obtaining time-series measurement data can be costly.
e.	**Flow and vacuum check**	Flow and vacuum check can be conducted shortly after probe installation or during the collection of soil gas samples for testing using field detectors The test is conducted using a vacuum gauge (digital manometer or magnehelic gauge) and flow meter (rotometer or mass flow meter) (see BC ENV 2020a for typical equipment set-up)

Table 3.1 Soil Gas Sampling Recommendations

	Topic	Summary
		Measure vacuum at planned sampling flow rate (*i.e.*, 100-200 ml/min) Evaluate vacuum relative to expected conditions. Unusually high vacuum could indicate probe blockage. Unusually low vacuum could indicate leakage. Vacuum that is slowly rising could indicate a slow leak. If there is an estimate of the soil-air permeability and measured air flow sampling rate, the corresponding vacuum can be estimated from analytical models for spherical flow to a point (Garbesi *et al*. 2003), appropriate for a small probe or radial flow to a well (Johnson *et al*. 2000), appropriate for a probe with a relatively longer screen. Flow and vacuum data can be used to verify requirements for laboratory samples (*e.g.*, pump or flow controller flow rates) Consider also measuring static pressure differential between probe and atmosphere (magnitude and direction) especially at sites with biogenic gas generation
f.	**Probe and sampling train leak tests**	Leak tracer testing and shut-in testing should both be conducted. **Leak Tracer Test** Leak tracer testing is conducted to determine if there is annular leakage along the probe or in probe valve and is typically conducted using a gaseous tracer (*e.g.*, helium). Each new probe should be subject to a leak test and thereafter (*i.e.*, during subsequent monitoring events) a minimum of 10% of probes should be checked for leaks (CSAP 2009). A greater frequency of probes should be tested if there is probe or seal disturbance or degradation. Leak tracer testing is commonly conducted during collection of samples for screening using field detectors. When conducting leak tracer testing of the probe and probe valve, place a shroud above the probe and flood with helium until the helium concentration is > 10% Because helium is expensive and sometimes in short supply, use helium sparingly. Use high purity helium (>99%). The use of "party-grade" helium is not recommended because of unknown impurities. While other gaseous tracers can potentially be used (*e.g.*, argon, sulphur hexafluoride), there is less experience with these tracers. Liquid tracers, while sometimes used (CA DTSC 2015) are generally not recommended because of possible cross-contamination. Purge probe until volume soil gas removed > subsequent sample volume (*e.g.*, if a 1.4 L canister sample is to be collected, then purge at least 1.4 L) Measure helium (He) in soil gas sample Calculate Leakage = He soil gas / He shroud x 100% Leakage should be < 2%; if not, fix probe or connections. Note BC ENV (2020a) procedure indicates acceptable leakage is 10%. This threshold is considered unnecessarily high as in most cases Leakage << 2%. Leak tracer testing can also be conducted to assess leakage in the sampling train using gaseous or liquid tracer (CA DTSC 2015) and is considered an optional additional test to a shut-in test when used for this purpose

Table 3.1 Soil Gas Sampling Recommendations

Topic		Summary
		An optional leak tracer test may also be conducted during collection of samples for laboratory analysis. For example, place canister under a shroud filled with helium and then test the canister sample for helium. Confirm procedure with laboratory prior to conducting this test. **Shut-in Test** A shut-in test is conducted to determine if there is leakage in the sampling train. Shut-in tests are performed both when conducting field screening (*e.g.,* with vacuum lung-box type sampler) and collecting canister or sorbent tube samples (see Appendix A figures). Conduct shut-in tests by creating a vacuum in the sampling train, then isolating the sampling train and shutting in the vacuum. The target vacuum is 10 in H_20 and absence of significant leakage is defined as less than 5% decline in vacuum over 5 minutes.
g.	**Probe purging and sampling**	Purging is required to remove stagnant air from the vapour probe and sampling train Generally, purging and sampling soil gas flow rates should range from 20-200 mL/min Higher purging rates are acceptable when groundwater monitoring wells are sampled Research studies (DiGuilio 2007; US EPA 2018; see Appendix A) indicate that in most cases, concentration stabilization is reached within two probe volumes Purge three probe volumes prior to sampling, with purge volume equal to the volume of probe, air-filled voids in filter pack over the screened interval and sampling train Avoid over-purging especially for shallow probes because of the potential to draw in atmospheric air An acceptable alternative purging method is to conduct a purge stabilization test where sequential samples are tested for field parameters (*e.g.,* organic vapour by PID, CO_2, O_2). A sample is obtained for laboratory analysis when concentrations stabilize (*e.g.,* within 10%). Conduct a purge stabilization test when sampling larger diameter soil gas probes or groundwater monitoring wells. Use of a downhole packer can potentially reduce purge volumes and requirements for conducting purge volume tests (*e.g.,* Sweeney and Ririe 2017). Where possible conduct purging and sampling such that the vacuum < 10 in of H_20 (note this is not a mandatory requirement). The maximum recommended vacuum is 100 in of H_20. The vacuum can be reduced by reducing the flow rate. With a higher vacuum there is the potential for either a negative bias from rate-limiting mass transfer of VOCs from soil with permeability contrasts or induced leakage or a positive bias from increased desorption of VOCs. There are limited data on either potential mechanism for bias. Polymer bags (*e.g.,* Tedlar) are used for collection of samples for field screening. Depending on analytical protocol (confirm with laboratory), bags may also be used for laboratory analysis for fixed gases (O_2, CO_2, N_2, *etc.*) and reduced sulphur compounds. Because bags tend to leak, polymer bag samples should be analyzed within 24 hours of collection (see studies cited in CCME 2016).

Table 3.1 Soil Gas Sampling Recommendations

	Topic	Summary
		2. Soil gas / air testing
a.	**Field detectors**	**PID** Measures organic and some inorganic vapours Moisture and dust can cause upward bias in concentrations Check that lamp energy matches ionization potential of target chemicals Typically calibrated to isobutylene Different chemicals have different response factors Not suitable for very-light hydrocarbons (*e.g.*, methane) **Combustible gas detector (CSD) (platinum element)** Measures combustible vapours Some CSDs have methane elimination mode, which eliminates most but not all methane Certain compounds can poison the element (*e.g.*, lead or sulphur compounds) Typically, calibrated either to methane or hexane Different chemicals have different response factors **Landfill-type meters** Measures O_2, CO_2, CH_4 and other gases Typically, infrared sensor used for CH_4, which is specific to absorption wavelength of CH_4 but can be affected by other gases To more accurately measure CH_4, use charcoal filter to remove most heavier compounds (Jewell and Wilson 2011) New hand-held laser-type field detectors available that can measure CH_4 to low ppm levels **All detectors** Should be calibrated regularly and bump tested daily to check calibration All detector sensors have varying T90 time, which is the time to 90% of maximum concentration based on detector flow rate and consequently the minimum volume required for accurate response

Table 3.1 Soil Gas Sampling Recommendations

Topic		Summary
b.	**Soil gas / air analytical methods**	An overview of common methods is provided. Sampling and analysis methods for VOCs in soil vapour are well developed and include active sorbent tubes analyzed by US EPA Method TO-17 and whole-air canisters analyzed by US EPA Method TO-15, which both involve analysis by gas chromatography / mass spectrometry (GC/MS) method (note these are air methods modified for soil vapour). Samples for fixed gases (O_2, CO_2, CH_4, N_2) may be obtained in canisters or polymer bags (check with laboratory) and analyzed using ASTM Method D1946 (fixed gases) or ASTM Method D1945 (fixed gases plus light hydrocarbons). Other analytical methods are available for petroleum hydrocarbon ranges, semi-volatile organic compounds, reactive compounds (*e.g.*, reduced sulphur compounds) and lead scavengers 1,2-dichloroethane and ethylene dibromide. Consult applicable BC ENV analytical protocols (BC ENV 2020b) and the analytical laboratory for guidance on methods and details on performance requirements. **Canister Sampling** Whole-air sample is collected in either Summa (stainless steel) or silco (glass lined) canisters. Silco canisters are used for reactive compounds. Canister volume typically ranges between 1 and 6 L Interior surfaces are passivated Canisters are evacuated (under vacuum) Suitable for large range of volatiles including up to naphthalene Not suitable for semi-volatiles (*i.e.*, chemicals with boiling point greater than that of naphthalene or about 218°C) unless canisters are heated, if permitted by the canister and valve, and specialized cleaning processes are followed (US EPA 2019) Flow controller dictates sampling rate, which typically is between 20 and 200 mL/min **Sorbent Tube Sampling (thermal tubes)** Concentration is calculated from measured mass and sample volume Typically, multi-bed tubes are used, which are designed to optimally control retention and desorption for high humidity conditions (soil gas tends to be at or close to 100% humidity) Suitable for a range of volatiles and semi-volatile chemicals Depending on sorbent some highly volatile (light molecular weight) compounds may have poor retention Critical to determine Safe Sampling Volume (SSV) in conjunction with laboratory. SSV is established based on desired detection limit when there are low concentrations and based on preventing breakthrough when there are high concentrations. Provide data on field PID concentrations to assist laboratory in determining SSV Make sure arrow on tube is pointing in the right direction Swagelok connections are highly preferred for connections between sorbent tube and tubing Do not over-tighten Swagelok fittings

Table 3.1 Soil Gas Sampling Recommendations

Topic		Summary
		Measure flow rate during sampling as vacuum can result in a significant reduction in the flow rate Flow rate is typically between 20 and 200 mL/min
c.	**Soil gas / air QA/QC**	**Sorbent tubes:** *Cleaning and Proofing*: Thermal tubes should as a minimum be batch proofed and usage history of each tube recorded. *Field duplicates*: Minimum frequency is 10% of samples analyzed; when < 10 samples, analyze at least 1 duplicate. *Tests for Breakthrough*: Laboratory should provide data on safe sampling volumes (SSV) that apply to each analyte tested. Testing of two tubes in series or distributed pair at differing flow rates is optional (and not required by the USEPA TO-17 method) but is good practice when SSV is uncertain. *Trip blank*: Typically obtained by removing the caps from tubes and leaving them in the sampling environment for a short time and placing caps back on the tube. Optional test that may be warranted when sampling in “dirty” environment. Recommended in BC ENV (2020b). *Equipment blank*: High purity inert gas is drawn through the sampling train and/or probe and analyzed to determine whether the materials are clean. Optional if new materials are used for train, mandatory if materials are reused. *Field Spikes*: Sample tubes spiked with known concentrations of analytes are used to evaluate the recovery of the spiked compound and accuracy of the extraction and analytical procedure. This test is not typically a field test but may be performed by the laboratory. *Sampling Flow Rate and Time*: The flow rate during sampling should be measured and sampling time accurately recorded. When obtaining duplicates, best practice is to measure flow rate for both tubes. *Storage*: Store tubes in cooler with cold packs but do not use ice; never store in same cooler as soil and groundwater samples. Store at ≤ 10°C during transport, and ≤ 6°C at the laboratory (BC ENV 2020b). Hold times are 30 days (BC ENV 2020b). **Canisters** *Cleaning and proofing*: Canisters and flow controllers should as a minimum be batch proofed as clean and usage history of each canister should be recorded by the laboratory to enable tracking if contaminant carryover is suspected. For low-level (sub-ppbV) analysis, individual proofing or “certification” of canisters is recommended. *Field duplicates*: Obtained by collecting two canisters using a splitter. A single flow controller is recommended. Minimum frequency is 10% of samples analyzed; when < 10 samples, analyze at least 1 duplicate. *Vacuum Measurements*: Canister vacuum prior to sampling should be > 27 in of Hg. Sample integrity is indicated by measurable vacuum at completion of sampling, ideally about 2-4 in of Hg but may be as high as 10 in of Hg (check with laboratory). Adjust vacuum for difference in field and laboratory temperature and atmospheric pressure using Ideal Gas Law because a small residual vacuum under cold temperatures or low atmospheric pressure (high elevation) may dissipate under laboratory conditions (*i.e.*, no vacuum measured). *Field transport blank*: Canister is filled either in the field with ultra high purity air or nitrogen supplied by the laboratory in a separate canister or by the laboratory upon receipt. The blank canister is handled the same way as other canisters (*i.e.*, vacuum is tested). Is considered an optional test given that

Table 3.1 Soil Gas Sampling Recommendations

Topic		Summary
		other quality control tests are typically performed such as laboratory certification of canisters and testing of the vacuum before and after sampling. Recommended in BC ENV (2020b). *Equipment blank*: High purity inert gas is drawn through the sampling train and/or probe and analyzed to determine whether materials are clean. Optional if new materials are used for train, mandatory if materials are reused. *Storage*: Samples should not be chilled. Hold times are 30 days (BC ENV 2020b). Review internal laboratory QC checks (*e.g.*, surrogates, spikes, blanks, duplicates) (BC ENV 2020b)
3.	**Passive soil gas samplers**	Passive diffusive samplers contain a hydrophobic adsorbent material that collects organic compounds over time, which are typically thermally desorbed and analyzed using GC/MS method Passive diffusive samplers can be used for a wide range of volatile compounds and some semi-volatile compounds depending on analytical protocol. Because passive samplers are typically deployed at shallow depth, they may not be appropriate for characterization of chemicals that aerobically biodegrade where there is a deeper source If the chemical uptake rate is known, the concentration can be calculated from the mass adsorbed over a known sampling duration Passive diffusive samplers have been used for decades for quantitative air analysis for industrial hygiene purposes and more recently for low-level analysis using thermal desorption methods (SERDP/ESTCP 2014; McAlary *et al*. 2014 a, b; CCME 2016) Passive diffusive samplers of soil vapour are widely used to obtain integrated measurement of mass and are an effective tool for identifying and delineating contamination sources (with sampling often conducted on a grid pattern or transects) Passive samplers are typically deployed in a small diameter borehole at between 0.5-1 m depth over a 7-14 day period Advantages of soil vapour passive samplers include they are minimally invasive, relatively easy to use and do not require some equipment required for active sampling A disadvantage of passive diffusive samplers is that they are generally not designed for quantitative analysis of soil vapour concentrations. However, low uptake passive samplers, for example, incorporating a polydimethyl-siloxane membrane, can provide quantitative estimates of concentrations, and relatively good comparisons have been obtained between passive diffusive and active methods of sampling (SERDP/ESTCP 2014; McAlary *et al*. 2014 a, b). A potential limitation of the passive diffusive sampling method is a potential starvation effect in fine-grained and/or high moisture content soils. Hers *et al*. (2016) describes mathematical modeling of potential starvation effect and three case studies where the Waterloo Membrane Sampler passive sampler was compared to active vapour sampling using canisters (US EPA Method TO-15). The passive concentrations were, on average, 10X, 2X and 4X less than active concentrations at three sites with fine-grained soils. With knowledge of geotechnical properties, sampling times can be optimized, and potential bias reduced (Hers *et al*. 2016). The BC ENV Field Sampling Manual indicates passive soil gas samplers can provide useful data but "cannot be used alone to make conclusions on site soil gas concentrations." The Field Sampling Manual indicates passive samplers are an acceptable method for ambient air.

The steps or topics on methods that should be considered to obtain representative soil vapour concentration data of suitable quality using active sampling are as follows (Table A1; Appendix A):

1. Drilling methods for probe installation.
2. Probe and sampling train design and materials.
3. Shallow probe pre-cautions.
4. Probe equilibration.
5. Flow and vacuum check.
6. Leak testing of probe and sampling train.
7. Purging and sampling of probe.
8. Field detectors for testing of soil gas samples.
9. Laboratory analysis of soil gas and air samples.
10. QA/QC and data interpretation.
11. The use of passive diffusive samplers as a measurement method is separately reviewed.

Example soil vapour sampling schematics are provided in Appendix A.

3.2 Factors that can Lead to False Positive and Negative Soil Vapour Concentrations

Factors that can result in false positive or false negative soil vapour concentrations are summarized in Table 3.2. These factors are related to sampling methodology and short-term environmental conditions that could result in non-representative vapour concentrations. Additional information on conceptual site model development is provided in ARIS and Golder (2020).

Table 3.2 Potential Factors Leading to False Positive and False Negative Vapour Concentrations

Issue	Potential Bias	Remedy
Contamination of probes or sampling train during handling	False positive	Use appropriate procedures to prevent contamination (*e.g.*, storage in sealed bags), use dedicated tubing, test equipment blank, when warranted
Contamination of borehole during drilling/installation of vapour probe (*e.g.*, by exhaust from drill rig or vehicle)	False Positive	To extent possible, limit use of drill rig, vehicle, *etc.* near probe, place temporary seal where practical, conduct additional purging, conduct repeat soil vapour testing
Contamination of indoor air caused by pathway created during drilling of subslab probes	False Positive	Conduct indoor air sampling prior to drilling of subslab probes, or seal borehole after drilling and wait at least 24 hours before obtaining indoor air sample

Table 3.2 Potential Factors Leading to False Positive and False Negative Vapour Concentrations

Issue	Potential Bias	Remedy
Contamination by off-gassing probe materials (*e.g.*, tape with glues, sealants containing VOCs, materials cut with cutting oils)	False Positive	Avoid all VOC-emitting materials, check MSDS or other information, consider testing materials for VOCs if uncertain
Leakage in vapour probe annulus seal	False negative	Conduct leak tracer test, follow best practices for sealing annulus and use a vapor-tight valve at probe head
Leakage in vapour sampling train	False negative	Conduct shut-in vacuum test and/or leak tracer test, use vapor-tight connections for tubing connections (*e.g.*, threaded)
Soil vapour sampling during or shortly after significant rainfall events[2] or snowmelt causes higher vacuums during sample collection, infiltrating water moves soil gas (downward or laterally), mass partitions into water reducing vapour concentrations; all causing altered vapour concentrations[3]	Often false negative but may cause false positive below building if infiltrating water pushes soil gas laterally to below building	Follow recommended wait times for sampling after rainfall events; suggested rule of thumb is waiting 1 day after rain ceases for coarse-grained soils and several days for finer-grained soils
Large and rapid change in barometric pressure causes changes to soil vapour concentrations at sites with thicker vadose zones	False positive when pressure falls; false negative when pressure rises; whether false will depend on sampling objective	Deeper soil vapour samples less affected by barometric pumping; depending on objectives, conducting repeat testing during different barometric pressure conditions may be warranted
Sorption of chemicals on sampling train materials	False negative, particularly for higher molecular weight compounds	Use of non-sorptive dedicated tubing such as Teflon or nylon
Insufficient equilibration time after probe installation	False negative	Wait sufficient amount of time, conduct additional purging, conduct repeat testing

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[2] Significant rainfall event will depend on initial moisture content of soil and soil type but is recommended to range from 0.5 to 1 cm

[3] Changes in soil moisture content result in seasonal changes in diffusive mass flux and soil vapour concentrations but are not considered false positive or negative concentrations. Seasonal sampling should be conducted to evaluate moisture related trends (Aris and Golder 2020)

Table 3.2 Potential Factors Leading to False Positive and False Negative Vapour Concentrations

Issue	Potential Bias	Remedy
High sampling vacuum (>> 10 in H_20) because of low permeability soils and/or high soil moisture content causes stripping or enhanced desorption of VOCs, causes mass transfer limitations in layered soil when purge volumes are high or creates leak in sampling train	False negative or positive	Reduce vacuum by reducing sampling flow rate, conduct sampling during drier periods (note that it is acceptable to obtain samples at up to 100 in H_20 provided protocols for leak and shut-in vacuum testing are followed)

3.3 Supplementary Methods

The toolbox for assessment of vapour intrusion continues to expand. Supplementary methods described in Table 3.3 are of particular benefit in assessing whether there is a driving force for vapour intrusion through monitoring of pressure and building pressure control tests; for assessment of foundation properties, pathways and attenuation factors through use of tracers; for assessment of factors affecting vapour intrusion and temporal variability through high frequency and resolution monitoring; and for assessment of potential background sources through use of several methods including tracers, isotopes and pressure control tests (Ma *et al*. 2020).

Table 3.3 Supplementary Methods

	Method	Summary of Technology	Objectives	Comments	General References
1.	Pressure monitoring	Differential pressure is measured between indoor air and outdoor air and/or subslab soil gas to determine pressure gradients	Magnitude and direction of the pressure difference during sampling program can indicate whether there is a 'driving force' for vapor intrusion. Differences in driving forces between sampling events may help explain variability in indoor air concentrations. SERDP/ESTCP (2012) demonstrated that indoor VI was correlated with building depressurization.	Pressure monitoring is recommended in several guidance (SABCS 2011; US EPA 2015, CCME 2016; ARIS and Golder 2020). Hand-held micromanometers can be used to obtain discrete measurements. Transducers with sensitivity to < 1 Pa and data loggers to enable collection of continuous data are preferred. Differential pressures as small as about 1 Pa are sufficient to result in soil gas advection as the driving force for mass flux into a building. Pressure leads that are outdoors should be protected from wind forces by placing lead in gravel bed or perforated vessel removed from the building wall.	ESTCP (2012) Holton *et al*. (2017) Lutes *et al*. (2019) (the above references are on building pressure control tests but also include information on pressure monitoring)
2.	Building Pressure Control (BPC) tests	Measure vapour concentrations under positive and negative indoor-outdoor air pressure conditions to either suppress or induce vapour intrusion; manipulate pressures in utility conduits to assess pathways	Distinguish between indoor/ outdoor air background and subsurface vapour sources Assess VI potential under worst case conditions and investigate preferential pathways such as sewers	Can be used to rapidly assess VI but is intrusive and may create non-representative conditions if induced pressure is excessive. Requires specialized equipment (*e.g.*, blower door, fan, manometers).	ESTCP (2012) Holton *et al*. (2017) Lutes *et al*. (2019) Guo *et al*. (2020b)

Table 3.3 Supplementary Methods

Method		Summary of Technology	Objectives	Comments	General References
3.	Tracers	Measure concentrations of natural tracer in soil (*e.g.*, radon gas) or introduced tracer (*e.g.*, helium, sulphur hexafluoride, nitrogen, perfluorocarbon) in different media (*e.g.*, subslab soil gas, indoor air) to assess vapour intrusion; release and monitor introduced tracer in building air	Measure subslab-to-indoor air attenuation factor Assess temporal variability in VI Investigate VI pathways Measure building ventilation rates	Radon has been shown to be an effective natural tracer (Schuver *et al*. 2018), radon is elevated in many natural soils and measurement protocols have been developed (McHugh *et al*. 2017); detailed studies of radon indicate partial correlation of varying precision between VI of VOC and radon (DOD 2017); when there are significant differences in subsurface distribution of radon and VOCs, the use of radon is less effective; the use of injected tracers typically is a research-level test; some tracers are GHGs and are relatively costly.	(Schuver *et al*. 2018) (McHugh *et al*. 2017) Ma *et al*. (2020b) US EPA (2020)1
4.	Isotopic analysis	Conduct compound specific (stable) isotope analysis (CSIA) of indoor air, outdoor air and/or soil vapour samples, *e.g.*, ^{36}Cl or ^{13}C, *e.g.*, ^{13}C, ^{2}H and ^{18}O in source determination of gases such as CH_4 and O_2, and ^{13}C, ^{2}H, ^{36}Cl in source determination of PHCs and chlorinated solvents	Distinguish between indoor/ outdoor air background and subsurface vapour sources	Enrichment in heavy isotopes caused by biodegradation in the subsurface commonly results in isotope ratios for the subsurface source that are distinct from those for manufactured sources found in consumer products; analysis commercially available from speciality laboratories (*e.g.*, using adapted US EPA TO-17 method) (Beckley *et al*. 2016; McHugh *et al*. 2017)	Beckley *et al*. 2016 McHugh *et al*. 2017

Table 3.3 Supplementary Methods

Method		Summary of Technology	Objectives	Comments	General References
5.	Continuous or high frequency chemical analysis	On-site gas chromatograph (GC) with photoionization detector (PID) or electron capture detector (ECD) with autosampler and multiplexer can be used to obtain low-level analysis of VOCs at high frequency and resolution in indoor air and soil gas.	Obtain temporal data to assess factors affecting VI Assess pathways for VI Assess potential background sources of VOCs Enable rapid monitoring of VI mitigation effectiveness	High frequency VOC analysis may be coupled with sensors providing data on differential pressure and weather data (temperature, wind speed, barometric pressure) to improve assessment of vapour intrusion processes (Hartman and Kram 2019) Advantageous for investigation of complex sites and understanding of specific factors affecting VI. Requires higher level of operator training than routine field instruments	Hartman and Kram (2019)
6.	High purge volume (HPV) soil gas sampling	A blower is used to remove soil gas from below a building at a relatively high flow rate (typically 100-1000 L/min) to collect an integrated sample and obtain a spatially averaged subslab soil gas concentration over a large area. Regular field screening is conducted to determine concentration trends. HPV more applicable for larger buildings.	Obtain spatially averaged soil vapour concentration Through tests at multiple locations and concentration *versus* time measurements can identify areas of elevated vapour concentrations	Can minimize risk of failing to identify an area of elevated concentrations and may reduce costs because of fewer slab penetrations; assumes radial flow to extraction point and that subslab fill has much higher permeability than underlying soil; with addition of steady-state (vacuum *versus* distance) and transient (vacuum *versus* time) measurements can provide information on subslab fill transmissivity and foundation slab leakage, which are data used in design of soil gas mitigation systems (McAlary *et al*. 2010)	McAlary *et al*. (2010); DOD (2017)

Table 3.3 Supplementary Methods

Method		Summary of Technology	Objectives	Comments	General References
7.	Mass flux / discharge methods	Measurements or model predictions to estimate mass flux into a building. Measurements can include air flow and concentrations in subslab depressurization systems or building ventilation systems.	Alternative method for estimating soil gas to indoor air vapour attenuation factors Estimate of indoor air concentrations Optimization of vapour mitigation systems	Advantages of mass flux method is that it can potentially provide a more accurate and less variable estimate of the attenuation factor than discrete samples. The Johnson and Ettinger (1991) model is a compartmental mass flux model. When using subslab depressurization data method assumes mass removed could potentially migrate into building under non mitigation conditions. Can be combined with BPC test by measurement of mass flux in exhaust.	Dawson *et al*. (2017) ESTCP / SERDP (2019).
8.	Building foundation tests	Conduct test involving measurement of soil gas extraction rates from temporary subslab extraction point and pressure across slab and radially from extraction point; these data with mathematical model are used to estimate slab conductivity and soil gas flow rate (McAlary *et al*. 2018)	Predict the intrusion rate of vapours into buildings and potentially vapour attenuation factor when building ventilation rates are available	Potentially enable a more accurate estimate of bulk volumetric soil gas flow rates into building and building-specific vapour attenuation factor (McAlary *et al*. 2018); requires specialized equipment, *e.g.*, blower and pressure transducers; the accuracy of model assumptions for air flow will vary depending on site	McAlary *et al*. (2018)

Table 3.3 Supplementary Methods

	Method	Summary of Technology	Objectives	Comments	General References
9.	Flux chamber	A sealed container is placed on the building foundation or on ground surface. The increase in chemical concentrations in a static chamber or steady state concentrations in a dynamic chamber is used to estimate the chemical mass flux rate	Measure flux through specific elements in building foundation (*e.g.*, cracks, openings) Measure flux through intact building foundation material (*e.g.*, to estimate diffusive flux) Use flux chamber tests on ground surface to assess intrusion into future building	Flux chambers can be used to estimate flux in scenarios where it is challenging to estimate VOC intrusion using conventional methods or when in-depth information on intrusion pathways or mechanisms is required. While flux chamber tests are conceptually simple and have been extensively used for fixed gas efflux measurements, they are less common for estimates of chemical VOC flux and dynamic tests are relatively complex. A passive diffusive flux chamber with high uptake sorbent is a promising new method (Heggie and Stavropoulos 2018). If the purpose is to estimate whole-building intrusion, scaling of measurements and accounting for potentially changed flux conditions (when conducted on bare ground) can be challenging.	Ma *et al*. 2020 Klenbusch 1986 Hartman 2003
10.	Thermal imaging	Images from thermal camera of the subsurface building foundation (*e.g.*, floor, walls, utilities) is used to identify temperature contrasts and possible areas where vapour intrusion could be occurring (usually colder areas).	Locate preferential pathways for vapour intrusion Document the effectiveness of mitigating preferential pathways Identify locations for subslab and/or indoor air sample locations	Thermal imaging technology continues to advance and become less expensive. For example, thermal camera attachments are available for smart phones.	DOD 2017

4.0 WASTE OIL PCOCS

Waste oil handling and storage are a common site activity of potential environmental concern. The scope requested by CSAP on this topic was to conduct a literature search and determine a generic list of waste oil vapour PCOCs.

The 2009 CSAP Soil Vapour Practice Guidelines identify that although waste oil is comprised of heavier molecular weight (C16+) hydrocarbons that are not considered to be volatile, the greater concern is volatile chemicals (*e.g.*, gasoline, diesel, solvents) introduced in the waste stream. The 2009 Guidelines include recommended analyte lists for gasoline and diesel but not waste oil.

The guidance prepared by PGL Environmental Consultants (PGL) for the CSAP Society on "*Potential Contaminants of Concern for Commercial and Industrial Land Uses*" (PGL 2018) provides information on recommended substance classes for waste oil and typical practices including the following: "*waste oil tanks are often improperly used to dispose of other substances, gasoline/diesel, solvents, and antifreeze for example*". However, recommendations on vapour PCOCs are specifically excluded in the PGL report.

4.1 General Background Information on Waste Oil

The CCME Code of Practice for Used Oil Management in Canada (CCME 1989) provides the following definition for used oil: "*an oil from industrial or non-industrial sources which has been acquired for lubricating or other purposes and has become unsuitable for its original purpose due to the presence of impurities or loss of original properties*." CCME (1989) describes the following categories of used oil: lubricating oils, hydraulic fluids, metal working fluids and insulating fluids.

Waste crankcase oils are defined as used lubricating oils removed from the crankcase of internal combustion engines (CEPA 1994). Unused crankcase oils consist of base lubricating oils that are comprised of a complex mixture of hydrocarbons (80 to 90% by volume) and performance-enhancing additives (10 to 20% by volume) (CEPA 1994). According to Wang *et al.* (2016), in general, lubricating oils have gas chromatograph (GC) profiles in the carbon range of C20–C40+ with boiling points greater than 340°C. Further, the low boiling fractions of petroleum hydrocarbons are generally not present in lubricating oil.

ATSDR (1997) describes used mineral-based crankcase oil as a mixture of aliphatic and aromatic hydrocarbons, lubrication additives, metals, and various organic and inorganic compounds. ATSDR (1997), referencing Vasquez-Duhalt (1989), report the composition of waste oil as follows: "*typically 73-80% weight/weight aliphatic hydrocarbons (primarily alkanes and cycloalkanes with l-6 rings); 11-15% monoaromatic hydrocarbons; 2-5% diaromatic hydrocarbons; and 4-8% polyaromatic hydrocarbons*." The lubrication additives are indicated to consist primarily of zinc diaryl, molybdenum disulfide, zinc dithiophosphate, metal soaps, and other organometallic compounds. Motor oil changes during use through physical and chemical processes (ATSDR 1997) and, additionally, motor oil can be contaminated by uncombusted gasoline that has leaked from faulty fuel injector lines (Brinkman 1985).

4.2 Information on Volatile Substances in Waste Oil

There is limited information on chemical composition in waste oil in relation to volatile substances or evaluation of waste oil with reference to potential vapour inhalation pathway concerns. Relevant information accessed through a literature search includes the following:

- Metzer (1985) describes a study of the environmental effects of treating roads with waste oil for dust suppression. As part of this study, waste oil samples were analyzed (Table 4.1).
- US EPA (1984) provides data on the composition of used oil that indicate concentrations of BTEX were several hundred to thousand parts per million (ppm), and that lower concentrations of trichloroethylene, tetrachloroethylene and 1,1,1-trichloroethane were measured (Table 4.2).
- US EPA (1996) states "*constituent chlorine in waste oils typically exceeds the concentration of chlorine in virgin distillate and residual oils. High levels of halogenated solvents are often found in waste oil as a result of inadvertent or deliberate addition of contaminant solvents to the waste oils.*"
- US EPA (2005) provides recommendations for analysis of a suite of chlorinated hydrocarbons based on measurement data for hazardous constituents in used oil consisting of "F001/F002" constituents that are: tetrachloroethylene, methylene chloride, trichloroethylene, 1,1,1-trichloroethane, 11 carbon tetrachloride, chlorinated fluorocarbons, 1,1,2-trichoroethane, chlorobenzene, 1,1,2-trichloro-1,2,2-trifluoroethane, orthodichlorobenzene, and trichlorofluoromethane.
- Rauckyte-Zak (2006) report on the determination of heavy metals and VOCs in used engine oils and sludges. Their analysis indicated the total content of BTEX and naphthalene in used oil and sludge samples was found not to be a significant factor to contamination (significant was not defined).
- ITRC (2014) states "r*esidual fuels (such as fuel oil Nos. 4, 5, and 6, lubricating oils, waste oils, and asphalts) are characterized by complex PAHs and other high-molecular-weight hydrocarbon compounds with carbon ranges that generally fall between C24 and C40. Residual fuels lack a significant amount of volatile compounds and, aside from the potential generation of methane, are generally assumed to pose a minimal vapour intrusion risk.*"

The data indicate the potential for a vapour intrusion concern associated with petroleum hydrocarbon and chlorinated solvent substances.

Table 4.1 Results of Waste Oil Analyses (adapted from Metzer 1985).

Substance	Samples Detecting Contaminant (%)	Concentration at 90th Percentile (mg/kg)	Concentration range (ppm)	
			Low	High
Metals				
Arsenic	100	16	0.4	45
Barium	79	485	0	3,906
Cadmium	46	28	0	36
Chromium	81	28	0.1	537
Lead	94	1,000	0	3,500
Zinc	98	1,500	0.7	5,000
Chlorinated Solvents				
Dichlorodifluoromethane	68	860	0	2,200
Trichlorotrifluoroethane	57	130	0	550,000
1,1,1 - Trichloroethane	85	1,300	0	110,000
Trichloroethylene	76	1,049	0	330,000
Tetrachloroethylene	89	1,200	1	3,900
Total chlorine	100	6,150	40	459,000
Other Organics				
Benzene	70	160	0	280
Toluene	83	1,300	0	5,100
Xylenes	79	570	0	139,000
Benzo(a)anthracene	82	35	5	660
Benzo(a)pyrene	58	33	3.2	405
PCBs	33	50	0.4	3,150
Naphthalene	100	580	110	790

Table 4.2 Select Measurement Data on VOC Concentrations in Waste Oil (adapted from US EPA 1984)

Substance	Concentration in waste oil (ppm)	
	Low	High
Benzene	1	3,600
Toluene	1	6,500
Xylene	1	14,000
Naphthalene	Not measured	Not measured
1,1,1 Trichloroethane	<1	1,000
Trichloroethylene	<1	16
Tetrachloroethylene	<2	660
Total chlorine	<100	4,700

4.3 Summary of Vapour Concern and Recommended PCOCs

Our review indicates motor oils based on parent composition do not contain volatile components that would cause motor oils to be a vapour intrusion concern. The primary concern is that waste oil tanks may be used to dispose of other substances that are volatile, such as gasoline and diesel, and automotive-related products, such as degreasing solvents, aerosol brake cleaners and aerosol carburetor cleaners. Chlorinated hydrocarbons are the main compounds of potential concern associated with solvents and cleaners. Current products containing chlorinated solvents are less common than historical products.

The potential vapour concern and PCOCs will vary depending on the specific site use associated with waste motor oil storage and handling. At automotive service stations, fuels are extensively used, and it is difficult to rule out inadvertent disposal or entrainment of fuels in waste oil. In addition, leaking fuel injector lines (Brinkman 1985) could add fuel to waste oil. However, at some service stations, it may be possible to rule out use of chlorinated solvents with a reasonable degree of confidence because of limited repair conducted or documented use of solvents that do not contain chlorinated hydrocarbons. Another site use where it may be possible to rule out chlorinated solvent use is an establishment where vehicle oil change is the primary business. In contrast, the characteristics of waste oil at facilities such as oil recyclers that collect oil from multiple sources is expected to be more variable.

The recommended approach is limited to service stations, oil change and maintenance facilities where waste motor oil is primarily collected, handled and stored. These are considered to represent most sites in BC where storage and handling of waste oil is of potential concern. The default vapour PCOCs for all sites meeting the above definition are a subset of the vapour PCOCs for gasoline and diesel in the 2009 Practice Guidelines, which are BTEX, hexane, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, naphthalene and VPHv (noting the investigator may choose to analyze for and report the results of the full gasoline and diesel lists if desired). A reduced list of compounds focused on likely more prevalent and toxic compounds is considered justified because the concentrations of compounds of concern in waste oil are likely much lower than in the parent fuel.

Additionally, the potential for chlorinated solvent use associated with waste oil should be evaluated at all sites. If there is information that indicates chlorinated solvents are PCOCs at the site, then waste oil PCOCs should include chlorinated solvents. The rationale for just selecting chlorinated solvents as PCOCs is that historical data reviewed indicates they were present at higher concentrations than other halogenated compounds (*e.g.,* fluorinated compounds) and are commonly identified as PCOCs in solvents.[4] The 2009 Practice Guidelines list of chlorinated solvent substance for dry cleaners is considered a reasonable list for waste oil because of the general commonality in solvents used for dry cleaning and cleaning of automotive parts.

In summary, the recommended generic PCOCs are:

- Waste motor oil at service station, oil change and maintenance facilities:
    - **All sites**: BTEX, n-hexane, n-decane, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, naphthalene and VPHv.
    - **Sites where chlorinated solvent have been identified as additional PCOCs**: tetrachloroethylene, trichloroethylene, cis-1,2-dichloroethylene, trans-1,2-dichloroethylene, vinyl chloride, chloroform, chloroethane, 1,1,1-trichloroethane, 1,1- dichloroethane, 1,2-dichloroethane, 1,1-dichloroethylene, carbon tetrachloride and methylene chloride.

The above approach does not exclude the potential option of PCOC refinement and exclusion through a detailed investigation of an existing waste oil tank that includes analysis of waste oil composition. However, because site use practices can change over time, it is often difficult to exclude PCOCs with certainty, and consequently, PCOC exclusion through waste oil analysis is not recommended unless there is appropriate supporting evidence.

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[4] The following references indicate tetrachloroethylene, methylene chloride, trichloroethylene and 1,1,1-trichloroethane are common PCOCs in solvents: 1) https://www.epa.gov/p2/case-studies-safer-alternatives-solvent-degreasing-applications; 2) https://www.berrymanproducts.com/chlorinated-vs-non-chlorinated-brake-cleaner/; 3) https://www.kellerheartt.com/blogs/news/the-difference-between-chlorinated-and-non-chlorinated-brake-cleaner; 4) https://www.envirofluid.com/articles/tetrachloroethylene-a-deadly-danger-in-brake-cleaner/

At sites other than waste motor oil at service station, oil change and maintenance facilities, a site-specific approach should be followed to determine vapour PCOCs and include all volatile PCOCs at a site that might be added to a waste oil tank.

5.0 IMPLEMENTATION OF BIODEGRADATION ATTENUATION ADJUSTMENT DIVISOR (BAAD)

The biodegradation of petroleum hydrocarbon (PHC) vapours is a significant process for concentration attenuation in the vadose zone. For this reason, BC ENV Protocol 22 includes a biodegradation attenuation adjustment divisor (BAAD) to optionally reduce the vertical attenuation factor for vapour transport when site conditions allow.

The scope requested by CSAP was to conduct a literature search of existing guidance and approaches adopted by US Environmental Protection Agency (US EPA), Interstate Technology & Regulatory Council (ITRC), and other jurisdictions for the determination of "biologically active soil" and other potential issues such as substances considered as part of the BAAD, vertical distances, surface cover, *etc.* Additionally, guidance and advice on applying a BAAD and supporting site data is required.

A detailed review of the science and guidance on aerobic biodegradation of petroleum hydrocarbons and petroleum vapour intrusion is provided in Appendix B. This review addresses the conceptual site model, factors affecting aerobic biodegradation including biologically active soil, a review of select guidance in other jurisdictions, a review of concrete and asphalt properties, a review of modeling studies, and discussion on application of a BAAD based on the results of the review. Additionally, a vertical screening distance approach for petroleum vapour intrusion (PVI) pathway exclusion is reviewed as a possible alternative or supplemental method to a BAAD approach.

This section provides practice recommendations that are applicable within the current BC regulatory framework that can be adopted by practitioners. In certain areas, recent science has suggested that future review of regulatory guidance and protocols may be beneficial. Note, under a generic standards approach, vapour investigations must follow applicable BC CSR regulatory standards and existing BC ENV protocols (*e.g.,* Protocol 22). and should follow applicable guidance (*e.g.,* Technical Guidance 4). As part of a detailed risk assessment, the recent science could be considered where there is supporting rationale. In these instances, approved professionals or qualified persons should consider seeking concurrence from BC ENV before implementing a detailed risk assessment approach including obtaining a pre-approval under Protocol 6 where warranted.

5.1 Background Information on BC ENV Protocol 22

BC ENV provides vertical vapour attenuation factors (VAFs) in Protocol 22, Table 1 for multiple land use scenarios. Under certain conditions, the Table 1 vertical VAFs may be adjusted to account for additional attenuation using a BAAD equal to 10 for select substances that readily biodegrade in aerobic environments.

The use of the BAAD is restricted to the following conditions:

- If nonaqueous phase liquids are not present in soil or ground water, and volatile hydrocarbons in water fraction C>6 – C10 (VHw6-10) is < 15,000 µg/L and extractable petroleum hydrocarbons in water fraction C>10 – 19 (EPHw10-19) is < 5,000 µg/L, then the BAAD can be applied if the building foundation (indoor exposure) or ground surface (outdoor exposure) and the vapour source (*i.e.,* all detectable vapour substance concentrations in soil and groundwater) are separated vertically by 2 m of biologically active soil.
- If nonaqueous phase liquids are present in soil or ground water, or VHw6-10 is > 15,000 µg/L and EPHw10-19 is > 5,000 µg/L, then the BAAD can be applied if the building foundation (indoor exposure) or ground surface (outdoor exposure) and the vapour source (*i.e.,* all detectable vapour substance concentrations in soil and groundwater) are separated vertically by 5 m of biologically active soil.
- If the BAAD is applied to measured soil vapour data, the vapour data must have been collected within 1 m of the vapour source.
- There must be no substantive surface cap at the site. Specifically, paved or other low permeability surfaces cannot represent more than 80% of the area surrounding the building.
- The BAAD can be used only for the aerobically biodegradable gasoline and diesel component substances listed in Protocol 22, Table 2 (provided below as Table 5.1) in conjunction with Protocol 22, Table 1 vertical VAF.

"Biologically active soil" is defined in BC ENV Procedure 8 "Definitions and Acronyms for Contaminated Sites" to not contain detectable concentrations of substances from CSR Schedule 3.3. The following geologic materials do not qualify as biologically active: coarse sand and gravel with low silt, clay and organic matter content, and a low moisture content that is less than two percent dry weight; fractured, faulted, or jointed consolidated rock; or consolidated rock with solution channels (*i.e.,* karst). Soil samples must be collected and analyzed for soil moisture, which must be greater than two percent by dry weight to indicate a biologically active soil.

Table 5.1 Substances Considered to be Readily Biodegraded in Aerobic Environments (from Protocol 22, Table 2)

Substance	Chemical Abstract Service #
Benzene	71-43-2
decane, n-	124-18-5
Ethylbenzene	100-41-4
hexane, n-	110-54-3
isopropylbenzene	98-82-8
methylcyclohexane	108-87-2
Naphthalene	91-20-3
Toluene	108-88-3
xylenes, total	1330-20-7
trimethylbenzene, 1,3,5-	108-88-3
trimethylbenzene, 1,2,4-	95-63-6
VPHv	None available

5.2 Summary in the Context of Protocol 22 BAAD Requirements

Based on the review conducted on aerobic biodegradation of PHC vapours and regulatory approaches (Appendix B), the key findings are summarized in the context of requirements in Protocol 22 BAAD.

5.2.1 Investigation to Support Application of BAAD

The application of a BAAD requires a robust CSM, well characterized sources and an evaluation of biologically active soil. The investigation requires assessment of the LNAPL *versus* dissolved-phase source extents. The source extents should be delineated and determined to be stable or shrinking following applicable BC ENV protocols and guidance.

The vertical distribution of LNAPL and dissolved-phase sources should be assessed through soil and groundwater sampling that provide sufficient spatial and temporal resolution to enable a representative estimate of the vertical separation distance between the source and building based on seasonal conditions. The vertical screening distance is taken from the top of the LNAPL source or seasonal high-water table for a dissolved-phase source. Accurate estimation of separation distances often requires relatively closely spaced samples in source zones and use of field screening and laboratory analyses of PHC concentrations. Additionally, the investigation of biologically active soil requires sampling and analysis of soil samples for indicator substances of PHC impact (such testing may not always be conducted for routine site investigations).

Soil gas data will generally improve the CSM and is a more direct measure of a potential vapour concern. Under Protocol 22, soil vapour PHC concentrations used in an assessment of contamination where a BAAD is applied are required to be obtained within 1 m of the PHC source. Under Technical Guidance 4, indoor vapour concentrations may be obtained following three different approaches consisting of direct measurement of vapour at the receptor, prediction from soil vapour data, and prediction from soil and/or groundwater concentration data. Measured soil vapour data often provide for a more representative estimate of source or near-source concentrations compared to estimation from soil and/or groundwater data.

The collection of additional soil gas data from vertical profiles and/or lateral transects (starting from sources and moving away) can provide information to support the CSM and assessment of vapour attenuation. Where possible, soil gas samples should be obtained below building slabs or asphalt surfaces if the goal is to investigate future building conditions.

Soil gas oxygen data may be useful to confirm conditions for aerobic biodegradation. Oxygen data is recommended when there is an existing larger building above the size threshold defined below for a substantive cap precluding condition.

5.2.2 Identification of Vapour Source Type and Vertical Distances

BC ENV Protocol 22 provides concentration criteria for volatile and extractable hydrocarbon ranges for identification of the presence and absence of NAPL (absence meaning there is a dissolved-phase source). The lines of evidence provided in ITRC (2014) (Table 3-1) are recommended as additional indicators of the likely presence and absence of NAPL. The vertical distances (2 m for dissolved-phase sources and 5 m for LNAPL sources) in Protocol 22 for determination of when a BAAD may be applied are considered appropriate based on the data reviewed. These distances are consistent with those recommended by US EPA (2015) for vertical screening distances for PVI pathway exclusion. A vertical distance screening approach is separately discussed below.

5.2.3 Definition of Biologically Active Soil

Criteria for biologically active soil for assessment of PVI are addressed in ITRC (2014), US EPA (2015) and CRC Care (2013). US EPA (2015) recommends soil concentration thresholds of 100 mg/kg total petroleum hydrocarbon (TPH) (fresh gasoline) and 250 mg/kg TPH (weathered gasoline and diesel) to determine when LNAPL could potentially be present. US EPA (2013a) identifies a benzene concentration of 10 mg/kg as a threshold for LNAPL presence. These concentrations were estimated using the so-called "Csat" equation for equilibrium partitioning between soil, water and gas phases, where the water-phase concentration is set at the solubility limit. The equation represents the lowest concentration where potentially a separate phase is predicted in soil and is considered a conservative estimate. The oxygen demand from aerobic biodegradation of low ppm concentrations of TPH is considered insignificant.

The US EPA (2015) criteria of 100 mg/kg TPH (fresh gasoline) and 250 mg/kg TPH (weathered gasoline and diesel) are recommended. There are a range of methods for TPH, but the common analytical method is US EPA Modified Method 8015, where gasoline range organics (GRO) represents purgeable organics in the C6 to C10-12 range and diesel range organics (DRO) represents extractable organics in the C8-12 to C24-26 range (ITRC 2018). In the BC context, VPHs (C6-10) is similar to GRO. LEPHs (C10-18) is reasonably comparable to DRO because the absence of higher molecular weight compounds would not be of concern for vapour intrusion.

Under Protocol 22 (through definition in Procedure 8) biologically active soil is defined as not containing any detectable substances of concern. This definition for biologically active soil must be implemented under Protocol 22. Under a detailed risk assessment approach, consideration could be given to adopting similar definitions to above regulatory guidance or other science-based methods as supported by data. Potentially applicable definitions are summarized below:

- soil with <u>benzene < 10 mg/kg, VPHs < 100 mg/kg and LEPHs < 250 mg/kg</u> are biological active, except when the following three precluding geologic conditions (US EPA 2015) apply or there is evidence of NAPL, as follows:
  - Coarse sand and gravel with a low content of silt, clay, and organic matter, and low moisture content that is less than 2 percent dry weight;
  - Fractured, faulted, or jointed consolidated rock;
  - Consolidated rock with solution channels (*i.e.*, karst); and
  - Presence of NAPL and hydrocarbon-like staining.

5.2.4 Precluding Conditions for Application of BAAD

Several precluding conditions are recommended by ITRC (2014) and US EPA (2015) for application of vertical screening distances. These precluding conditions are considered useful when evaluating application of a BAAD because the BAAD is based on a similar conceptual model of source type and source-receptor distance as the screening distances. The following precluding conditions adapted from ITRC (2014) with the addition of a condition for methane and soil gas pressure are recommended:

- anthropogenic preferential pathways such as sewers or tunnels connecting a contamination source with the building (see Section 6.0);
- expanding or migrating LNAPL and/or dissolved-phase sources or plumes;
- fractured or karst media;
- greater than 10% v/v ethanol in gasoline;
- excessively dry soil (less than 2% moisture based on dry weight);
- excessively high organic content soil (greater than 4%); and
- excessively high methane in soil gas (greater than 5% v/v) and/or soil gas under pressure such that soil gas advection is a more significant process than diffusion.

A surface cap condition is addressed below.

5.2.5 Definition of Substantive Surface Cap

A potential concern associated with a substantive surface cap is that oxygen recharge is reduced causing decreased attenuation of PHC vapours from aerobic biodegradation. The empirical data and modeling studies reviewed indicate that an oxygen shadow is unlikely to occur for a dissolved-phase PHC source for a 2 m source-building separation distance but could occur for larger buildings and a LNAPL source with high source vapour concentrations for a 5 m source-building separation distance (US EPA 2013a; US EPA 2013b; Knight and Davis 2013; Yao *et al*. 2014; Verginelli *et al*. 2016). The empirical data suggests the potential for a slight oxygen shadow below asphalt pavement or building foundation slabs for LNAPL sources, although the data were inconclusive (US EPA 2013a).

Under Protocol 22, there must be no substantive surface cap at the site, and specifically, paved, or other low permeability surfaces cannot represent more than 80% of the area surrounding the building. Based on recent science, alternative approaches that depend on the source type and building size are described below. These approaches could have application under a detailed risk assessment approach where there is supporting rationale.

For a dissolved-phase source (no NAPL), empirical data and modeling suggest there will be sufficient oxygen flux through building foundations and hard surfaces to support aerobic biodegradation of PHC vapours, in typical urban environments. For a NAPL source, a surface cap precluding condition is not considered warranted for hard surfaces adjacent to buildings in typical urban environments because of oxygen migration through porous surfaces, cracks, and open areas. However, a surface cap precluding condition is considered warranted for larger buildings where there is potential for a significant oxygen shadow below the building. There are limited data and uncertainty in available modeling studies on the oxygen shadow effect, which makes establishing criteria for building size challenging. The available modeling studies suggest that an oxygen shadow may begin to form below buildings overlying LNAPL sources with a 5 m source-building separation when building dimensions are greater than between 20 m and 30 m (*i.e.,* for a square building).

Under detailed risk assessment, the definition for a substantive surface cap precluding condition could consider:

- Application of a biological adjustment factor or vertical screening distances is precluded for building size greater than 20 m on the shortest side (US EPA 2015) unless soil gas data are obtained below the building and the oxygen concentration > 2% v/v. For a future building condition, soil gas data should be obtained within 1 m of the vapour source.
- Application of a biological adjustment factor or vertical screening distances is precluded for all buildings when the building is surrounded by an *impermeable* surface cap such as a geomembrane liner or concrete that is specifically treated or coated to create an impermeable barrier.

5.2.6 Summary

The recommendations on the development of the CSM for PHC biodegradation, characterization of source type and distribution, and precluding factors for application of the BAAD are considered applicable under current BC regulatory framework.

Based on recent science, the following precluding conditions could be considered under a detailed risk assessment approach, as warranted:

- Definition of "biologically active soil" based on concentration-based criteria following US EPA (2015) and ITRC (2014).
- Definition of substantive surface cap at the site primarily based on potential oxygen shadow below building, *e.g.,* consistent with the USEPA (2015) precluding condition for building size greater than 20 m on the shortest side.
- The above definitions may be refined based on site-specific soil gas data.

5.3 Vertical Screening Distance Approach

A vertical screening approach is supported by the CSM, empirical data and modeling studies that indicate rapid vapour attenuation over short vertical distances. Consequently, a vertical screening approach will generally be more accurate in representing the attenuation that occurs at sites from aerobic biodegradation. The concentration attenuation results in a non-operable exposure pathway when vertical distances are sufficient (*i.e.,* there is much greater reduction than the 10-fold BAAD).

ITRC (2014) and US EPA (2015) provide guidance on a vertical distance screening approach for PVI pathway exclusion for aerobically biodegradable PHCs, an approach that has been adopted by several regulatory jurisdictions.

Consideration could be given to development of a vertical screening distance approach for exclusion of the PVI pathway as an alternative or supplemental approach to a BAAD approach as supported by the recent science (note vertical screening distances are not part of Protocol 22 and currently could only be adopted under detailed risk assessment). A preliminary evaluation of a vertical screening distance approach is included in Appendix B.

6.0 UTILITIES

6.1 Background and Overview of Issue

The assessment of soil vapour intrusion to buildings has historically focused on the ingress of soil gas through building foundations into indoor air. The role of sewer lines, utilities and, in some cases, natural features such as preferential pathways for the migration of subsurface vapours has been recognized for some time but, to date, there has been limited guidance on identification, investigation and characterization of such pathways. A growing body of research and case studies has highlighted the importance of this pathway and prompted the need for further guidance. The research program conducted by ESTCP included a range of residential, commercial and industrial buildings. Preferential pathways, including utilities, may be of concern for both residential as well as commercial/industrial buildings.

BC ENV Procedure 8 defines "preferential flow pathway" and "preferential pathway" as "*a pathway that is significantly (greater than 1 order of magnitude) more water or gas permeable than the soil media that surrounds it and may be anthropogenic (including pathways such as underground utilities for sewers, water and gas lines) or natural (including pathways such as fractured bedrock, surface depressions, streambeds and ditches that intersect and drain shallow aquifers).*"

Draft BC guidance, prior to 2009, for vapour assessment prohibited the use of BC ENV default vapour attenuation factors, as well as reliance on a 30 m lateral screening distance, where preferential pathways exist. The 2009 CSAP soil vapour guidance recommended that, in the absence of a direct connection between a utility line and indoor air, the situation would be similar to the presence of contamination within 1 m of a building foundation and that an attenuation factor (AF) of 0.02 would be applicable. If there is a direct connection of the utility to indoor air, use of the crawlspace AF of 0.1 was recommended.

These recommendations were subsequently incorporated into the original version of BC ENV Technical Guidance 4, as well as the current version of Protocol 22 which states: *"If there is a* *preferential flow pathway through the foundation slab or other direct connection between a utility backfill and indoor breathing zone (such as an unlined inspection or clean-out box), then use of the preferential flow pathway vapour attenuation factor (i.e., 2.0×10^{-2}) is not permitted. Apply the crawlspace vapour attenuation factor (i.e., 1.0×10^{-1}) and sampling restrictions instead."* The current version of Technical Guidance 4 continues to preclude use of the 30 m lateral screening distance where preferential pathways exist.

Beyond the above, little guidance is available in BC for addressing soil vapour intrusion through utilities or other preferential pathways. The 2020 CSAP soil vapour guidance (ARIS and Golder 2020) reviewed much of the available literature up to 2020, as well as guidance available from other jurisdictions. The document recommended that further consideration be given to methods of sampling and vapour monitoring of preferential pathways and estimation of attenuation factors.

The present document updates the literature review conducted for the 2020 CSAP guidance, with the aim of developing practice recommendations under the following categories:

- Pathway identification and conceptual model development;
- Pathway screening and risk identification;
- Investigation and sampling; and
- Use of attenuation factors.

This section provides practice recommendations that are applicable within the current BC regulatory framework that can be adopted by practitioners. In certain areas, recent science has suggested that future review to regulatory guidance and protocols may be beneficial (*e.g.*, with respect to vapour attenuation factors). Note, under a generic standards approach, vapour investigations must follow applicable BC CSR regulatory standards, existing BC ENV protocols (*e.g.*, Protocol 22) and should follow applicable guidance (*e.g.*, Technical Guidance 4). As part of a detailed risk assessment, the recent science could be considered where there is supporting rationale. In these instances, approved professionals or qualified persons should consider seeking concurrence from BC ENV before implementing a detailed risk assessment approach including obtaining a pre-approval under Protocol 6 where warranted.

6.2 Literature Review

The literature review is an update of that presented in the 2020 CSAP guidance, and is presented in Appendix C. Key findings from the literature review include the following:

- Preferential pathways include both natural features (permeable soil units, fractured bedrock, karst features) and anthropogenic features (sewers, utility conduits, backfill, disturbed soils, and occasionally tunnels and other "unfilled" spaces and structures);

- Sewers and conduits are potentially important vapour intrusion pathways. Migration of VOCs into indoor air spaces can occur from sanitary sewers through dry plumbing traps, degraded seals and openings in plumbing, or from storm sewers or drains that are connected to permeable fill surrounding a building foundation;
- Sources of VOCs in sewers include both subsurface ingress of contaminants through cracks and joints, and direct permitted or non-permitted discharges to sewers;
- Vapour migration can occur both within the utility conduit (sewer or tunnel airspace) and within the backfill surrounding the utility. However, evidence has shown that migration through pipes and unfilled spaces is more important than migration through backfill, although the latter may still need to be considered as a potential preferential pathway;
- Conventional methods used to assess vapour intrusion, such as subsurface sampling outside or beneath a building, may not adequately represent the potential risks posed by VOCs when preferential pathways are present;
- Preferential pathways should be identified and considered in developing conceptual site models for vapour intrusion. Conceptual models should include identification of factors contributing to preferential pathway migration such as mechanisms of vapour ingress to utility lines and subsequent entry to indoor air;
- Studies have shown that higher VOC concentrations may arise in utility airspace where the utility directly intersects contaminated groundwater, NAPL or a vadose zone vapour source, or where there is evidence of direct VOC discharge to a sewer, than in a utility located within the vadose zone above a contaminant plume. The former scenario(s) would be considered a higher risk for vapour intrusion; the latter would be considered a lower risk;
- Time series data of VOC concentrations in sewer air showed that short term variations (1-3 days) were typically less than 10x, whereas longer term variations (12 to 18 months) were up to 34x, suggesting that repeat monitoring is required to estimate long term average concentrations; and
- Monitoring of VOCs and tracer gases at multiple sites has enabled the estimation of attenuation factors between concentrations in groundwater (equilibrium vapour concentration from Henry's Law) and sewer air, and between sewer air and indoor air. Median attenuation factors between groundwater and sewer air ranged from 1.4×10^{-4}, for a sewer line above the vapour source, to 7.5×10^{-3}, for a sewer line intersecting the vapour source. Attenuation factors from sewers to building air ranged from less than 1×10^{-3} to 5×10^{-2}.

6.3 Recommended Practice Guidance

6.3.1 Pathway Identification and Conceptual Model Development

General guidance and recommendations for developing a CSM for vapour intrusion were provided in the 2020 CSAP guidance (ARIS and Golder 2020). Specific factors relevant to preferential pathways to be determined during the desktop data review and/or site reconnaissance are discussed below.

The following definitions are relevant with respect to identifying potential preferential pathways and developing a CSM:

- Preferential pathway: A pathway that is significantly (greater than 1 order of magnitude) more water or gas permeable than the soil media that surrounds it and may be anthropogenic (including pathways such as underground utilities for sewers, water and gas lines) or natural (including pathways such as fractured bedrock, surface depressions, streambeds and ditches that intersect and drain shallow aquifers) (BC ENV Procedure 8). Similar definitions are found elsewhere; for example, CalEPA (2020) describes the term as generally defining all high-capacity transport pathways for vapours from the subsurface source to the building foundation or into the building;
- Vapour conduit: A subset of preferential pathways that provide little or no resistance to vapour flow. For example, the pipes of a sanitary sewer utility conduits, or other drains or conduits (CalEPA 2020); and
- Vapour entry point: Any penetration in the building foundation such as cracks, expansion joints, utility conduits, sumps and elevator shafts, through which subsurface vapours can be transported into the building (CalEPA 2020).

As with any CSM, a pathway must be complete, including a source, transport medium (or media) and exposure mechanism at a receptor location, in order to be considered operative. Factors relevant to establishing the presence of a complete preferential pathway are summarized in Table 6.1.

Table 6.1 Factors Relevant to Establishment of a Preferential Pathway

Factor	Indicators and relevant information
Nature and location of vapour source	Potential contaminants of concern (PCOCs) Phases present (NAPL, dissolved, adsorbed, vapour) Location and depth of plume or NAPL source Proximity of plume to buried infrastructure Distance of source from building(s) Evidence of direct VOC discharge to sewers
Subsurface conditions	High permeability materials such as cobbles or clean, coarse gravel (native or backfilled) Fractured bedrock Karst features
Subsurface infrastructure and potential vapour conduits	Presence and depths of sewer lines and connections to buildings Tunnels or other utilities enclosed in conduits Land drains Building perimeter drains Wells (active or abandoned)
Building features	Foundation condition and integrity Potential vapour entry points – cracks, sumps, drains, other openings, plumbing fixtures (especially aged, damaged or dry fixtures)
Other factors	Reported or suspected VOC presence in indoor air (especially when present at higher concentrations on upper floors or in vicinity of plumbing fixtures)

The above information should be captured in the CSM in tabular, flow chart or pictorial format. An example of a pictorial CSM that includes identification of such features is presented in Figure 2 (modified after McHugh *et al*. 2017).

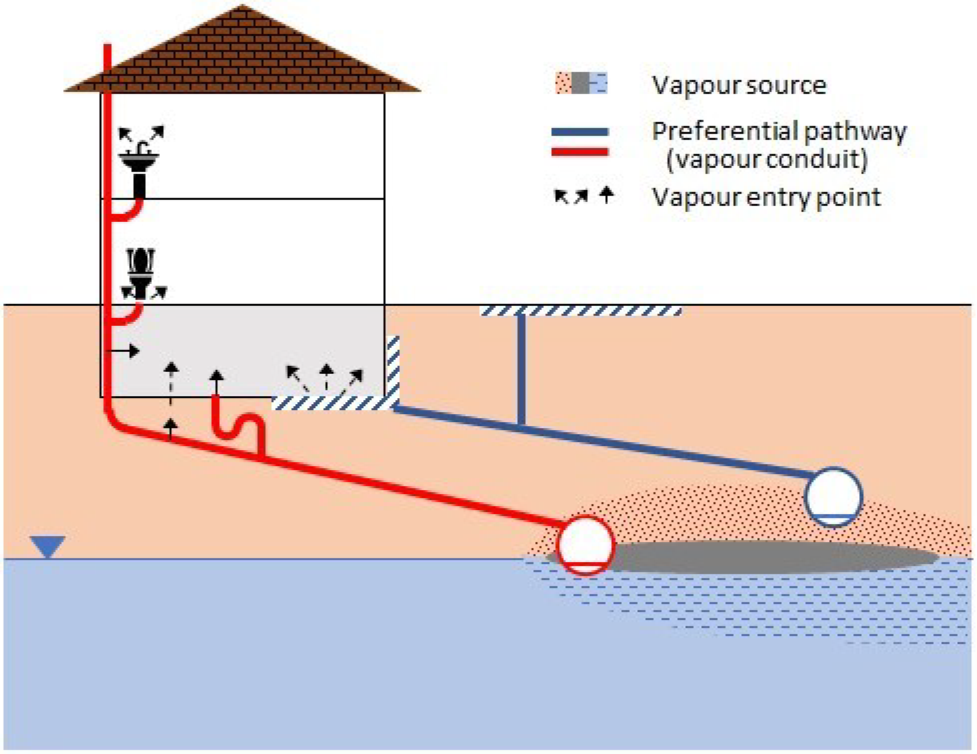

Figure 2 Typical Preferential Pathway Conceptual Site Model (modified after McHugh *et al*. 2017)

6.3.2 Pathway Screening and Risk Identification

As discussed in more detail in Appendix C, studies have shown that the greatest risk for vapour intrusion *via* preferential pathways arises when the sewer line or utility tunnel directly intersects a potential contaminant source. Higher risk scenarios are typically those where a sewer line or tunnel intersects contaminated groundwater, nonaqueous phase liquids (NAPL) or a vadose zone vapour source (*e.g.*, residual or immobile NAPL within the vadose zone), or where there is direct evidence of VOC discharge to the sewer line (see Figures C4 and C5, Appendix C). A lower risk scenario is one in which the sewer or utility tunnel passes through the vadose zone directly above a groundwater or NAPL plume (ESTCP 2018). A higher risk scenario also has the potential to result in potential VI impacts to structures connected to the sewer line or tunnel, both upstream and downstream of the contaminant source.

It is noted that the above screening approach refers to sewer lines, tunnels or other "unfilled" spaces that serve as vapour conduits. As noted previously, utility line backfill is typically less important in the context of preferential pathways than sewers and tunnels, and would generally be considered to give rise to a lower risk scenario.

Based on this, Figure 3 presents a flow chart (modified after ESTCP 2018) which can be used to classify preferential pathway risk in order to guide the subsequent vapour investigation strategy.

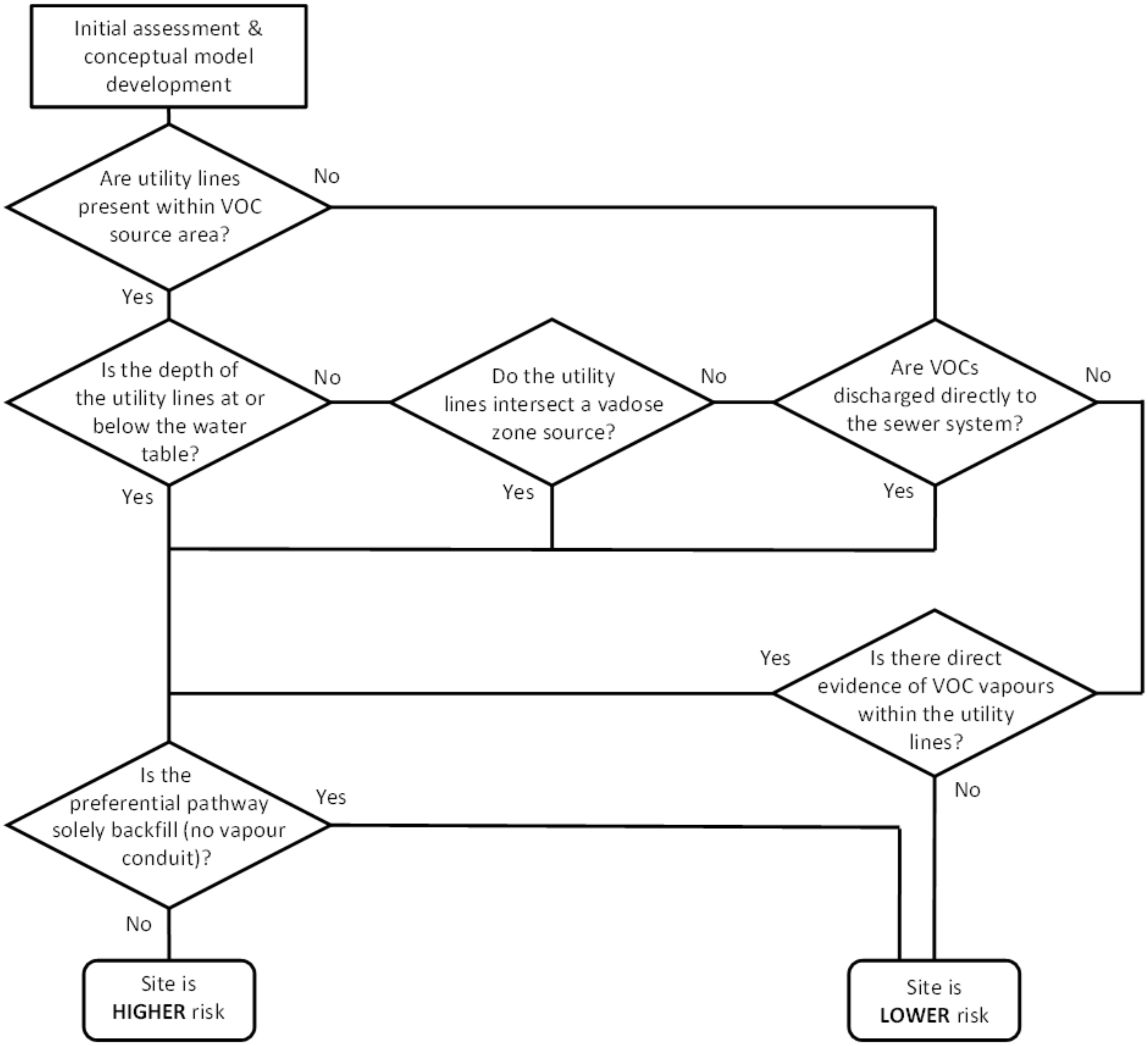

Figure 3 **Risk Classification Flow Chart (modified from ESTCP 2018)**

6.3.3 Investigation and Sampling

General guidance for vapour investigations is provided elsewhere (*e.g.*, Technical Guidance 4, ARIS and Golder 2020, Health Canada 2010, SABCS 2011) and additional recommendations on sampling are provided in previous sections of the present document. The following discussion is aimed at identifying situations where preferential pathways may be important and where standard vapour investigation approaches may be insufficient to characterize risks.

ESTCP (2018) has developed an investigation protocol to guide field investigation activities at sites with preferential pathways, depending on risk classification. Figure 4 presents a flow chart (modified after ESTCP 2018) which can be used to assist in determining where a standard vapour investigation would suffice, or where a focused preferential pathway investigation (and possible mitigation) may be required.

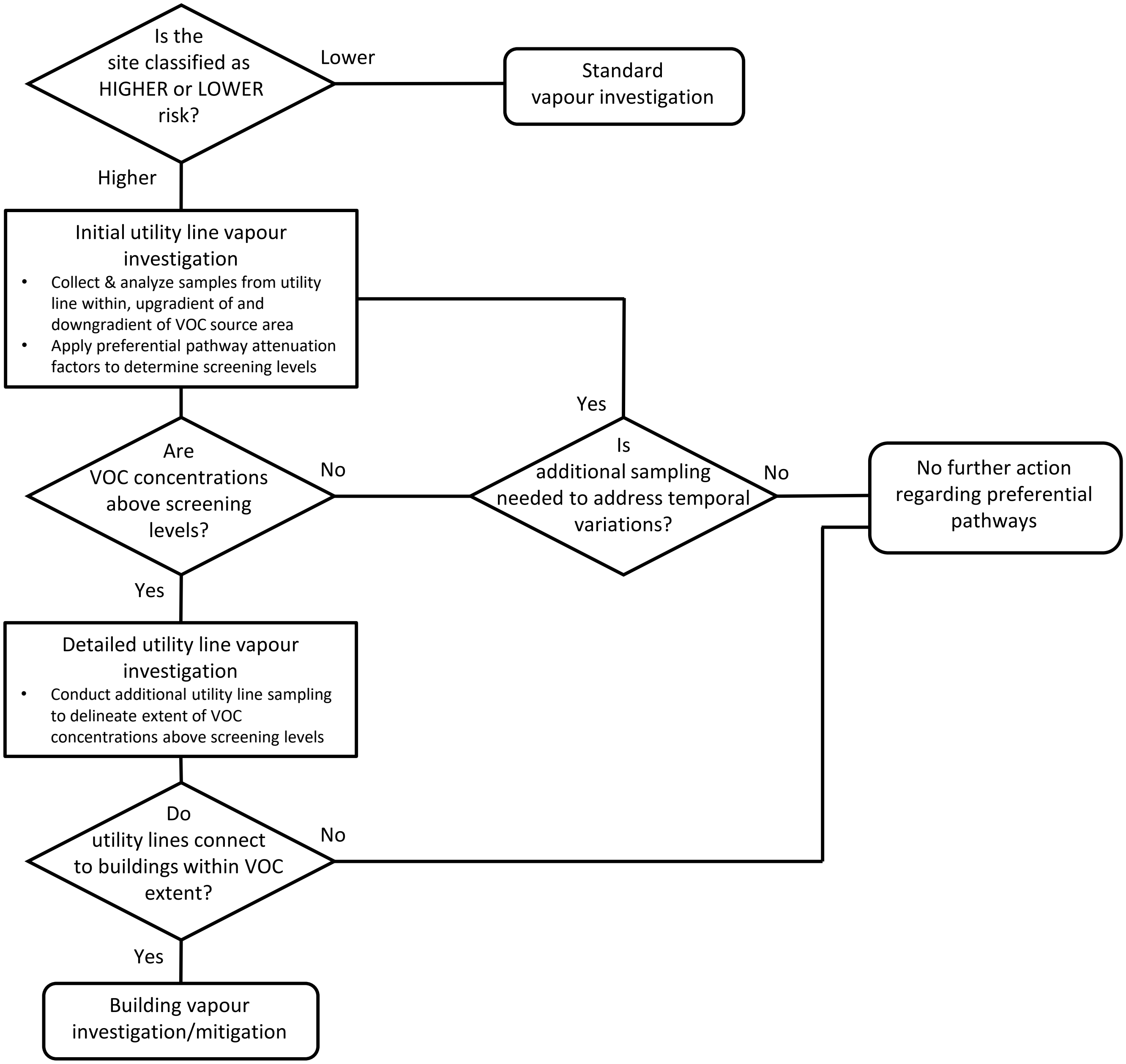

Figure 4 **Preferential Pathway Investigation Flow Chart (modified after ESTCP 2018)**

The "standard" vapour intrusion investigation, applicable at lower risk sites where there is no evidence of a sewer/utility line as preferential pathway, would include source area and vadose zone sampling, together with subslab and indoor air sampling if warranted (*e.g.*, BC ENV Technical Guidance 4; ARIS and Golder 2020). The initial sewer/utility line investigation at higher risk sites, where there is evidence of a potential preferential pathway, would include sewer and/or manhole sampling from access points within or immediately downstream of the area where the sewer interacts with groundwater or NAPL, at appropriate times to assess temporal variability, in addition to the standard vapour intrusion investigation. Subsequent sampling would include delineation of sewer/utility line impacts, both upgradient and downgradient of the source, as well as testing of buildings (ESTCP 2018).

Further recommendations made by ESTCP regarding sampling and the assessment of temporal variations include the following:

- If groundwater elevations vary seasonally, sample during high water levels.
- Sample when the baseline sewer flow is low (typically between 9am-3pm), and not within 48 hours following significant rainfall (>0.25 cm (>0.1 in));
- Minimize venting of manholes;
- Collect grab vapour sample 0.3 m (1 ft) above bottom of pipe or water level;
- Compare initial field tests against conservative screening levels (calculating using a sewer to indoor air attenuation factor and maximum VOC concentration measured in sewer);
- Collect delineation samples from access points both upstream and downstream of the source and delineate to screening levels (aim for two successive points that are below screening levels). Testing of sewer laterals should generally be conducted as part of the building investigation; and
- Existing protocols may be used for building testing; however, it is also recommended that building sewer laterals be tested if the sewer pathway is suspected. P-traps may be sampled if the laterals are inaccessible; in this case sample tubing would need to extend past the liquid barrier.

The use of vapour attenuation factors to determine screening levels, as referenced in Figure 4, is discussed further in the following section.

6.4 Use of Attenuation Factors

BC ENV Protocol 22 specifies that a vapour attenuation factor of 2 x 10^{-2} should be used to estimate indoor air concentrations based on samples obtained within a preferential flow pathway. This factor is equivalent to that applicable to a sub-slab sample or other sample collected at a depth of less than 1 m below the foundation. Protocol 22 also specifies that this value should not be used where there is a preferential pathway through the building foundation or other direct connection between the utility line backfill and the indoor breathing zone; in this case an AF value of 1 x 10^{-1} should be used, equivalent to that for an unlined crawlspace.

Based on monitoring of VOC concentrations and tracer gas testing at a number of sites, ESTCP (2018) recommended a value of 3 x 10^{-2} as a reasonable upper bound AF between sewer air and indoor air. A further upper bound AF of 3 x 10^{-2} was recommended for groundwater (equivalent equilibrium vapour concentration) to sewer air, for an overall upper bound value of 1 x 10^{-3} to be used when calculating screening values for groundwater vapour to sewer air to indoor air.

In summarizing the study data, ESTCP (2018) do not explicitly distinguish between the presence or absence of a direct connection between utility lines and building air. However, the empirical data presented by ESTCP (2018), as well as their recommended AF values for screening, suggest the vapour attenuation factors prescribed in BC's Protocol 22 are conservative, especially where a direct connection between utility lines and building air is not known to exist.

It is noted that, under the existing Protocol 22 and Technical Guidance 4, the prescribed vapour attenuation factors are default values to be used in determining the presence of vapour contamination using two of three prescribed approaches (Approaches A and C). Vapour contamination may also be characterized by direct measurements in the breathing zone (Approach B), and alternative (*i.e.*, site-specific) vapour attenuation factors may be used under detailed risk assessment. These latter approaches represent "refinement" stages of a vapour investigation whereby conservatism in the default values could potentially be reduced under detailed risk assessment. Therefore, it is recommended that the default vapour attenuation factors presented in Protocol 22 for preferential pathways be used for screening purposes to determine the need for more detailed preferential pathway vapour investigation and the potential implementation of detailed risk assessment.

7.0 LATERAL ATTENUATION

Baseline soil vapour investigations typically follow an approach where vertical attenuation factors (VAFs) are applied to assess receptors that are laterally adjacent to the soil vapour measurement point (*i.e.*, the receptor is conservatively assumed to overlie the measurement point). Where the measurement point is near the edge or boundary of a vapour contamination source (where source concentrations are decreasing laterally), the use of VAFs may significantly underestimate the vapour attenuation that occurs in a lateral direction depending on vertical and lateral attenuation distances. For this reason, BC ENV Protocol 22 includes a lateral attenuation adjustment divisor (LAAD) that may be optionally applied to reduce the VAFs if certain site conditions apply. The scope requested by CSAP on this topic was to describe how the LAAD can be applied to improve vapour investigations for different scenarios including where there is urban infrastructure (*e.g.*, utilities, roads, underground parking garages) that can pose challenges for soil vapour investigations. An additional component was to assess the definition of the boundary of the vapour source for potential future modification of protocol and guidance for lateral vapour attenuation.

This section includes best practices and example calculations that are applicable within the current BC regulatory framework that can be adopted by practitioners. In certain areas, recent science has suggested that future review of regulatory guidance and protocols may be beneficial (*e.g.*, with respect to precluding conditions for application of LAAD). Note, under a generic standards approach, vapour investigations must follow applicable BC CSR regulatory standards, existing BC ENV protocols (*e.g.*, Protocol 22) and should follow applicable guidance (*e.g.*, Technical Guidance 4). As part of a detailed risk assessment, recent science could be considered where there is supporting rationale. In these instances, approved professionals or qualified persons should consider seeking concurrence from BC ENV before implementing a detailed risk assessment approach including obtaining a pre-approval under Protocol 6 where warranted.

7.1 Background

BC ENV Technical Guidance 4, in answering how far should one look for vapour contamination, indicates receptors that are more than 30 m laterally away from detectable vapour substance concentrations in soil, sediment, and water have a low potential for vapour intrusion (assuming there are no precluding factors). For substances that aerobically biodegrade, the lateral distance is 10 m.

BC ENV Protocol 22 states that, in certain circumstances where the target breathing zone (*e.g.*, current or future building, outdoor receptor location) is offset laterally from the point at which vapours have been characterized, the VAFs may be adjusted using the LAAD to account for additional attenuation in the lateral direction. LAADs can only be applied if the following conditions are met: 1) site conditions do not preclude the use of the VAFs; 2) the measured or predicted vapour concentration in indoor or outdoor air at the point of measurement is less than or equal to 10 times the vapour standard of the Regulation; 3) the point of application of the LAADs (*i.e.*, the point at which subsurface or subslab vapours have been characterized) must in all cases be beyond the vapour source in soil or groundwater (*i.e.*, at the boundary of detectable concentrations in soil and groundwater); and 4) the contaminant plume must be stable or decreasing in concentration and extent (also see footnotes in Protocol 22).

The development of the LAAD was supported by a review in a report by Golder Associates Ltd. (Golder) entitled "Updated Review of Lateral Vapour Attenuation Factors for Potential Adoption in British Columbia Regulatory Framework", dated February 23, 2017 (Golder 2017).[5] The review addressed the CSM for lateral vapour migration and options for lateral screening distances and lateral attenuation factors for the vapour intrusion pathway. The following methodology was proposed for calculating lateral attenuation factors:

Lateral attenuation factor = TG4 attenuation factor (vertical distance) / Reduction Factor

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[5] https://www2.gov.bc.ca/assets/gov/environment/air-land-water/site-remediation/docs/policies-and-standards/golder_memo_to_csap_on_laaf_p22.pdf

Reduction Factor = TG4 attenuation factor (vertical distance) / TG4 attenuation factor (lateral offset distance).[6]

The Reduction Factor, which is equal to the LAAD, only applies when the lateral offset distance > vertical distance. The Protocol 22 LAAD generally followed concepts presented in the review except that Golder (2017) additionally provided an option to define the vapour source based on soil and groundwater concentrations estimated from partitioning relationships and back-calculated soil vapour criteria as described below.

7.2 Conceptual Site Model

The conceptual site model is that diffusive transport of vapours in the unsaturated soil zone readily occurs in all directions unless there is significant vertical anisotropy from, for example, interlayered fine-grained and coarse-grained soil deposits with large soil permeability and moisture contrasts. While conceptually a surface capping effect could contribute to enhanced lateral migration of vapours practically there is expected to be limited effect from typical hard surfaces, which are porous and allow gas transport. Consequently, large differences in the attenuation of vapours in lateral and vertical directions are not expected at most sites. For this reason, particularly when there is a shallow vapour contamination source, there will be rapid attenuation of vapour concentrations in the lateral direction beyond the vapour source extent. The modeling studies reviewed in Golder (2017) predict a rapid decline in vapour concentration or mass flux as the lateral distance from a vapour source increases. The decline in concentration or flux can be several orders of magnitude over relatively short distances (*e.g.*, Lowell and Eklund 2004).

7.3 Rationale for LAAD

The LAAD is intended to support more efficient vapour investigations when there are relatively low vapour concentrations that are within 10X the applicable CSR standard and particularly when there are site access restrictions that prevent further lateral delineation (but not exclusively so). Types of site scenarios where it may be advantageous to apply a LAAD include:

- On site receptor (building) laterally removed from a contamination source (where future use that could invalidate a LAAD is not applicable)
- Vapour contamination at or near a site boundary where off-site constraints such as a roadway or utilities preclude additional investigation closer to an off-site receptor (*e.g.*, land-use across the roadway) or where access to a neighbouring parcel is denied.

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[6] Note the Golder report referred to TG4 attenuation factors because at the time report was written attenuation factors were provided in TG4.

- Other constraints that could preclude vapour investigation such as a building with a basement (*e.g.,* underground parking garage, where obtaining a representative depth vapour sample is precluded) or subsurface utilities.

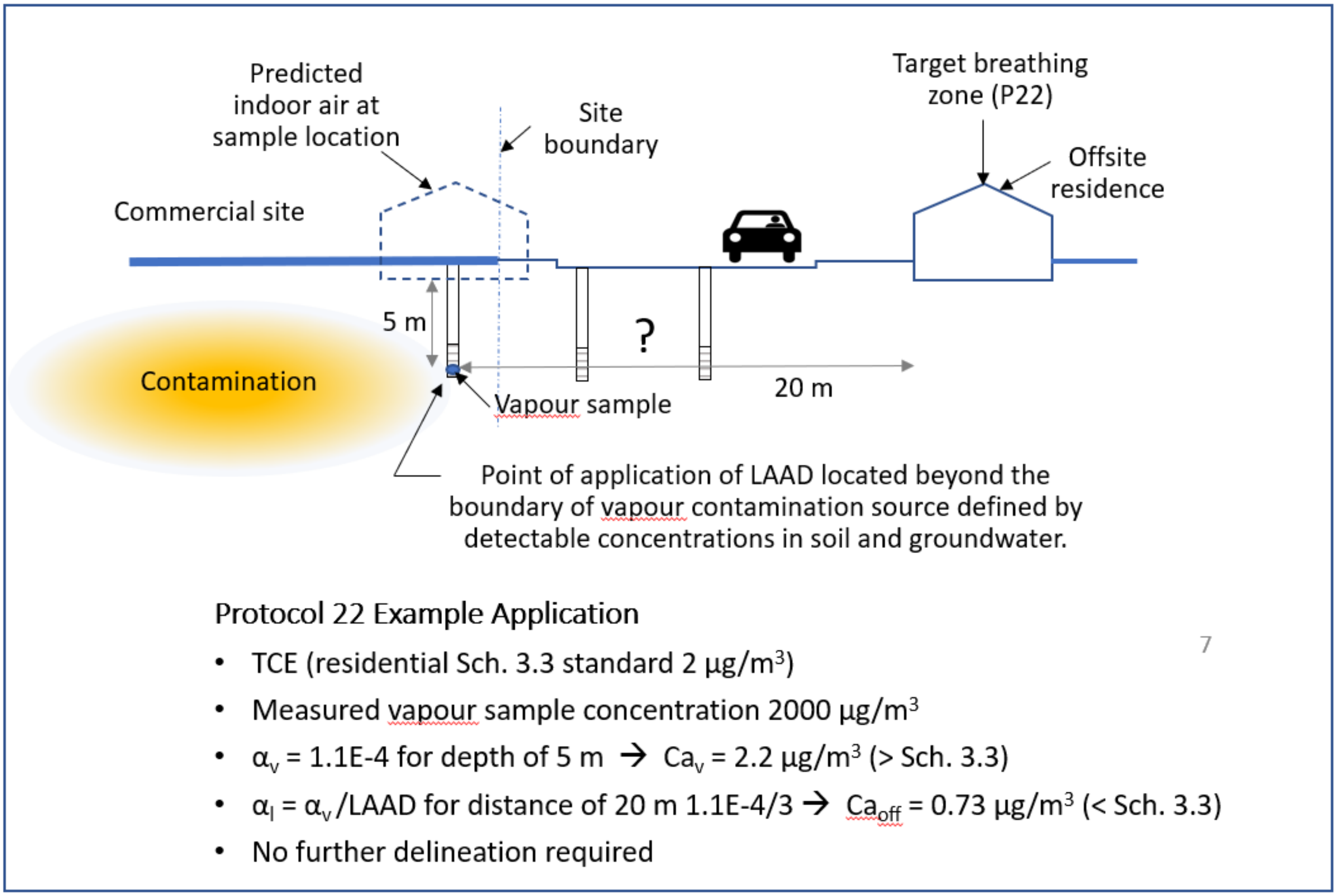
7.4 Considerations for Application of LAAD

Examples calculations for application of the LAAD are described for Protocol 22 and Golder (2017) below.

7.4.1 Protocol 22

The CSM for application of the LAAD in Protocol 22 assumes the point of application of the LAAD is located beyond the boundary of the vapour contamination source as defined by detectable concentrations in soil and groundwater. The attenuated vapour concentration (using the VAF) at the measurement point may be up to 10X the applicable standard calculated assuming the receptor overlies the measurement point. The groundwater plumes should be stable as demonstrated following BC ENV Technical Guidance 8 and the vapour contamination source and plume must also be stable. An example application of the LAAD is shown in Figure 7.1. As shown, the target breathing zone is an off-site residence. The presence of the roadway and utilities practically precludes soil vapour delineation. Because soil vapour TCE concentrations are within 10X the CSR vapour standard based on VAF, a LAAD equal to three may be applied, which results in a predicted vapour concentration that meets the CSR vapour standard at the target breathing zone. The point of application of the LAAD is beyond the boundary of the vapour source defined by non-detect concentrations in soil and groundwater.

The Protocol 22 requirement for non-detect concentrations for application of the LAAD is evaluated by estimating the soil vapour concentrations of benzene based on typical reporting limits in soil (0.005 mg/kg) and groundwater (0.5 ug/L) and conservatively assuming an equilibrium partitioning model (Protocol 22 Table 1). When the soil vapour concentrations are multiplied by an VAF of 2.8E-03 for residential (RL) land use and 1 m distance between receptor and soil vapour measurement point (this the maximum VAF under which a LAAD could apply at a site), the predicted indoor air concentrations of benzene are 3.7 ug/m^3 from soil and 0.2 ug/m^3 from groundwater (Table 7.1). This compares to CSR RL and commercial (CL) land use vapour standards of 1.5 ug/m^3 and 4.0 ug/m^3, respectively. Compared to benzene, which has relatively low CSR vapour standards, most substances will have predicted indoor air concentrations that are less than the vapour standards. The implication is that the Protocol 22 requirement for non-detect soil and groundwater concentrations will result in the LAAD having limited application at sites because in most cases there would be an absence of vapour contamination based on VAFs at the point of application.



Protocol 22 Example Application

- TCE (residential Sch. 3.3 standard 2 µg/m^3)
- Measured vapour sample concentration 2000 µg/m^3
- α_v = 1.1E-4 for depth of 5 m → Ca_v = 2.2 µg/m^3 (> Sch. 3.3)
- $\alpha_l = \alpha_v$/LAAD for distance of 20 m 1.1E-4/3 → Ca_{off} = 0.73 µg/m^3 (< Sch. 3.3)
- No further delineation required

Figure 7.1 Example Application of the LAAD According to BC ENV *Protocol 22*

Table 7.1 Example Calculations of Partitioning Calculations for Source Vapour Boundary Based on *Protocol* 22 and Golder (2017) Definitions

BC Protocol 22 Example Calculation					
Prediction of Indoor Air Concentration at Soil Vapour Source Boundary using Typical Soil Detection Limit			**Prediction of Groundwater Concentration at Soil Vapour Source Boundary using Typical Groundwater Detection Limit**		
Soil concentration at DL	mg/kg	0.005	Groundwater concentration at DL	ug/L	0.5
Predicted soil vapour concentration	ug/m^3	1.32E+03	Predicted soil vapour concentration	ug/m^3	7.14E+01
VAF	-	2.80E-03	VAF	-	2.80E-03
Predicted indoor air concentration	ug/m^3	3.7	Predicted indoor air concentration	ug/m^3	0.2
Golder (2017)					
Back-calculation of Soil Criterion for Soil Vapour Source			**Back-calculation of Groundwater Criterion for Soil Vapour Source**		
Acceptable indoor air concentration	ug/m3	1.5	Acceptable indoor air concentration	ug/m3	1.5
VAF (100X adjustment)		2.80E-05	VAF (10X adjustment)		2.80E-04
Back-calculated soil vapour criterion	ug/m3	5.36E+04	Back-calculated soil vapour criterion	ug/m3	5.36E+03
Back-calculated soil criterion	mg/kg	2.00E-01	Back-calculated groundwater criterion	ug/L	3.80E+01
Notes: Fixed parameters are:					
Chemical	-	Benzene	Fraction organic carbon	-	0.005
Soil temperature	oC	15	Water-filled porosity	-	0.055
Dimensionless Henry's law constant	-	0.14	Total porosity	-	0.375
Assumed soil type	-	Sand	CSR RL vapour standard	ug/m^3	1.5

7.4.2 Golder (2017)

The CSM for application of a LAAD in Golder (2017) assumes the soil vapour measurement point is near to but within the boundary of the vapour contamination source, the vapour contamination source is stable and source concentrations are laterally decreasing in the direction of application of the LAAD. As shown in Table 7.1, the maximum allowable vapour source is defined by partitioning relationships and soil vapour criteria back-calculated from the VAF and CSR vapour standard based on a 10X reduction of the VAF for groundwater (consistent with soil vapour) and a 100X reduction for soil (added 10X to account for conservatism in soil partitioning relationships, see Golder 2017).

Building on the example in Figure 7.1, for the soil calculation, an adjusted benzene soil vapour criterion of 53,600 ug/m^3 is calculated based on RL land use and VAF of 2.8E-03 reduced by 100X, which corresponds to a soil criterion of 0.20 mg/kg based on an equilibrium partitioning model (Table 7.1). For the groundwater calculation, an adjusted benzene soil vapour criterion of 5,360 ug/m^3 is calculated based on VAF reduced by 10X, which corresponds to a groundwater criterion of 38 ug/L based on an equilibrium partitioning model. The Golder (2017) approach may not be applied under Protocol 22.

7.5 Possible Risk-based Approach for Application of LAAD

The Protocol 22 implementation of the LAAD may be overly conservative because of the prohibition for application when there are detectable soil and groundwater concentrations. It is acknowledged that this condition reduces the uncertainty in the definition of the vapour contamination source. Currently, requirements of Protocol 22 must be followed for generic application of VAF and LAAD.

Soil vapour investigations should typically begin in inferred source areas based on soil and groundwater chemistry data. As the LAAD will typically provide minimal relief, soil vapour contamination should be delineated in the lateral direction through step-out soil gas probe locations, which may require probes close to a site boundary and potentially offsite.

The Golder (2017) approach for defining the soil vapour contamination source provides greater flexibility for implementation of the LAAD but is generally not recommended as the basis for a risk-based standards approach. This is primarily because the Golder (2017) check using soil and groundwater concentration data could be non-conservative if there is close to equilibrium partitioning between soil, groundwater and soil vapour (*i.e.,* within 10X of equilibrium concentration for groundwater partitioning and 100X for soil partitioning).

To address the above concerns, it is recommended that risk-based approaches consider appropriate methods for defining acceptable soil and groundwater concentrations at the soil vapour source boundary that increase flexibility for use of LAAD while being protective. Such approaches could consider the following:

1. Back-calculation of soil and groundwater criteria using equilibrium partitioning relationships and soil vapour criteria with conservative partitioning adjustments, *e.g.,* 10X for soil partitioning and no adjustment for groundwater.
2. Site characterization data indicate soil, groundwater and/or soil vapour concentrations are decreasing or attenuating in the direction of application of the LAAD.

A combination of these two approaches based on partitioning and attenuation will enable greater flexibility in application of the LAAD while providing for a conservative approach where the LAAD is only applied where additional lateral concentration attenuation will occur. Each requirement is discussed below.

7.5.1 Soil and groundwater criteria for Determining Soil Vapour Contamination Source Boundary

The soil vapour criteria are back-calculated from the applicable CSR Sch 3.3 vapour standard and the applicable VAF assuming the target breathing zone is translated to over the point of application. A soil vapour criterion is separately calculated for soil and groundwater as follows:

$$C_{v\text{-}s} = C_{av} \times PAF_s / \alpha_v \qquad \text{Eq. 1}$$

$$C_{v\text{-}g} = C_{av} \times PAF_g / \alpha_v \qquad \text{Eq. 2}$$

Where

Cv-s = soil vapour criteria for definition of soil concentration source boundary

Cv-g = soil vapour criteria for definition of groundwater concentration source boundary

Cav = Sch 3.3 vapour standard

αv = vertical attenuation factor (Table 1 in Protocol 22)

PAFs = partitioning adjustment factor for soil = 10

PAFg = partitioning adjustment factor for groundwater = 1

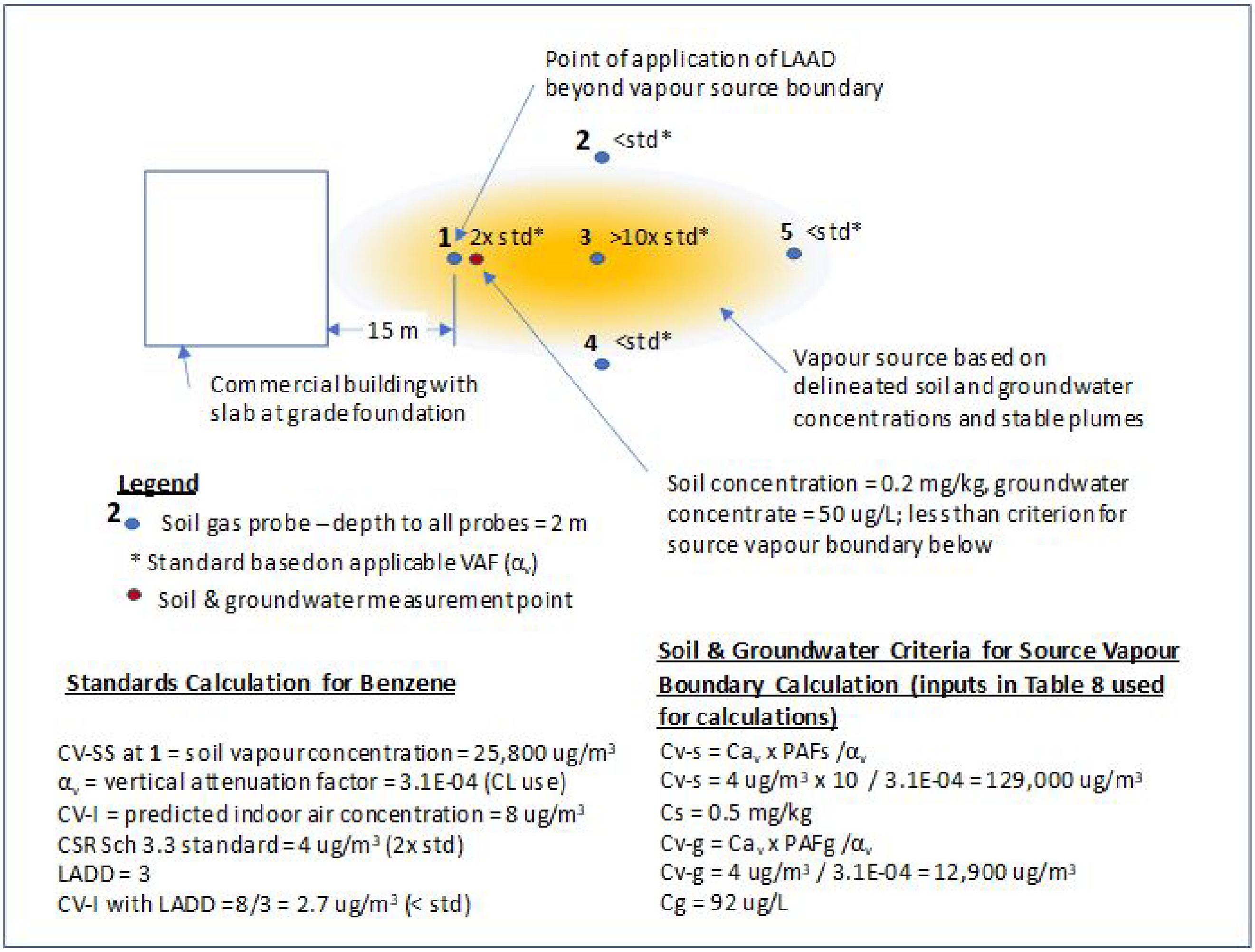
The soil and groundwater criteria are, in turn, calculated from the soil vapour criteria using partitioning relationships. The rationale for the PAFs = 10 for soil partitioning is that comparisons between co-located soil and soil vapour concentration data indicate equilibrium partitioning relationships for prediction of soil vapour concentrations from soil concentrations are often highly conservative (Golder 2017). The requirement for predicted indoor or outdoor air concentrations being less than 10X the applicable CSR vapour standard based on VAF and the soil vapour concentrations at the point of application remains. This approach could also be applied using measured soil and groundwater data and estimates of soil vapour concentrations using partitioning relationships (Method B in BC Technical Guidance 4).

7.5.2 Demonstration of Lateral Concentration Attenuation

Site investigations require characterization of source zones (*e.g.*, NAPL) and groundwater plumes. For application of the LAAD, NAPL source zones and groundwater and soil vapour plumes should be stable. Additionally, there should generally be data available to assess the attenuation of soil, groundwater, and soil vapour concentrations in the direction of intended application of the LAAD. Different media concentrations indicating concentration attenuation increases the confidence in this approach. Where warranted, quantitative methods can be used to statistically evaluate attenuation trends, for example, tools described in CSAP Remediation Toolkit 2 (link).

7.6 Example Scenario for Implementation of LAAD

An example scenario is provided for implementation of LAAD using one possible risk-based method for definition of the vapour contamination source boundary (Figure 6). The example shown is for an onsite receptor (building) but the concept is similar for potential off-site contamination. The LAAD is intended to enable vapour delineation when there are site access restrictions that would prevent further lateral investigation, but access restrictions are not a requirement for its use. When applying the VAF only to the probe located closest to the building, the predicted indoor air concentration exceeds CSR Sch 3.3 standard. When the LAAD is applied, the predicted concentration is less than the standard and no further delineation is required. The point of application of the LAAD is beyond the boundary of the vapour contamination source defined by soil and groundwater concentrations that are less than the soil and groundwater criteria calculated from partitioning relationships and soil vapour criteria calculated using Equations 1 and 2. Under risk-based approaches, adoption of the LAAD in Protocol 22 may be appropriate. There are also other models for estimation of lateral concentration attenuation (*e.g.,* see Lowell and Eklund 2004 and other references in Golder 2017) that generally predict significantly greater lateral attenuation than the Protocol 22 LAAD. Models used should be appropriately supported by the CSM and site-specific data.



Standards Calculation for Benzene

CV-SS at **1** = soil vapour concentration = 25,800 ug/m^3
α_v = vertical attenuation factor = 3.1E-04 (CL use)
CV-I = predicted indoor air concentration = 8 ug/m^3
CSR Sch 3.3 standard = 4 ug/m^3 (2x std)
LADD = 3
CV-I with LADD = 8/3 = 2.7 ug/m^3 (< std)

Soil & Groundwater Criteria for Source Vapour Boundary Calculation (inputs in Table 8 used for calculations)

Cv-s = Ca$_v$ x PAFs /α_v
Cv-s = 4 ug/m^3 x 10 / 3.1E-04 = 129,000 ug/m^3
Cs = 0.5 mg/kg
Cv-g = Ca$_v$ x PAFg /α_v
Cv-g = 4 ug/m^3 / 3.1E-04 = 12,900 ug/m^3
Cg = 92 ug/L

Figure 6 Example Application of LAAD including Proposed Vapour Source Boundary Calculation

7.7 Summary

The Protocol 22 LAAD is intended to support more efficient vapour investigations when receptors (target breathing zone) are laterally offset from point of application of the vapour standards (*e.g.*, soil vapour measurement point). The implementation of a LAAD requires that the extent of the vapour contamination source (volatile substances) in soil and groundwater be characterized. The source of vapours, whether NAPL or a groundwater plume, and the soil vapour plume should be stable or shrinking (Aris and Golder 2020). Under Protocol 22, the point of application for the LAAD must be beyond the vapour source in soil or groundwater defined as soil and groundwater concentrations must be below the detection limits.

Under a risk assessment approach, consideration may be given to defining acceptable soil and groundwater concentrations using partitioning relationships based on acceptable soil vapour concentrations and requirements for lateral concentration attenuation. Implementation of a risk assessment approach may require pre-approval under Protocol 6 for legal instrument application and supporting rationale for use of risk-based models.

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APPENDIX A: TABLES

Table A1 Soil Gas Sampling Sources of Information

		BC ENV 2020a	CCME 2016	ITRC 2014	CA DTSC 2015	Other technical literature
1. Active Soil Gas Sampling						
a.	Drilling methods for probe installation	N	Y	Y	Y	
b.	Probe and sampling train design and materials	Y	Y	Y	Y	Hayes *et. al.* (2006) Caro (2009) Schumacher *et al.* (2009)
c.	Shallow probe pre-cautions	Y	N	Y	Y	CSAP (2009)
d.	Probe equilibration	Y	Y	Y	Y	DiGuilio *et. al.* (2006) Haar & Jones (2017) Green (2017)
e.	Flow and vacuum check	Y	Y	N	N	McAlary & Cramer (2006)
f.	Leak testing of probe and sampling train	Y	Y	Y	Y	Hawai'i DOH (2017) US EPA (2018)
g.	Probe purging and sampling	Y	Y	Y	Y	McAlary & Cramer (2006) DiGuilio (2007) Tetra Tech (2010) Jewell and Wilson (2011) Sweeney and Ririe (2017) US EPA (2018)
2. Active Soil Gas / Air Testing						
a.	Field detectors	Y	Y	Y	Y	Jewell and Wilson (2011)
b.	Soil gas / air analytical methods	Y	Y	Y	Y	
c.	Soil gas / air QA/QC	Y	Y	Y	Y	
3.	**Passive soil gas samplers**	Y	Y	Y	Y	SERDP/ESTCP (2014) McAlary *et. al.* (2014 a, b) ASTM D7758-17 (2017)

Note: The following guidance also cover most of the above topics: Aris and Golder (2020), NJDEP (2018), ASTM D7663-12 (2018), Hawaii DOH (2017), and CCME (2008).

Example schematics of a soil gas probe (Figure A-1), helium leak tracer testing and field sample collection (Figure A-2), canister sampling (Figure A-3) and sorbent tube sampling (Figure A-4) are provided below. Typical sampling devices, gauges and pumps are shown. The use of a vacuum chamber is a common method of collecting a gasbag sample without drawing the soil gas through the pump. The vacuum chamber principle is that the bag fills with soil gas when a slightly higher vacuum is created in the chamber than the sampling line. When there are low permeability soils, a stronger pump may be needed to create a vacuum, as common air sampling pumps often turn off when vacuum is too high. The flow rate measured during sampling with the air flow meter can be compared to the flow rate estimated from the approximate volume of soil gas in the bag and time to fill the bag. There may be inaccuracies in the flow rate measured by the air flow meter if there is a slight leak in the vacuum chamber. To the extent possible, air-tight swag-loc fittings or barbed connectors should be used for connections in the sampling train.

The helium leak tracer test procedure shown is commonly used in field soil gas sampling to verify absence of leakage (i.e., prior to collecting a canister sample). A shut-in vacuum test is commonly used to test the sampling train immediately prior to canister sampling. An acceptable alternative may be to collect the canister sample within the helium-filled shroud. This method requires that the laboratory test the sample for helium. Prior arrangements should be made with the laboratory to conduct helium testing. A disadvantage of this method is that the results are not available until laboratory test data is reported. A less common leak tracer test method is use of iso-propanol. Typically, iso-propanol is added to small pieces of clean cloth that are wrapped around fittings. Care must be exercised so as not to cause cross-contamination from use and handling of iso-propanol. Prior arrangements should be made with the laboratory to conduct iso-propanol testing and confirm there will be no interference in the analysis from iso-propanol use.

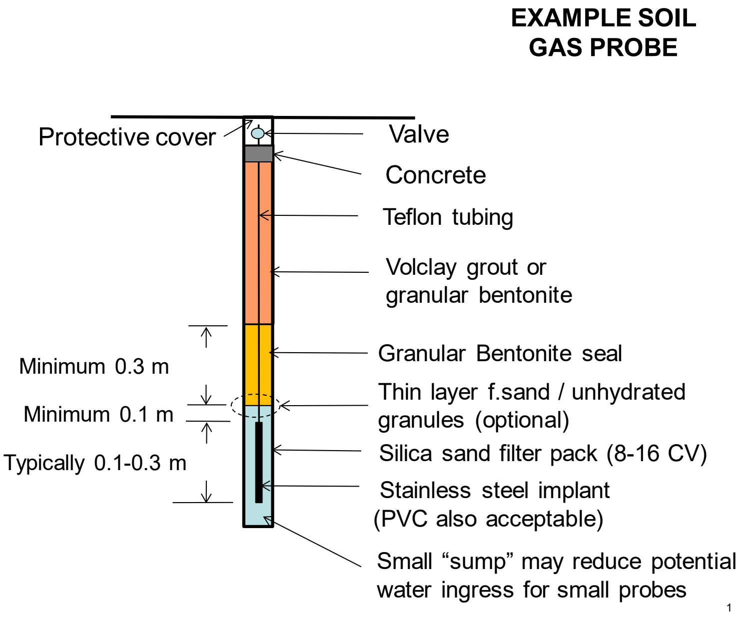


Figure A-1 Example Soil Gas Probe

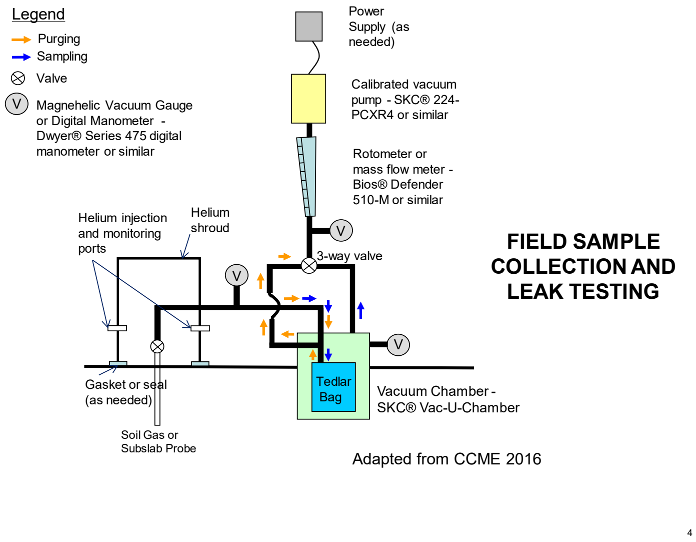
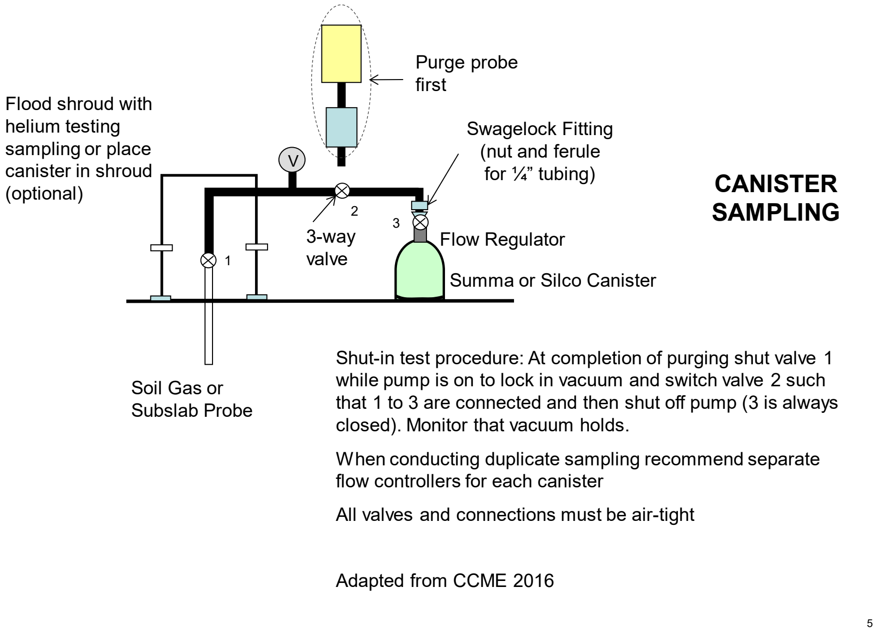


Figure A-2 Schematic of Field Sample Collection and Leak Tracer Testing



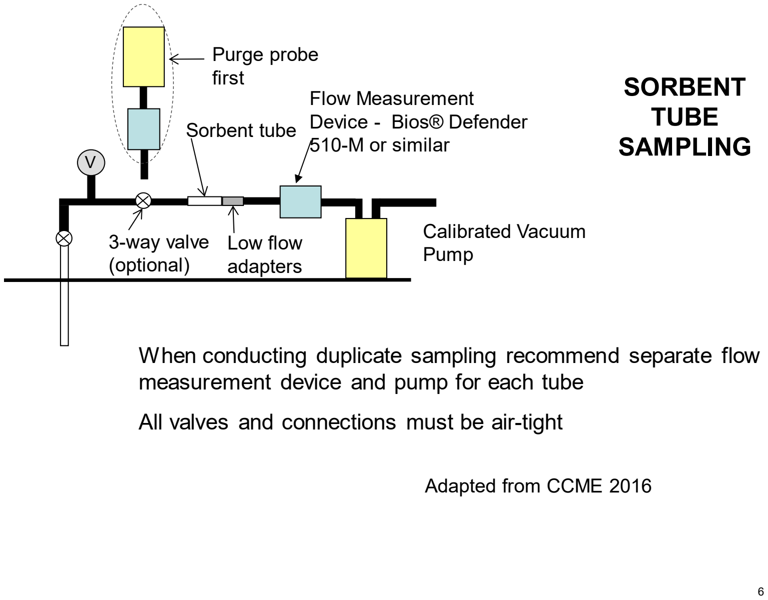
Shut-in test procedure: At completion of purging shut valve 1 while pump is on to lock in vacuum and switch valve 2 such that 1 to 3 are connected and then shut off pump (3 is always closed). Monitor that vacuum holds.

When conducting duplicate sampling recommend separate flow controllers for each canister

All valves and connections must be air-tight

Adapted from CCME 2016

Figure A-3 Schematic of Canister Sampling



When conducting duplicate sampling recommend separate flow measurement device and pump for each tube

All valves and connections must be air-tight

Adapted from CCME 2016

Figure A-4 Schematic of Sorbent Tube Sampling

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
		1. Active soil gas sampling
a.	**Drilling methods for probe installation**	
	BC ENV 2020a	Limited discussion; drilling method may be dictated by depth of vapour probe
	CCME 2016	Multiple methods exist: -Probes installed in boreholes using conventional drilling techniques (*i.e.*, rotary drill rig) - Probes installed in boreholes using direct push techniques - Probes driven into subsurface by hand, electric rotary hammer or direct push rig Drilling methods that create smaller boreholes with least amount of disturbance are preferred Advantage of probes installed in drilled boreholes or direct push is that a filter pack and seal may be constructed, and soil stratigraphy may be inspected prior to probe installation Driven probes have potential cost and access advantages, but screens tend to clog in fine-grained soil, and may fracture the soil. Driven probes are not recommended in fine-grained soils Rotary sonic methods are acceptable but use of air or water should be avoided. Air rotary or hydro-vac methods should not be used unless there are no alternatives Consider possible generation of trihalomethanes when using water
	ITRC 2014	Driven probe rods can be advanced by hand methods, direct-push systems, or with larger drill rigs using a wire-line hammer Soil gas sampling tubing may be buried in holes created with hand-driven rods, direct-push systems, hand augers, drills (for sub foundation samples) or drill rigs for deeper samples Soil gas samples can be collected from groundwater wells that are screened across the water table and retrofitted with an air-tight cap and valve
	CA DTSC 2015	Multiple methods exist including direct push, hollow stem or hand auger Drilling methods which significantly disrupt soil gas equilibrium (air rotary, rotosonic) may be used if longer equilibration times are used prior to sampling Mud rotary drilling is not acceptable
	Other	N/A

Table A2 Soil Gas Sampling and Analysis Review

	Topic	Summary
b.	**Probe and sampling train design and materials**	
	BC ENV 2020a	Both temporary or permanent probes are acceptable Drilling of boreholes for installation of permanent probes can result in significant disturbance Filter pack should extend 0.15 m above and below probe Dry bentonite should be placed above filter pack to avoid infiltration of water or bentonite slurry from above into filter pack Surface seal of subslab probes can consist of sculpting clay, swelling (“hydrating”) concrete, bentonite, wax, Teflon tape and VOC-free epoxy Probe materials should be composed of stainless-steel (*e.g.*, solid, braided, wire) or rigid PVC pipe (with threads wrapped with Teflon) Caro (2009) study on probe materials indicated Teflon and Nylon are “good” materials; LDPE, silicon and Tygon should be avoided. Rigid PVC is acceptable but should avoid scratching PVC as this will emit VOCs Avoid use of Teflon when sampling soil gas for PFAS compounds (per- and polyfluoroalkyl substances)
	CCME 2016	Temporary or permanent probes are acceptable Probe and sampling train should be constructed of inert and non-porous materials Stainless steel, Teflon and PVC are acceptable materials, except avoid use of Teflon when sampling soil gas for PFAS compounds Nyaflow (nylon) tubing is acceptable for most volatile chemicals, with exception of naphthalene and similar compounds Do not use construction materials (glues, tapes) that could emit volatiles Preference for new materials, except when using temporary steel probes **External Soil Gas Probes** Commonly are continuous rigid PVC to ground (with short slotted section) or stainless steel mesh screens (implants) attached to flexible tubing to ground Probe diameter of 25 mm (1 inch) or smaller should be used to minimize purge volumes/reduce potential for short-circuiting Short screens (0.1 to 0.3 m long) should generally be used unless there are thick vadose zones (*i.e.*, >10 m) For rigid PVC pipe probes, 19 mm (3/4 inch) diameter pipe is recommended, screens may consist of No. 10 to No. 40 slot pipe For probes constructed of implants, a common diameter is 12.5 mm (1/2 inch), with length of 0.1 to 0.3 m. Typically, 6 mm (1/4 inch) diameter tubing is used to connect the implant to the ground surface Couplings should be air-tight compression fittings, barbed fittings or threaded fittings. Slip fittings should not be used. Probes should be completed with an air-tight cap (for PVC pipe) and valve at surface

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	CCME 2016	Step-by-step instructions for installation of external soil gas probes into a borehole, through direct push technology or driven probes are provided **Subslab Soil Gas Probes** Common installations are probes installed in a sealed drilled hole or core hole in the slab (permanent) or an expanding plug-type probe (typically temporary) Consist of inert materials such as steel or brass tubes and Teflon fittings When not in use the probe is sealed with a recessed threaded cap For sampling, the threaded cap is replaced with a fitting with threads on one end and ¼-inch compression or barbed fitting on the other end Expanding plug-type probes should be installed in a properly size drilled hole with smooth walls Concrete grout should consist of cement, aggregate and water, and should not contain any additives that could contain volatiles A bentonite seal or other non-VOC containing products such as polyethylene glue or bees-wax should be placed around the temporary probe A bentonite seal may also be placed around a permanent probe when sampling as an additional protective measure Step-by-step instructions for installation of subslab soil gas probes are provided
	ITRC 2014	Driven probe rods are typically constructed of hollow steel rods with an external diameter ranging between 12.5 mm and 50 mm (0.5 inches and 2 inches). Soil gas sampling tubes typically constructed of an inert tube or pipe (stainless steel, Teflon, polyvinyl chloride, high density polyethylene, polyether ether ketone, Nylaflow, or similar), except avoid use of Teflon when sampling for PFAS compounds Subslab probe is typically constructed from small diameter (⅛ inch or ¼ inch outer diameter) stainless steel or another inert material and stainless-steel compression fittings. Probes are cut at a length to either float in the slab or to extend to the base of the slab. Clean sand is used as backfill around the tip, and the remainder of the borehole annulus is sealed, usually with a bentonite and water slurry Use tubing material that does not adsorb or off-gas volatile hydrocarbons. USEPA-ORD (Schumacher *et. al.* 2009) show that nylon, Teflon, and stainless steel all give comparable results for typical PHCs. Polyethylene tubing should not be used for soil vapor samples Stainless steel, aluminum, ceramic, or plastic (choice depends upon project specifications) probe tips are recommended Swagelok fittings or plastic valves (two-way plastic valves or stop cocks) are best for sealing tubing that will remain in the ground for an extended time Options for surface termination include flush mounts on the floor/surface, below ground termination (with or without a locking cover), and various aboveground completions that are commercially available. The most common surface sealing technique is to grout the surface contact of the probe

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	CA DTSC 2015	Filter sand pack should extend 0.15 m above and below probe At least 0.15 m of dry granular bentonite should be placed on top of filter sand pack, then an appropriate sealing material to surface For temporary soil gas wells (<1 year) the annular seal can be hydrated bentonite, or other materials as appropriate. Annular bentonite seals are discouraged for long term wells due to potential for desiccation. For permanent soil gas wells (>1 year) the annular seal can be neat cement with 1-5% bentonite The use of a down-hole probe support rod is recommended for boreholes deeper than 4.5 m Small diameter non-reactive tubing (1/8 to ¼ in diameter) tubing is typically used for probe construction; larger diameter tubing maybe be necessary when soil moisture is high and/or finer-grained materials are present Metal tubes should be used to collect hydrogen sulfide samples Nylaflow, polyetherketone (PEEK) and Teflon are recommended for soil vapour, except when sampling soil vapour for PFAS compounds Low density polyethylene should not be used
	Other	Hayes *et. al.* (2006) report on a study of sorption of different tubing where the recovery for naphthalene was 87% for Teflon and 31% for Nylaflow
c.	**Shallow probe pre-cautions**	
	BC ENV 2020a	Recommend that CSAP (2009) guidance be followed Recommended minimum sample depth is 0.45 m below ground surface Place a surface seal such as an inert plastic sheet of dimensions 1.5 m by 1.5 m for samples collected within 1 m of ground surface. The surface seal should be installed 24 hours prior to purging and sampling
	CCME 2016	N/A
	ITRC 2014	When a high volume of soil gas is purged there is greater potential for atmospheric air to be drawn into the probe, especially when sampling at shallow depths (< 1 m). If soil gas data from depths <1 m are collected, additional sampling events may be appropriate to ensure representative values due to potential for greater temporal variability.
	CA DTSC 2015	Where screens and associated sand packs are <1.5 m below surface grade, sample collection containers should be less than or equal to 1 L to avoid potential for atmospheric air to be drawn into probe
	Other	N/A
d.	**Probe equilibrium**	
	BC ENV 2020a	Direct push: 2 hours to 2 days depending on depth that rod is pushed into undisturbed soil and whether installed in day-lighted pre-hole Auger: 2 days Rotosonic or air rotary: conduct time-series testing of CO_2 and O_2 to assess when concentrations stabilize Subslab: 2 hours

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	CCME 2016	A minimum three probe volumes of air (consisting of probe volume, tubing volume and air-filled pore volume of sand pack) should be removed during development Time required for equilibration is dependent on disturbance caused during installation Driven probes: 20 minutes Probes installed in small diameter boreholes (< 50 mm), no fluids (air or water) used for drilling: 1 day Probes installed in larger diameter boreholes (> 50 mm), no fluids (air or water) used for drilling: 2 days Probes installed in hydro-vac hole (not recommended, but potentially no alternative): 1 week Probes installed in borehole where fluids (air or water) used for drilling (not recommended): Conduct field screening over several weeks until concentrations stabilize
	ITRC 2014	Based on a US EPA study (Tetra Tech EM 2010) recommend: • Sampling through probe rod installed by hand: 15 minutes • Sampling through probe rod installed with direct-push methods: 30 minutes • Sampling through probes where tubing is buried in a sand pack in the ground: 8 hours
	CA DTSC 2015	Subslab: 2 hours Direct push: 2 hours, up to 2 days in finer-grained material Hollow stem or hand auger: 2 days Combination of hand auger drilling or hollow stem and direct push: 2 hours provided at least 1.5 m of the borehole was drilled using direct push, and the well screen is located in the portion that was direct pushed. If above the 1.5 m interval then 2 days. Rotosonic or air rotary: once equilibrium has been empirically demonstrated; may vary from few days to a few weeks
	Other	Haar and Jones (2017) reporting on results of study where different equilibration times were evaluated conclude there was no evidence for significant differences in soil gas concentrations after 48 hours (soil gas probed are inferred to have been installed in direct push hole) Green (2017) reporting on results of study where different equilibration times were evaluated suggest that for samples obtained using Geoprobe PRT system (temporary driven probe) 30 minutes is a sufficient equilibration time To assess how long it would take for a sand pack to equilibrate with surrounding soil gas, DiGuilio *et. al.* (2006) used a model to estimate equilibration times for different distances and soil water contents. For a 50 mm diameter borehole, the equilibration time for the sand pack ranged from a few minutes to a few hours
e.	**Flow and vacuum check**	
	BC ENV 2020a	Flow and vacuum should be measured at each probe during each sampling event Flow test conducted to ensure adequate soil gas flow is achievable (probe is not constricted) Induced vacuum should not exceed 10 in H_20 (ASTM D7663), higher vacuum can bias concentrations high because of contaminant desorption

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	CCME 2016	Flow and vacuum (probe performance) check conducted to verify that an acceptable gas flow rate and vacuum can be achieved and the calculated air-soil permeability is consistent with geologic materials in which probe screen is completed If the vacuum exceeds 10 in H_20, a lower flow rate should be used, where practical (note it is acceptable to obtain samples at higher vacuums)
	ITRC 2014	N/A
	CA DTSC 2015	N/A
	Other	N/A
f.	**Probe and sampling train leak tests**	
	BC ENV 2020a	Leakage test should be performed using tracer gas to determine if the sample apparatus has leaks and whether there is leakage around the probe. If tracer gas concentration in sample < 10% of the concentration in the shroud, sampling system integrity is acceptable. If the concentration > 10%, seals, connections and fittings should be checked, and the leak test re-run. Shut-in vacuum test can also be used as a leak test. Apply 100 in H_2O vacuum to sampling train with the valve to the sampling probe closed and the sampling vessel attached but with its valve closed; effectively isolating the sampling train between the probe and sampling vessel. The applied vacuum should be observed for at least 1 minute and preferably for 5 minutes. The vacuum loss should be equal to or less than 5% of the applied vacuum for an acceptable test. If the test fails all fittings/connections should be checked, tightened (replaced if necessary) and the shut-in test repeated (ASTM D7663, 2012).
	CCME 2016	Leak test should be conducted at each new soil vapour probe installed and repeated if there are indications that the probe or surface seal has been disturbed Most common leak test method uses helium introduced in a shroud placed above the probe, which measures potential annular and valve leakage. Leakage is calculated as the ratio of helium concentration in soil gas sample to shroud multiplied by 100% If leakage identified during a leak test > 2%, fix or replace probe or sampling train and re-check leakage Conduct shut-in vacuum tests twice daily by creating at least 10 in H_20 column vacuum in sampling train. Close valves at probe and pump and monitor vacuum over time. There should be no more than 5% loss of vacuum over 5 minutes.
	ITRC 2014	For a shut-in test, the applied vacuum should hold steady (not decrease) for at least 30 seconds. For leak testing if the tracer concentration in the probe tubing or sample collection device is greater than 15% of the concentration in the shroud, then the leak should be found and corrected before opening the canister
	CA DTSC 2015	A shut-in test and a leak test should be conducted at each soil gas probe location prior to purging or sampling. A shut-in test is not a replacement for a leak test/ For a shut-in test, evacuate the system to a minimum measured vacuum of about 100 in H_20 with a purge pump, observe for 1 minute or longer for an observable loss of vacuum

Table A2 Soil Gas Sampling and Analysis Review

	Topic	Summary
g.	**Probe purging and sampling**	
	BC ENV 2020a	Purging is required to remove stagnant air from the vapour probe and sampling train Default of three purge volumes should be used, where the purge volume includes the internal probe and tubing, sand pack (if applicable) and dry bentonite above the sand pack (if applicable) An alternative to using three well volumes is to purge until the purged gas concentrations stabilize (*e.g.*, O_2, CO_2, CH_4 or vapours analyzed on a portable detector) Purging should be conducted prior to sampling regardless of whether the probe is new or old, shallow or deep Purging should be conducted at the same flow rate as the sample collection flow rate although when sampling groundwater wells a higher flow rate of 5 L/min may initially be used to reduce sampling time. Flow rates should be between 0.1 L/min and 0.2 L/min and should not exceed 0.2 L/min. Low flow rates and low vacuums will minimize the potential for VOCs to partition from soil and or pore water to vapour and prevent the introduction of ambient air into the sample Vacuum should be maintained at less than 10 in H_2O (if the vacuum is greater reduce the flow rate) Polymer bags (*e.g.*, Tedlar™, FlexFilm, Kynar) are used for collection of samples for field screening. Depending on analytical protocol, bags may also be used for fixed gas analysis (O_2, CO_2, N_2, *etc.*). Because bags leak, samples for vapours should be analyzed within 6 hours and samples for fixed gases should be analyzed within 24 hours of collection.
	CCME 2016	Purging options: • Basic purge method – remove three purge volumes • Purge stabilization test – samples collected after field readings stabilize • Initial purge volume test – conduct purge volume test on subset of probes to determine optimal purge volume Modeling study referenced in CCME (2016) indicates three purge volumes are required to be removed to achieve representative concentrations because of mixing and turbulent effects when purging air Once purging is complete and atmospheric conditions are reached, connect sampling device and collect samples at a flow rate between 20 to 200 mL/min Samples for field screening may be obtained in polymer bags (*e.g.*, Tedlar). Studies cited indicate significant leakage of polymer bags can occur over 24-48 hours of sample collection.
	ITRC 2014	At a minimum, sufficient volume of gas should be withdrawn prior to sample collection to purge the probe and collection system of all ambient air or purge gas (1 purge volume) Generally, recommend flow rate equal to or less than 200 mL/min for sampling; this is less important in coarse soils Limiting flow rate may not be necessary in soils permeable enough to maintain vacuums less than 15% of atmospheric (about 5 in of Hg, 60 in of H_2O)

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	CA DTSC 2015	When purging a default of three purge volumes should be used. Purge volume testing is no longer recommended. Flow rates between 100 to 200 mL/min and vacuums less than 100 in of H_2O should be maintained during purging and sampling For deep wells with larger diameter tubing a flow rate > 200 mL/min may be used; however, a vacuum of 100 in of H_2O or less must be maintained
	Other	Sweeney and Ririe (2017) describe a small purge method and low flow method (< 1 L/min) to sample vapour from groundwater monitoring wells across the water table where sample tubing is placed in the well to the desired depth of soil gas sample and optionally a packer is placed downhole near the top of the screen. Sequential purging and monitoring of CO_2 and O_2 can be conducted with and without the packer to assess whether a packer is required. Jewell and Wilson (2011) describe field testing of a large purge method where typically the flow rate was 10 L/min and volume of soil gas removed was > 200 L. Samples were obtained for analysis after 5 probe volumes of air had been removed. DiGuilio (2007) present the results of testing of sequential purging on soil vapour concentrations where concentration stability of chlorinated solvents was achieved within approximately 1 probe volume (not including the sand pack). Small probes installed in a Geoprobe hole were tested after 3-month equilibration periods. US EPA (2018) present the results of time-series testing on soil vapour concentrations designed to evaluate effect of purge volume on soil vapour concentrations. Concentration stabilization was achieved within approximately two probe volumes where the purge volume included the air-filled voids in the filter pack at all probes with exception of several shallow probes for the first monitoring event where greater that three or four purge volumes were required. Hawai'I DOH (2017) recommends a minimum of three tubing-volumes be removed following equilibration, as the sand pack is assumed to be in equilibrium with the surrounding native soils.
2. Soil gas / air testing		
a.	**Field detectors**	
	BC ENV 2020a	A SOP provides detailed instructions on use of organic vapour meters (OVM), combustible gas meters (CGM) and photo-ionization detectors (PID)
	CCME 2016	Photoionization detectors (PID) are appropriate for a broad range or organic vapors Combustible gas detectors often used for petroleum hydrocarbon testing Multi-gas detectors often used when there is potential concern for biogenic gases Be aware of cross-sensitivity and bias Calibrate and bump-test in accordance with manufacturer's specifications, and keep calibration records Do not connect field detector directly to probe, instead collect soil gas sample a gas-bag using a vacuum chamber. Gas-bags may be re-used for field screening if the gas-bags are cleaned (flushed several times with air) and air concentrations in the gas-bag (measured using a PID) reflect ambient air. Field readings from gas-bags should be measured within one-hour of sample collection

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	ITRC 2014	Field screening with handheld PIDs or FIDs enables rapid screening for vapor migration routes around and into structures Identify potential for PID to be biased high from high humidity. A study on potential bias of PID by Maine DEP is referenced.
	CA DTSC 2015	Field detectors may produce biased results in the presence of water vapor or other compounds Routine calibration of field detectors is required Hydrogen sulfide samples should be analyzed by a hand-held instrument within 30 minutes of collection
	Other	N/A
b.	**Soil gas / air analytical methods**	
	BC ENV 2020a, b	Sampling methods include active sorbent tubes and whole-air samples (passive samplers are separately discussed) **Sorbent Tubes** Wide range of sorbents available Sorbents used for soil vapour should perform well under high humidity conditions **Whole-air sampling vessels** Whole-air sampling vessels should be air-tight and handled in a manner which ensures the integrity of the sample. Do not keep samples in a chilled cooler. Canisters come passivated (*i.e.*, under vacuum) and vacuum readings should be taken prior to sampling to ensure integrity of the canister. Typically, the canister is returned to the laboratory under a slight vacuum (*i.e.*, 2 in to 4 in of Hg). Summa canisters are constructed of electropolished stainless steel. Silco canisters are glass-lined steel
	CCME 2016	US EPA TO-15 – broad range of VOCs US EPA Method TO-17 – wide volatility range Modified NIOSH 1501 or OSHA 7 – typically BTEX and other PHC ASTM D1946-90 (2006) or D1945-03 (2010) – fixed gases and light molecular weight hydrocarbons ASTM D5504 – reduced sulphur compounds Potential advantages with sorbent tubes: easier to clean and provide for better recovery of higher molecular weight compounds (*i.e.*, heavier than naphthalene). Disadvantages: possible breakthrough requiring careful selection of safe sampling volumes, requirement for a pump, and accurate flow measurements during sampling. Potential advantages of evacuated canisters: more direct measurement and easier sample collection. Disadvantages: poor recovery of higher molecular weight compounds, challenges with hardware (*e.g.*, fittings, controllers, gauges) and greater difficulty in cleaning canisters compared to tubes.

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	ITRC 2014	Method TO-15 is commonly used for VOCs in indoor and ambient air samples Sorbents based methods (TO-17) allow for the capturing of VOCs and SVOC's beyond the capability of TO-15; TO-17 can be used for compounds in the C3–C28 volatility range Analytical methods used for quantitation of soil gas, indoor and ambient air samples include using GC/FID (TO-3, 8015B/8015D, USEPA 3C, ASTM D-1946, ASTM D-1945, 8015 mod.), GC/MS (TO-13A, TO-13A SIM, TO-15, TO-15 SIM, TO-17, TO-173, 8260, 8260B, MADEPAPH,), GC-PID (8021B modified), GC/ECD (TO-4A or TO-10A) and various detectors (TO-14A)
	CA DTSC 2015	Reporting limits should be based on the data quality objective Analytical methods should be selected to achieve the reporting limits that are below regulatory or risk-based screening levels Reporting limits for the leak check compound should be reported at the reporting limit of the target analytes When reporting limits are elevated due to sample dilution, the laboratory should provide a written explanation why project specific reporting limits were not achieved There are no approved US EPA methods specifically to analyze soil gas samples, modified versions of existing US EPA methods are adopted instead: modified GC/MS methods include US EPA 8260, TO-15, TO-17; modified GC methods include US EPA 8015 and 8021 At sites that are not fully characterized, soil gas samples should be analyzed using only US EPA modified analytical methods 8260B, TO-15, TO-17, or equivalent Using an autosampler with modified US EPA 8260 B/C is considered unreliable
	Other	N/A
c.	**Soil gas / air QA/QC**	
	BC ENV 2020a, b	All samples should be handled and stored to minimize sun exposure, especially transparent sampling vessels, to prevent photodegradation of the sample (CalEPA, 2015) Trip blanks should also be considered when setting data quality objectives but are typically only required when polymer bags (*i.e.,* Tedlar) or sorbent tubes are used, depending on the analysis method. Trip blanks when collecting canister samples are not necessary (ASTM D7663, 2012). If high concentrations are expected, two tubes should be connected in series to detect potential breakthrough in contaminants Sorbent tubes (*e.g.,* TD tubes) should be stored at a temperature of about 4°C.

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	CCME 2016	**Sorbent tubes:** *Cleaning and Proofing*: Thermal tubes should as a minimum be batch proofed and usage history of each tube recorded *Field duplicates*: Minimum frequency is 10% of samples analyzed; when < 10 samples, analyze at least 1 duplicate *Tests for Breakthrough*: Laboratory should provide data on safe sampling volumes (SSV) that apply to each analyte tested. Testing of two tubes in series or distributed pair at differing flow rates is optional (and not required by the USEPA TO-17 method) but is good practice when SSV is uncertain. *Trip blank*: Typically obtained by removing the caps from tubes and leaving them in the sampling environment for a short time and placing caps back on the tube. Optional test that may be warranted when sampling in "dirty" environment. *Equipment blank*: High purity inert gas is drawn through the sampling train and/or probe and analyzed to determine whether the materials are clean. Optional if new materials are used for train, mandatory if materials are reused. *Field Spikes*: Sample tubes spiked with known concentrations of analytes are used to evaluate the recovery of the spiked compound and accuracy of the extraction and analytical procedure. This test is not typically a field test but may be performed by the laboratory. *Sampling Flow Rate and Time*: The flow rate during sampling should be measured and sampling time accurately recorded. When obtaining duplicates, best practice is to measure flow rate for both tubes. *Storage*: Store tubes in cooler with cold packs but do not use ice; never store in same cooler as soil and groundwater samples. Store samples at < 10°C. **Canisters** *Cleaning and proofing*: Canisters and flow controllers should as a minimum be batch proofed and usage history of each canister should be recorded by the laboratory to enable tracking if contaminant carryover is suspected. For low-level (sub-ppbV) analysis, individual proofing or "certification" of canisters is recommended. *Field duplicates*: Obtained by collecting two canisters using a splitter. A single flow controller is recommended. Minimum frequency is 10% of samples analyzed; when < 10 samples, analyze at least 1 duplicate. *Field transport blank*: Canister is filled either in the field with ultra high purity air or nitrogen supplied by the laboratory in a separate canister or by the laboratory upon receipt. The blank canister is handled the same way as other canisters (*i.e.,* vacuum is tested). Is considered an optional test given that other quality control tests are typically performed such as laboratory certification of canisters and testing of the vacuum before and after sampling. *Equipment blank*: High purity inert gas is drawn through the sampling train and/or probe and analyzed to determine whether materials are clean. Optional if new materials are used for train, mandatory if materials are reused. *Vacuum Measurements*: Canister vacuum prior to sampling > 27 in of Hg. At completion of sampling should be measurable vacuum, ideally about 2-4 in of Hg but may be as high as 10 in of Hg (check with laboratory).

Table A2 Soil Gas Sampling and Analysis Review

Topic	Summary
ITRC 2014	Required laboratory QC samples: mass spectral tuning, initial calibration, continuing calibration verification, laboratory control spike, method blank Additional QC samples (if needed): trip blank(s), method blank(s) Per US EPA TO-15 analysis of canister samples to be completed within 30 days of collection
CA DTSC 2015	Laboratories should comply with the project quality assurance project plan, USEPA methods and the criteria in CA DTSC (2015) All calibration and QA/Q standards should be documented by the laboratory Vapor phase standards should be used to calibrate lab instruments Surrogate recovery limits should be approximately 70 to 130% (30% deviation) Sample blanks should include method, trip, material and equipment blanks At least one field duplicate/replicate sample should be collected and analyzed per 20 samples, or per batch A 50% relative percent difference is acceptable when comparing results from field duplicate/replicate samples Liquid and gaseous leak check compounds should be included in the laboratory analyte list Recommend soil gas probe, tip and tubing be blank tested at a frequency of one analysis per new batch of tubing or material used
Other	N/A
3. Passive soil gas samplers	
BC ENV 2020a	Samplers rely on diffusion of vapours through a hydrophobic sorbent material Method for assessing a contaminant source in vadose zone, delineating contamination and refining the CSM Typically installed in a grid pattern Samplers are inserted into a hole drilled approximately 2.5 cm in diameter and 15 cm to 1 m deep and typically deployed for 7-14 days Minimally invasive, easy to conduct, and inexpensive Disadvantages include potential starvation effect or insufficient amount of sorbent Passive samplers alone cannot be used to make conclusions on site soil gas concentrations
CCME 2016	Passive diffusion samplers contain a hydrophobic adsorbent material that collects organic compounds over time Adsorbed compounds are removed from the adsorbent by thermal desorption or solvent extraction, and typically analyzed using GC/MS methods Passive soil vapour method provide a time-integrated sample of mass, but in typical applications cannot reliably be used to estimate soil vapour concentrations Passive soil vapour samplers can be useful in mapping the location of subsurface plumes and for identifying pathways

Table A2 Soil Gas Sampling and Analysis Review

Topic		Summary
	ITRC 2014	Passive samplers detect VOCs and SVOCs, including aliphatic and aromatic hydrocarbons in the range of C4–C20, volatile PAHs related to, for example, MGP sites, and VOCs related to petroleum refining and blending (such as lead scavengers and other fuel additives) Useful when active methods may not be applicable, such as in low-permeability and high-moisture settings Published methods describe the procedures to generate contaminant concentration data from a passive sorbent-based sampler in air in the absence of soil (ASTM 2002, ASTM 2003a, b); efforts are ongoing to demonstrate the applicability of the method to soil gas (ASTM 2012) Analytical procedures, deployment depths and sampling durations based on manufacturer's procedures The adsorbent material should be hydrophobic in order to minimize water intake Exposure time depends on the objectives of the sampling program and the adsorbent materials used. Samplers constructed of weaker adsorbents (surface areas less than 100 m^2/g) should be exposed for shorter periods of time to avoid saturation of the adsorbent and potential back diffusion of highly volatile compounds. The absorbed compounds can be removed from the adsorbent by thermal desorption or solvent extraction and analyzed using GC or GC/MS, typically following USEPA method protocols when applicable (such as USEPA SW846) Installation involves a narrow diameter hole (for example, 2.54 cm or 1 inch) advanced to the desired sampling depth using hand tools if shallower, or mechanical/invasive means if deeper Because there is no sample train and no forced extraction of soil gas, no leak integrity testing is required.
	CA DTSC 2015	Results from a passive sampler must be corrected by a contaminant-specific sampling rate Analytical procedures, deployment depths and sampling durations based on manufacturer's procedures Typically deployed in hand-drilled boreholes that are 1 to 1.5 m deep (1" diameter) Typical deployment duration is 10 to 14 days Analysis of the absorbent material conducted by US EPA Methods 8260, 8270 or TO-17 Two trip blanks should be collected and analyzed – one trip blank should accompany the passive samplers to the field, and then analyzed, the second should accompany the samples from the field to the laboratory
	Other	N/A

APPENDIX B: REVIEW OF SCIENCE ON AEROBIC BIODEGRADATION OF PETROLEUM HYDROCARBON VAPOURS AND INCORPORATION OF BIODEGRADATION IN ASSESSMENT OF PETROLEUM VAPOR INTRUSION

Appendix B. Review of Science on Aerobic Biodegradation of Petroleum Hydrocarbon Vapours and Incorporation of Biodegradation in Assessment of Petroleum Vapor Intrusion[1]

This appendix presents a review of the science on aerobic biodegradation of petroleum hydrocarbon (PHC) vapours and the incorporation of biodegradation in assessment of petroleum vapour intrusion (PVI). The organization of this appendix is as follows:

- Section 1.0: Conceptual site model for biodegradation of petroleum hydrocarbon vapours;
- Section 2.0: Review of PVI Guidance from US EPA and ITRC;
- Section 3.0: Review of Regulatory Guidance in Select Other Jurisdictions;
- Section 4:0: Review of Properties of Concrete and Asphalt;
- Section 5.0: Review of Modeling Studies; and
- Section 6.0: Implications for Application of Biodegradation Attenuation Adjustment Divisor (BAAD) in BC ENV *Protocol 22.*

Section 6.0 is a longer version of the summary provided in the main body of the report (some information is repeated). It is included in this appendix to provide a single comprehensive document providing a summary of the findings.

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[1] The author of this appendix is Dr. Ian Hers, P.Eng., CSAP of Hers Environmental Consulting, Inc. The appendix incorporates and syntheses recent research and previous research, knowledge, work and projects conducted for and in collaboration with public and private organizations and regulatory bodies in Canada and the United States including but not limited to Health Canada, CCME, US EPA, ITRC, BC ENV, Ontario MOECC, ARIS Environmental Ltd. and Golder Associates Ltd. The past contributions of all entities are acknowledged.

1.0 CONCEPTUAL SITE MODEL FOR BIODEGREDATION OF PETROLEUM HYDROCARBON VAPOURS

The key elements of the CSM for soil vapour intrusion are as follows:

- Volatilization from PHC sources into air-filled pores of the soil;
- Diffusive transport of hydrocarbons in the vadose zone;
- Absorption of hydrocarbons into organic matter present in the soil matrix or adsorption onto mineral surfaces;
- Aerobic biodegradation of PHC that ultimately results in break down to carbon dioxide and water;
- Advective transport of soil gas in the vadose zone and into buildings;
- Potential migration of chemicals through preferential pathways (*e.g.*, utilities); and
- Migration of PHCs through subsurface foundation and mixing of vapours in building air.

The dominant process for vadose zone transport of PHC vapours is diffusion in the absence of significant pressure and thermal gradients that cause soil gas advection. The primary mechanism for concentration attenuation of PHC vapours is aerobic biodegradation. PHC-related constituents are to varying degrees affected by sorption processes that retard (delay) transport. Aerobic biodegradation, in conjunction with sorption, further increases attenuation and reduces hydrocarbon vapour transport distances. The key processes controlling attenuation are typically the upward diffusive mass flux or discharge[2] of PHC vapours and the downward mass flux or discharge of oxygen caused by the removal of oxygen through biodegradation.

1.1 Aerobic Biodegradation of Petroleum Hydrocarbons

The differences in vapour attenuation between PHC compounds, which aerobically biodegrade, and many chlorinated solvent compounds, which do not aerobically biodegrade is summarized in US EPA (2012), and the CSM shown in Figure B-1. There is extensive research that indicates PHC vapours are readily degraded through aerobic biodegradation. Modelling and field studies indicate that there often is orders-of-magnitude attenuation in PHC concentrations over relatively short distances when aerobic biodegradation occurs (Hers *et. al.* 2000; Roggemans *et. al.* 2001; Ririe *et. al.* 2002; Fitzpatrick and Fitzgerald 2002; Abreu and Johnson 2006; DeVaull 2007a; Abreu *et. al.* 2009). The typically rapid biodegradation of PHC vapours limits the potential for vapour intrusion.

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[2] Mass flux is defined as mass per unit area while discharge is mass per area of interest

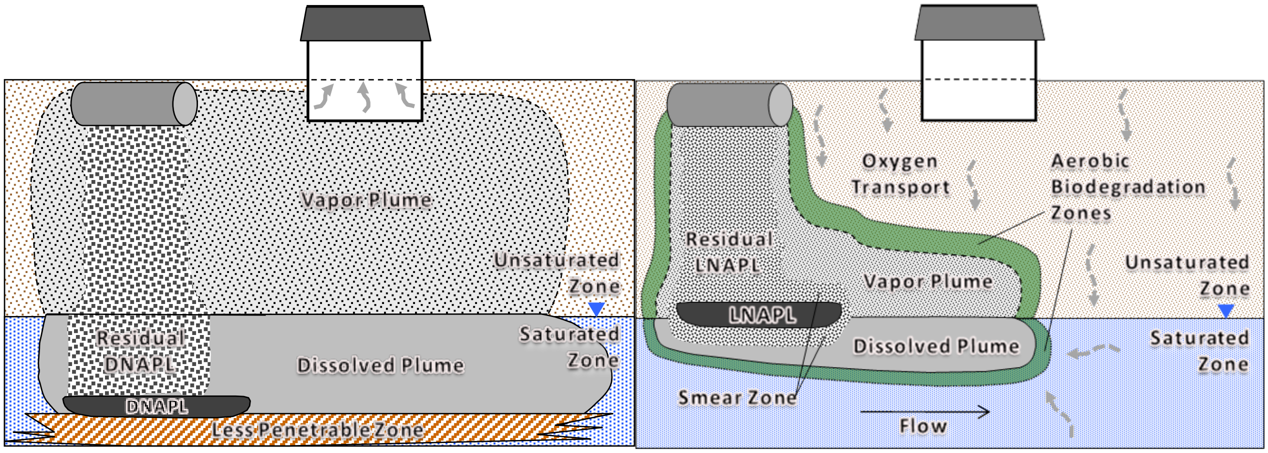

Figure B-1 Conceptual Model for Petroleum Hydrocarbon and Chlorinated Solvent Fate and Transport in Vadose Zone (adapted from US EPA 2012)

1.1.1 Key Factors

Naturally-occurring microorganisms are ubiquitous in the subsurface and consequently the aerobic biodegradation of PHCs has been demonstrated under a wide range of environmental conditions (*e.g.*, Leeson and Hinchee 1996; DeVaull 1997b; Davis *et. al.* 2009; DeVaull 2011). Key factors influencing aerobic biodegradation of PHC vapours include the following (US EPA 2013a):

- Source PHC concentration, vadose zone PHC mass flux, and PHC composition (including methane from degradation of PHC or other sources);
- Biodegradation rates and the minimum oxygen concentration required to support aerobic biodegradation processes;
- Oxygen demand (*i.e.*, the oxygen required to biodegrade the available PHCs and natural soil organics) and oxygen supply (*i.e.*, flux of atmospheric oxygen into the subsurface);
- Distance between the PHC vapour source and the building or ground surface;
- Soil type and properties (*e.g.*, soil porosity and moisture); and
- Size of building and properties of the building foundation and adjacent land surface.

For dissolved-phase vapour sources, case studies and database evaluations reported in the literature suggest absence of a complete PVI pathway for a wide range of site conditions (Davis 2010; McHugh *et. al.* 2010). As described in US EPA (2012), site conditions that may result in increased potential for PVI include direct contact between contamination (either dissolved or LNAPL) and a building foundation, insufficient thickness of oxygenated soil between the building foundation and the contamination, preferential transport pathways, a surface capping effect (*e.g.*, from building slab) in combination with an insufficient source-separation distance and high source concentration, and methane flux sufficient to create significant soil gas advection and/or reduced biodegradation of other hydrocarbon components.

Key CSM considerations are further described in the sections below.

1.1.2 LNAPL and Dissolved-Phase PHC Sources

The source vapour concentration and mass flux will vary depending on whether there is a LNAPL or dissolved-phase PHC source (Lahvis *et. al.* 2013; ITRC 2014). This is because the vapour concentration at the source is highly dependent on whether partitioning occurs directly from LNAPL in the unsaturated soil zone or from compounds present as a dissolved phase in groundwater.

The source vapour concentration from a LNAPL source is typically much higher than for a dissolved-phase source. In the case of a dissolved-phase source, chemicals must diffuse through water in the capillary fringe before reaching continuous gas-filled soil pores, and hydrocarbons may also be attenuated through biodegradation and sorption within the capillary fringe.

For a dissolved-phase source, the aerobic biodegradation zone is often located close to the hydrocarbon source. For a LNAPL source, the biodegradation zone position is more variable but typically is located at greater distances from the source than for dissolved-phase sources because of the greater PHC mass flux.

1.1.3 Biodegradation Rates

There are extensive data on aerobic biodegradation rates of PHC compounds (*e.g.,* Ririe and Sweeney 1995; Lahvis and Baehr 1996; Ririe *et. al.* 1998; Aronson *et. al.* 1999; Hers *et. al.* 2000; DeVaull 2007b; Patterson and Davis 2009; Davis *et. al.* 2009; DeVaull 2011; ITRC 2014). The ITRC (2014) guidance includes a comprehensive compilation of biodegradation rates from field studies. These rates indicate a relatively wide range of aromatic and aliphatic hydrocarbons are readily degraded through aerobic biodegradation reactions.

PHC biodegradation rates are rapid with half-lives on the order of hours to days (DeVaull 2007a,b, 2011; Davis *et. al.* 2009) and much faster than the rate of hydrocarbon transport by diffusion within the unsaturated zone. For this reason, there are typically sharp reaction fronts where the PHC vapour concentrations attenuate by orders of magnitude over short distances (*e.g.,* 0.3 to 1.5 m [1 to 5 ft]) and where there is a corresponding rapid decrease in the oxygen concentrations, as observed in several field studies (Lahvis and Baehr 1999; Hers *et. al.* 2000; Sanders and Hers 2006; Davis *et. al.* 2009; Luo *et. al.* 2009).

Insight on PHC vapour attenuation distances can be obtained from estimates of the reaction length (L_R), based on the equation below:

$$L_R = \sqrt{\frac{D_{eff} \cdot H_i}{\theta_w \cdot k_w}}$$

Where *Deff* is the effective diffusion coefficient (L^2/T), *Hi* is the dimensionless Henry's Law constant, *θw* is the water-filled porosity (unitless) and *kw* is the biodegradation rate (1/T). The aerobic diffusive reaction length is a measure of the distance required for biodegradation to decrease the vapour concentration by 50% under aerobic conditions in a diffusion-dominated system.

Reaction lengths estimated from biodegradation rates are provided in DeVaull (2011). The median reaction lengths are less than 0.4 m for the compounds evaluated. The reaction lengths were similar for many compounds indicating a range of PHCs consistently aerobically degrade over relatively short distances. The reaction length estimates support a screening approach based on distances as described in the sections below.

1.1.4 Oxygen Threshold for Biodegradation

A minimum threshold concentration of oxygen is required to support aerobic biodegradation of PHC vapours in the subsurface. DeVault (2007b) states that this minimum threshold concentration ranges from 1 to 4%. The two studies reviewed below provide additional data on the minimum oxygen concentration required to support aerobic biodegradation:

- Gomez *et. al.* (2008) report experimental data that supports a Monod kinetic reaction and half-saturation constant for oxygen of 0.21 mg/L-water, which is equivalent to an oxygen concentration of 0.49% v/v in the gas-phase. In the context of a Monod-type reaction, the biodegradation rate reaches half of its maximum at 0.49% v/v oxygen and begins to approach the maximum rate at between 1 and 2% v/v.
- Bordon and Bedient (1986) report that aerobic biodegradation was observed when the oxygen concentration in groundwater was greater than 0.1 mg/L-water. This corresponds to an equilibrium oxygen concentration of 0.24% v/v in the gas-phase.

Based on these data, a threshold of 2% v/v for the minimum oxygen required to support aerobic biodegradation is considered reasonable. Aerobic biodegradation will continue to occur at lower oxygen concentrations than the threshold, but at slower rates.

1.1.5 Natural Soil Respiration Rate

Respiration of natural organic carbon will consume oxygen in the subsurface. A potential concern is high rates of natural soil respiration that reduce the biodegradation of PHC vapours. The natural soil respiration will depend on organic carbon content, the type of organic carbon (*e.g.*, how labile) and microbes present.

DeVaull (2007) presents a relationship for estimation of the baseline soil respiration rate as follows:

$$\text{Baseline Soil Oxygen Respiration Rate } = 1.69(\text{mg } 0_2/\text{g-oc day}) \times f_{oc}$$

Where f_{oc} is the fraction of organic carbon. For a f_{oc} of 0.005, which is 5,000 mg-organic carbon (OC)/kg-soil or 5 g-OC/kg-soil, the baseline rate is calculated as 8.5 mg-oxygen ($O_{2)}$/kg-soil).

Hong *et. al.* (2010) presents results of measured baseline respiration rates that were 2 to 25 mg-O_2/kg-soil in shallow organic rich soil and less than 1 mg-O_2/kg-soil in deeper soil. Hong *et. al.* (2010) infers there could be oxygen limitations for aerobic biodegradation of PHC vapours for the high range of reported respiration rates and states that the potential effect of natural organic carbon can be evaluated through model simulations.

1.1.6 Effect of Surface Cover on Aerobic Biodegradation

The subsurface transport of oxygen to below a building will depend on the size and properties of the building (*e.g.*, foundation) and adjacent land cover (*e.g.*, pavement or shallow soil). These factors affect both the diffusive and advective transport of oxygen.

The diffusive transport of oxygen is dependent on the material characteristics. For porous media, the effective diffusion coefficient is a function of the water-filled and total porosity. For materials such as concrete and asphalt, the processes for diffusive transport are more complex, but research indicates concrete and pavement are porous materials (see Section 4 of this appendix). Additionally, diffusion will occur through cracks, openings, utilities and areas without hard surfaces (*e.g.*, landscaped areas).

The advective transport of oxygen is largely dependent on pressure gradients, which in proximity to a building result from pressure differences between the building and ambient air and soil, and through external forces such as wind and barometric pressure. The processes for advection and movement of air and soil gas in buildings and foundation subsoil are dynamic. Studies indicate there can be pressure cycling and movement of air from buildings into subsoils (US EPA 2013a). It is important to recognize that depressurization of buildings causes migration of ambient air into soil adjacent to a building and then laterally to below the building foundation. Consequently, oxygen in ambient air drawn to below buildings is available for biodegradation reactions.

Snow cover and frost has been identified as a potential cap that could reduce oxygen migration. However, a research study on cold climate vapour intrusion indicated that snow cover and cold temperatures did not significantly affect biodegradation rates at a site in North Battleford, Saskatchewan (Hers *et. al.* 2014). Snow is a porous material that does not impede gas diffusion.

1.1.7 Ethanol in Gasoline

While ethanol in gasoline is a potential source of methane and thus oxygen sink, model simulations using a numerical code that incorporated an ethanol-to-methane degradation sub-model suggests the commonly available 10% ethanol-gasoline blend is unlikely to result in significantly reduced biodegradation of other hydrocarbon components (Jourabchi *et. al.* 2013).

Ma *et. al.* (2014) present results of a modeling study of the effect of methane on benzene vapour intrusion using a 3D numerical model (Abreu *et. al.* 2006). The Ma *et. al.* (2014) study indicated that for scenarios with elevated methane concentrations (above approximately 5%) and methane flux, a reduction in the benzene vapour attenuation was predicted. The modeling did not include a sub-model for prediction of the methane flux from ethanol degradation but inferred that "*current approaches to manage the vapour intrusion risk for conventional fuel releases might need to be modified when dealing with higher ethanol blend fuel (i.e., E20 up to E95) releases*." A limitation of the Ma *et. al.* (2014) modeling study is that gas transport through the bulk building foundation was not simulated (*i.e.,* the foundation slab was assumed to be impermeable).

1.1.8 1,2-Dichloroethane and Ethylene Dibromide in Leaded Gasoline

To prevent fouling of vehicle engines with deposits of lead oxide, leaded gasoline historically contained 1,2-dichloroethane (1,2-DCA) and ethylene dibromide (EDB) (Falta *et. al.* 2005) commonly referred to as "lead scavengers". Leaded gasoline was banned in Canada in 1990. Both 1,2-DCA and EDB aerobically biodegrade but at slower rates than most other PHC compounds (Ma *et. al.* 2016; Kolhatkar *et. al.* 2019; Kolhatkar *et. al.* 2021; Hers *et. al.* 2021). Consequently, greater transport distances and longer reaction lengths are predicted for 1,2-DCA and EDB. The available empirical data, while limited compared to BTEX data, indicates soil gas concentrations of 1,2-DCA and EDB decrease to below thresholds of potential concern within the vertical screening distances recommended by US EPA (2015) of 6 ft (1.8 m) for dissolved-phase sources and 15 ft (4.6 m) for LNAPL sources at underground storage tank (UST) sites (Kolhatkar *et. al.* 2019; Kolhatkar *et. al.* 2021; Hers *et. al.* 2021). In contrast, modeling studies by the same authors listed above indicate the potential for 1,2-DCA and EDB to migrate beyond the US EPA (2015) screening distances depending on assumed source vapour concentration and soil type.

2.0 REVIEW OF PVI GUIDANCE FROM US EPA AND ITRC

Guidance on PVI is available from US EPA (2015) and ITRC (2014). Both guidance documents present a rationale for assessment of PVI based on vertical screening distances to identify sites where the vapour pathway can be excluded based on a low potential for a complete soil vapour intrusion pathway. The US EPA and ITRC guidance frameworks for assessment of PVI were based on a detailed review of empirical data and modelling studies. While the context of these studies was an assessment of screening distances, they provide valuable general information on PHC vapour biodegradation. Other important database and modeling studies include Peargin and Kolhatkar (2011), Wright (2011), Lahvis *et. al.* (2013), Kolhatkar *et. al.* (2019) and Kolhatkar *et. al.* (2021).

2.1 Vertical Screening Distances

The US EPA (2013a) compiled an empirical PVI database consisting of soil gas and groundwater data from 74 sites in the US and Canada. The empirical database was established to better understand attenuation of PHC vapours and to support technically defensible and efficient approaches for site screening. The database provides evidence for relatively rapid bioattenuation of vadose zone concentrations of benzene, toluene, ethylbenzene and xylenes (BTEX) and other PHC compounds.

A two-part data verification process was followed where data were screened to establish minimal acceptable data quality for inclusion in the database and use in the analysis, and data quality indicators were developed to ensure the included data were of known, acceptable, and documented quality. Soil gas measurements from sites spanning a range of environmental conditions and geographic regions and obtained between 1995 and 2011 were included in the US EPA database. In total, there were 893 benzene soil vapour records, 655 oxygen records and 829 records with paired benzene soil vapour and groundwater data. In addition, an independent dataset of 1,083 paired soil vapour and groundwater source concentrations from 124 sites in Australia (Wright 2012) was reviewed and found to be generally comparable to the North American data.

An unquantified proportion of the sites in the database were inferred to have gasoline sources containing 10% ethanol. In the US, ethanol was added to fuels as early as 1998 (Denver, CO) and by 2003 ethanol began to replace MTBE in California.[3] There was a steady rise in US ethanol production between 2000 and 2010.[4] The median soil gas sampling date in the US EPA database is 15 December 2004, and the median date in the Australian database is 1 July 2008. Therefore, it is expected that a portion of the sites in these databases will have been impacted by gasoline containing up to 10% ethanol.

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[3] http://www.fuel-testers.com/ethanol_fuel_history.html

[4] https://en.wikipedia.org/wiki/Ethanol_fuel_in_the_United_States

Given the importance of the contamination source type on soil vapour concentrations, analyses were conducted separately for dissolved-phase and LNAPL sources. A multiple lines of evidence approach consisting of direct (*e.g.*, LNAPL in wells, sheens) and indirect (*e.g.*, concentrations, PID readings) indicators was followed to identify LNAPL sites. The dataset for LNAPL sites was further divided into underground storage tank (UST) sites and non-UST sites consisting of terminal, refinery and petro-chemical sites.

The analysis of empirical data by US EPA (2013a) led to the following vertical screening distances published by US EPA (2015):

- Dissolved sources: 6 ft (1.8 m) (beneath buildings of any size); and
- LNAPL sources at underground storage tank (UST)/aboveground storage tank (AST) sites: 15 ft (4.6 m) (beneath buildings up to 66 ft (20 m) on the shortest side).

The ITRC PVI guidance (ITRC 2014) recommends the following screening distances:

- Dissolved sources: 5 ft (1.5 m) (no building size criteria);
- LNAPL sources at UST/AST sites: 15 ft (4.6 m) (no building size criteria); and
- LNAPL industrial sites: 18 ft (5.5.m) (no building size criteria).

UST/AST sites are typically characterized by relatively smaller petroleum releases, while industrial sites such as refineries and terminals are typically characterized by relatively larger releases.

Guidance on factors to consider when evaluating site data for the current or historical presence of LNAPL include product in wells, sheens, staining; benzene or other PHC concentrations; and ultraviolet fluorescence (UV) or laser induced fluorescence (LIF) response in the LNAPL range (Lahvis *et. al.* 2013; ITRC 2014).

The analysis of the soil gas database by US EPA (2013a) included analysis of BTEX, hexane, naphthalene, methyl tert-butyl ether (MTBE) and Massachusetts Department of Environmental Protection (MADEP) hydrocarbon fractions. Benzene was the risk driver and resulted in the largest vertical screening distance.

The vertical screening distances adopted in the US EPA and ITRC PVI guidance documents are based on certain assumptions for PHC compounds and fractions of concern and toxicity factors. If these screening distances are to be considered for application in Canadian jurisdictions, these assumptions should be reviewed as to their applicability.

2.2 Clean Soil Requirement

Both the US EPA (2015) and ITRC (2014) guidance include a requirement for there to be clean soil between the source and receptor for the zone that defines the vertical screening distance. US EPA (2015) states:

> *"Clean soil does not necessarily mean that it is contaminant-free, but rather that the level of any contamination present is low enough so that the biological activity of the soil is not diminished and the subsurface environment will support sufficient populations of microorganisms to aerobically biodegrade PHC vapors. This means that LNAPL is not present. The oxygen demand of all of the contamination present in the soil should not deplete the available supply of oxygen to such an extent that the rate of biodegradation is reduced."*

Based on the concept that clean, biologically active soil does not contain LNAPL, US EPA (2015) recommends soil concentration thresholds of 100 mg/kg Total Petroleum Hydrocarbon (TPH) (fresh gasoline) and 250 mg/kg TPH (weathered gasoline and diesel) to determine when LNAPL could potentially be present.

According to US EPA (2015), certain geologic materials do not qualify as biologically active soil and vertical separation distances would not apply to such sites. Precluded geologic materials include:

- Coarse sand and gravel with a low content of silt, clay, and organic matter, and low moisture content that is less than 2 percent by dry weight;
- Fractured, faulted, or jointed consolidated rock; and
- Consolidated rock with solution channels (*i.e.*, karst).

ITRC (2014) does not specifically define criteria for clean soil but indicates clean soil criteria may include volatile organic compound (VOC) or TPH analysis of subsurface soil adjacent to or beneath the building, or measurements of fixed gases (oxygen (O_2), carbon dioxide (CO_2), methane (CH_4)), and other gases. ITRC (2014) includes as indicators of the presence of LNAPL a TPH soil concentration of 250 mg/kg and a benzene soil concentration of 10 mg/kg. The presence of LNAPL indicates non-clean soil.

US EPA (2015) recommends soil gas data be obtained when the vertical screening distances are not met or when there are large buildings. ITRC (2014) does not require that soil gas data (*e.g.*, oxygen) be obtained to support application of vertical screening distances.

2.3 Precluding Conditions

US EPA (2015) includes the following precluding conditions following precluding conditions for when a vertical distance screening approach should generally not apply:

- influence of methanogenesis on oxygen demand (especially for higher ethanol blends of gasoline);
- effect of extensive high organic matter content soils (*e.g.*, peat) with potentially high natural oxygen demand;
- reduced oxygen flux caused by certain geologic conditions such as low permeability surface layer overlying coarse-grained soils;
- limited knowledge of vapour attenuation behavior in fractured rock;
- limited soil gas data for non-UST (*e.g.*, petroleum refinery, fuel terminal) sites;
- limited data on vapour attenuation behavior of aliphatic compounds;
- lack of soil vapour data for the lead scavengers 1,2-DCA and EDB;
- exceptionally dry soils (< 2 percent soil moisture);
- areas covered by extensive impervious paving or large buildings; and
- presence of preferential transport pathways.

While not identified as a precluding condition, US EPA (2015) also states "*for very large buildings, or where there is extensive impermeable surface cover and the vapor source is relatively shallow, additional investigation is recommended to verify that biodegradation is occurring beneath the building.*" An "extensive" impermeable surface cover is not defined.

ITRC (2014) includes the following precluding conditions for when a vertical distance screening approach should generally not apply:

- fractured media;
- anthropogenic preferential pathways such as utilities;
- mobile plumes;
- very dry soil (*i.e.*, less than 2% moisture based on dry weight); and
- very high organic content soil (greater than 4%).

ITRC (2014) indicates there are insufficient data to draw conclusions as to fuel types that contain lead scavengers (1,2-DCA and EDB) and gasoline containing greater than 10% v/v ethanol. These factors are identified as precluding factors in ITRC Internet-based Training (as of spring 2021).

2.4 Empirical Data on Surface Cover and Building Size

The US EPA (2013a) database included data from 39 sites where there were subslab soil gas data below buildings. Additionally, there were data from sites with soil gas data obtained from below pavement and uncovered ground surface. The building footprint sizes in the US EPA (2013a) database were less than 10,000 ft^2 (929 m^2) in all cases, and generally less than 5,000 ft^2 (464 m^2).

The empirical soil gas data were analyzed for three different cases, below buildings, below pavement, and below uncovered ground. A qualitative analysis indicated that the differences in soil gas concentrations (*e.g.*, oxygen) and benzene vapour concentrations for these cases were relatively small. The observed trends were as follows:

- For LNAPL sources at UST sites, there were lower oxygen concentrations and less attenuation in benzene vapour concentrations below paved surfaces compared to uncovered ground, but there was no significant difference in data for the below building and uncovered ground cases (for approximately similar depth data); and
- For LNAPL sources at fuel terminal and refinery sites, there were lower oxygen concentrations below buildings compared to uncovered ground, but there was no significant difference in the oxygen data for below pavement and uncovered ground (there were insufficient data to evaluate trends in vertical benzene vapour concentrations).

The data suggest a limited potential for an oxygen shadow effect resulting from pavement or building cover but the differences in the results for the three cases were small. There was no consistent pattern in the results for sites with pavement and buildings. A slight reduction in the oxygen concentration is not expected to result in significant differences in the vertical screening distances. Further study of the potential for an oxygen shadow was recommended in US EPA (2013a).

2.4.1 Evaluation of Methane

The empirical data were analyzed for occurrence of methane because of the potential for oxygen depletion and reduction in PHC vapour attenuation. The US EPA PVI database included methane data for 27 sites. Methane concentrations exceeded 5% vol/vol (*i.e.*, lower explosive limit (LEL) in air) at five sites (three UST sites and two petroleum refinery sites) but were less than 1% v/v at the remaining 22 sites. Three of five sites with elevated methane concentrations were investigated prior to 2000, so the methane at these sites was likely not associated with ethanol in gasoline. There was no apparent correlation between methane and benzene vapour concentrations, possibly because of the limited data. Further evaluation of the effect of methane on attenuation of hydrocarbon vapour concentrations is considered warranted.

3.0 REVIEW OF REGULATORY GUIDANCE IN SELECT OTHER JURISDICTIONS

Guidance from the Canadian Council of Ministers of the Environment (CCME), Ontario Ministry of Environment and Climate Change (MOECC), select U.S. states and Australia are summarized below.

3.1 CCME (2014) Guidance

The CCME (2014) guidance indicates the following bioattenuation reduction factors may be applied to vapour attenuation factors calculated using the Johnson and Ettinger (1991) model for select PHC compounds:

- 10X for distances between vapour source and building that are between 1 and 3 m;
- 100X for distances between 3 and 5 m; and
- 1000X for distances greater than 5 m.

The bioattenuation reduction factors may only be applied for the following conditions: there is no LNAPL, the total hydrocarbon source vapour concentrations are < 10 mg/L and the region above the source and below the building is oxygen-rich (> 5% O_2). Degradation is assumed to occur for most aliphatic and aromatic hydrocarbons where sufficient oxygen is present. Absence of data to demonstrate the oxygen distribution is considered a precluding factor. The rationale for the 5% threshold for oxygen is not provided.

The source of the 10 mg/L criteria is not stated but may be based on results of modeling presented in Abreu *et. al.* (2009), reproduced as Figure B-2 below, which shows a significant decrease in the predicted attenuation factor for soil gas TPH concentrations greater than 10 mg/L. The 10 mg/L threshold may also correspond to a conservative upper threshold for a dissolved-phase hydrocarbon source.

The Abreu *et. al.* (2009) modeling did not include oxygen transport through the concrete building slab and other processes for oxygen migration including soil gas advection near a building. Because of greater oxygen migration rates, lower attenuation factors would likely have been predicted if these processes were included. The CCME guidance does not include precluding factors that address building size or the presence of slabs or paved surfaces and their potential effect on aerobic biodegradation.

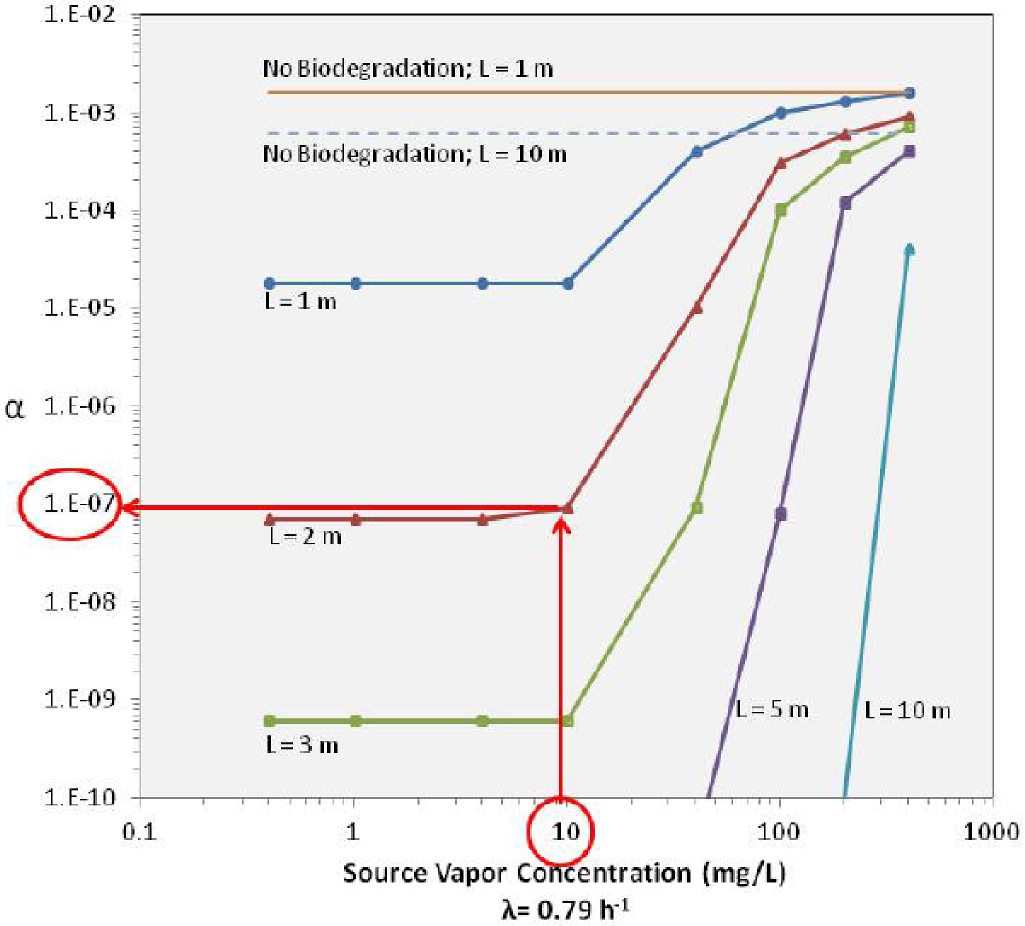

Figure B-2 Attenuation Factor Versus Source Vapour Concentration (from Abreu *et. al.* 2009)

3.2 Ontario Ministry of Environment and Climate Change (MoECC) 2013 Soil Vapour Guidance

The Ontario MOECC Vapour Intrusion Guidance (Ontario MOECC 2021) includes a CSM for petroleum hydrocarbon vapour intrusion that describes key factors affecting biodegradation below buildings such as the contaminant source type and concentrations, depth of the source below the building, building size, presence of surface cover (and potential capping effect) and distribution of contamination below the building. The MOECC Guidance includes depth- and concentration-dependent bio-attenuation factors (BAFs) equal to 10X and 100X that apply to both dissolved-phase and LNAPL sources.

The MOECC Guidance includes as an alternative, a vertical inclusion distance approach based on the ITRC (2014) and USEPA (2015) guidance to screen sites out from further PVI assessment. This approach is intended only for PHC impacted sites with stable and well characterized sources. An evaluation of the PVI pathway is only triggered if the vertical inclusion distance is within:

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

Precluding conditions for application of the vertical inclusion distances generally follow those recommended in US EPA (2015) and ITRC (2014) and include *"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)."*

3.3 New Jersey

New Jersey Department of Environmental Protection (NJDEP 2018) adopted the ITRC (2014) vertical screening distances for PVI. Soil gas sampling and minimum oxygen concentrations are not prescribed but the guidance indicates that vertical profiles of soil gas may be used to verify that biodegradation is occurring. The guidance does not include precluding factors that address building size or the presence of slabs or paved surfaces and their potential effect on aerobic biodegradation.

3.4 Wisconsin

The Wisconsin Department of Natural Resources (DNR) (2017) has developed a screening approach based on a vertical screening distance of 5 ft (1.5 m) for clean, unsaturated soil between a residual petroleum source and a building. Clean soil is defined as having an oxygen content greater than or equal to 5%. Investigation of the vapour intrusion pathway is required where 5 ft (1.5 m) of clean, aerated soils are not present or where there are other conditions, including free-phase product that has the potential for off-gassing vapours and underlies a building or is within 30 ft (9.1 m), horizontally or laterally of a building foundation. The guidance does not include precluding factors that address building size or the presence of slabs or paved surfaces and their potential effect on aerobic biodegradation.

3.5 California

The California Department of Toxic Substance Control (DTSC) Low-Threat Underground Storage Tank Closure Policy[5] includes the following vertical exclusion distances:

- Unweathered LNAPL in soil or groundwater: 30 ft (9.1 m);
- Dissolved source without oxygen data or oxygen < 4%:
  - Weak source: 5 ft (1.5 m); and
  - Stronger source: 10 ft (3 m).
- Dissolved source with oxygen data where oxygen > 4%:
  - Weak or stronger source: 5 ft (1.5 m).

Clean soil is defined as TPH concentrations that are less than 100 mg/kg.

The California guidance was developed before and without the benefit of the empirical analysis that was conducted for US EPA (2013a). A potential gap in the guidance is the attenuation observed in empirical concentrations for smaller or weathered LNAPL sources, which would support vertical screening distances that are less than 30 ft (9.1 m). The guidance does not include precluding factors that address building size or the presence of slabs or paved surfaces and their potential effect on aerobic biodegradation.

3.6 Australia

The Australian PVI guidance (CRC Care 2013) includes a hybrid approach where PHC concentrations are initially compared to generic criteria. If the generic criteria are exceeded, there is the option to apply a vertical screening distance approach. The vertical screening distances are 2 m and 8 m, for dissolved phase sites, and LNAPL or strong dissolved-phase sites, respectively (“strong” is intended to mean high concentrations). Detailed criteria for defining sources are provided in the guidance.

The screening distances do not apply for refinery sites and sites where the building size is such that the distance between the centre of the building and edge of the building is greater than 7.5 m (because of the potential for an oxygen shadow). The guidance indicates that screening distances are based on empirical data where biodegradation has been considered and so application of these distances does not require collection of oxygen data.

4.0 REVIEW OF PROPERTIES OF CONCRETE AND ASPHALT

The properties of concrete and asphalt with respect to primarily gas diffusion are summarized below.

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[5] http://www.waterboards.ca.gov/board_decisions/adopted_orders/resolutions/2012/rs2012_0016atta.pdf

4.1 Concrete

The diffusion of oxygen through concrete occurs through air- and water-filled pores. However, the rate of oxygen diffusion will be much greater through air-filled pores. Oxygen diffusion is a function of pore size and structure and relative humidity of concrete and decreases rapidly as the relative humidity approaches 100%. The typical water-cement (w/c) ratio of concrete is 35 to 40% while an optimum relative humidity of concrete is on the order of 50%.

Tittarelli (2009) measured oxygen diffusion coefficients for normal non-hydrophobic concrete mixture and concrete with admixture (alkyl-alkoxy-silane) to make it hydrophobic (both mixes had superplasticizer added). The concrete specimens were cured at 100% relative humidity for 48 hours, and then air-dried for 30 days. The oxygen diffusion coefficient for normal non-hydrophobic mixture for a w/c ratio of 0.45 was 7.7E-06 cm^2/sec. The oxygen diffusion coefficient for hydrophobic concrete was 3.6E-04 cm^2/sec.

Kaboyashi and Shuttoh (1990) measured oxygen diffusion coefficients of concrete specimens with different properties. For air-dried ordinary concrete at 60% moisture content, the oxygen diffusion coefficient was 1E-03 cm^2/sec. The diffusion coefficient decreased by a factor of two for concrete cured in water for seven days and by a factor of four for concrete cured in water for 28 days. Kaboyashi and Shuttoh (1990) found that the diffusion coefficient was highly sensitive to moisture content (and decreased with increasing moisture content) but was less sensitive to the water-cement ratio.

Bertolini *et. al.* (2013) report oxygen diffusion ranges for three different concrete admixtures, consisting of Ordinary Portland Cement (OPC) (2.8E-04 to 6.5E-04 cm^2/sec), 30% fly ash (1.6E-04 to 6.6E-04 cm^2/sec) and 70% slag (1.3E-04 to 5.0E-04 cm^2/sec). The Swiss Federal Laboratories for Materials Testing and Research (EMPA), a construction testing laboratory, report an oxygen diffusion coefficient of about 1.0E-04 cm^2/sec for OPC at 50% w/c[6].

Oxygen diffusion through concrete is of concern due to corrosion of steel reinforcing. Concrete oxygen diffusion coefficients the Handbook of Concrete Bridge Management (Branco and de Brito 2004) are summarized in Table B1.

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[6] http://www.empa.ch/plugin/template/empa/*/95265/---/l=1

Table B1 Oxygen Diffusion Coefficient in Concrete in Branco and de Brito (2004)

Concrete Quality	Oxygen Diffusion Coefficient
High	<5E-05 cm²/sec
Average	5E-04 cm²/sec to 5E-05 cm²/sec
Low	>5E-04 cm²/sec

Kranc and Sagues (1992) present the results of a model used to evaluate concrete corrosion where a representative oxygen diffusion coefficient of 1E-05 cm²/sec was chosen. Bentur *et. al.* (1997) present measurement data showing the influence of w/c ratio and relative humidity on oxygen diffusion coefficient. At low humidity (30%), the effective diffusion coefficient of oxygen for this study ranged from about 4E-04 cm²/sec to 1E-03 cm²/sec, depending on the w/c ratio. At moderate humidity (50%), the effective diffusion coefficient ranged from about 2E-04 cm²/sec to 8E-04 cm²/sec. At high humidity (70%), the effective diffusion coefficient ranged from about 5E-05 cm²/sec to 4E-04 cm²/sec. For comparison, Patterson and Davis (2009) report a measured effective diffusion rate of 3E-04 cm²/sec for cyclohexane.

The above diffusion coefficients are for intact concrete. When there are cracks in concrete, there will be higher oxygen diffusion rates through the cracks, although the proportion of mass flux through the concrete *versus* cracks will depend on the crack ratio and properties of concrete and cracks.

When there is a water vapour barrier directly below the concrete slab, a lower oxygen diffusion rate is expected. No literature was found documenting oxygen diffusion rates for concrete with vapour barriers, although one study involving radon transport was obtained. Daoud and Renken (1999) present laboratory testing results where the radon gas effective diffusion coefficient for fractured concrete was 1.1E-03 cm²/sec. When a thin-film plastic liner consisting of polyethylene naphthalate or Polyethylene Terepthalate Glycol (PETG) was attached to the concrete, the effective diffusion coefficient decreased by about 98 percent for both liners. In contrast, the diffusion coefficient decreased 27 percent for a polysulfide liner. Surface floor coverings are also expected to reduce the oxygen effective diffusion coefficient.

Based on the above review, the range of typical oxygen effective diffusion coefficients in concrete are:

- Upper value: 6E-04 cm²/sec;
- Best estimate: 2E-04 cm²/sec; and
- Lower value: 1E-05 cm²/sec.

To evaluate the relative flux potential for oxygen diffusion through intact concrete and cracks, the upper, best and lower estimates of the effective diffusion coefficient multiplied by the relative area of the intact concrete (0.999) was compared to the estimated effective diffusion coefficient calculated from the Millington and Quirck (1961) model multiplied by the crack area (0.001). The results in Table 2 indicate that the oxygen diffusion flux on an area basis is predicted to be about eight times greater through intact concrete, compared to the cracks, when the best estimate of the oxygen effective diffusion coefficient is input in the calculations.

Table B2 Comparison of Estimated Oxygen Flux through Concrete and Dust-filled Cracks

Concrete O_2 Diffusivity	Effective O_2 Diffusivity of Concrete (cm²/sec)	Ratio $D^{eff\text{-}concrete}$ x concrete area/ $D^{eff\text{-}cracks}$ x crack area
Upper Estimate O_2 Diffusivity	6E-04	2.3E+01
Best Estimate O_2 Diffusivity	2E-04	7.8E+00
Lower Estimate O_2 Diffusivity	1E-05	3.9E-01

Note: Crack ratio = 1E-03; total porosity of dust-filled cracks = 0.4; water-filled porosity of 0.05; free-air diffusion coefficient of oxygen = 0.136 cm²/sec

4.2 Asphalt

Asphalt pavement is a visco-elastic material with properties that are intermediate to a solid and liquid (Glaser *et. al.* 2015). The asphalt binder exists as a separate phase coating the mineral components of the pavement causing it to be cemented together. Asphalt pavements are porous and permeable to some extent, depending on the mix design. Because of the likely absence of continuous air-filled pores, the chemical transport in intact asphalt pavement is expected to occur by diffusion within the binder. Oxygen can be consumed through oxidation reactions in the asphalt (Glaser *et. al.* 2015).

There are few data on gas diffusion coefficients for asphalt pavement. While there are reported diffusion coefficients for bitumen membranes or seals, these data are not considered representative of asphalt pavement in typical settings. Diffusion coefficients for radon from field testing of asphalt seals reported by Haug and Pauls (2001) indicate diffusion coefficients of 7E-05 to 2E-04 cm²/sec for cold mix pavement materials (20 to 22% asphalt content) and 6E-06 cm²/sec for hot rubberized asphalt (100% asphalt content). The asphalt content in pavement is typically between 3 and 7 percent.[7] The diffusion coefficient values for cold mix pavement are considered more representative of typical pavements. The limited available data suggests the diffusion coefficient of unweathered asphalt is likely within the same order of magnitude as concrete. Because asphalt is subjected to weathering

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[7] https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/rap132.cfm

and traffic loading, it will crack and degrade over time. Therefore, diffusion rates are expected to increase over time.

5.0 REVIEW OF MODELING STUDIES

This section summarizes the results of four modelling studies that evaluate the impact of buildings or slabs on oxygen transport and aerobic biodegradation of PHC vapours. The studies are as follows:

- US EPA (2013b) describe the results of a 3D numerical modelling study investigating the influence of variable building size on oxygen migration below buildings;
- Knight and Davis (2013) describe a 2D analytical solution for vapour diffusion and sharp boundary interface for biodegradation assuming an impermeable slab;
- Verginelli *et. al.* (2016) describe a modeling study to evaluate the potential for an oxygen shadow below a pervious slab; and
- Yao *et. al.* (2014) describe a modeling study comparing an analytical model to 3D numerical model and BioVapor model simulations.

5.1 US EPA (2013b)

The US EPA (2013b) study comprises numerical modeling of petroleum and oxygen vapour transport and aerobic biodegradation for a range of conditions for vapour source strength, source-building separation distance and building size scenarios. The scenarios are designed to evaluate the potential for an oxygen shadow to develop beneath a building or paved surface that would impede aerobic biodegradation. The term oxygen shadow is used to describe soil with oxygen concentrations below 1%, considered in this study as the minimum concentration required for biodegradation to occur.

For this study, the 3D finite difference model developed by Abreu and Johnson (2006) was used. This model incorporates the following key processes:

- Soil gas pressure field and associated flow field based on building depressurization;
- Oxygen-limited first-order degradation of hydrocarbon (represented by benzene);
- Advective and diffusive transport of multiple chemicals (oxygen and benzene);
- Flow and chemical transport through foundation cracks; and
- Chemical mixing in indoor air.

The foundation and walls in the model are assumed to be impermeable barriers to vapour transport (applying to both hydrocarbons and oxygen). Transport only occurs through the foundation cracks. This is consistent with the assumption made in the Johnson and Ettinger model, where vapour transport is assumed to only occur in the soil and soil-filled cracks of the building foundation.

The building, source and soil conditions considered in this study are summarized in Table B3. The source concentrations were selected to represent dissolved-phase hydrocarbon concentrations in groundwater from leaking underground storage tanks. Oxygen-limited aerobic biodegradation according to a first-order reaction with respect to the concentration of benzene was assumed at a rate of 0.79 per hour. The minimum oxygen threshold for biodegradation was 1% v/v.

Table B3 Model Scenarios in the US EPA (2013b) Study

Input Parameter	Values
Soil properties	Homogeneous, relatively dry sandy soils
Building depressurization	5 Pa
Source depths	1.6, 4.6, and 9 m
Source hydrocarbon (benzene) vapour concentrations	10,000 to 10,000,000 µg/m3
Building size	Square building, width ranging from 10 to 632 m
Building mixing height	2.44 m
Building air change per hour	0.5
Perimeter crack width	0.001 m

For most scenarios, relatively dry sandy soils and slab-on-grade buildings were assumed. However, the study also included scenarios with a basement or 1 m of silty clay layer of soil overlying sand soil.

The modeling was conducted for source benzene vapour concentrations that ranged between 10,000 to 10,000,000 µg/m^3 (0.01 to 10 mg/L). Benzene was a surrogate for TPH. For comparison, based on an analysis of near-source soil gas data (within 1 m of the source) in US EPA (2013a), the following 95th percentile TPH vapour concentrations were estimated:

- Dissolved-phase source: 0.4 mg/L (N=43).
- LNAPL source: 200 mg/L (N=130).

Based on the simulations presented, for a shallow 5 ft (1.5 m) thick vadose zone (source-building separation distance) and lower vapour concentration of 0.1 mg/L, an oxygen shadow did not develop beneath the largest building simulated of 2,073 ft x 2,073 ft (632 m x 632 m). For a shallow vadose zone at the intermediate vapour concentration of 1 mg/L, an oxygen shadow did not form beneath a building of 98 ft x 98 ft (30 m x 30 m) size but did develop beneath a building with dimensions of

131 ft x 131 ft (40 m x 40 m). The model predictions suggest that an oxygen shadow is unlikely for dissolved-phase sources even for relatively large buildings.

Based on an analysis of near-source soil gas data (within 1 m of the source) in US EPA (2013a), for LNAPL impacts, the 95th percentile TPH concentrations was 200 mg/L (N=130). This TPH concentration is representative of a gasoline vapour source.

The maximum TPH concentration adopted in the simulations was 10 mg/L. For a deeper 15 ft (4.6 m) thick vadose zone, an oxygen shadow did not form beneath a building of 66 ft x 66 ft (20 m x 20 m) size but did develop beneath a building of 98 ft x 98 ft (30 m x 30 m) size. The model predictions suggest an oxygen shadow is possible for LNAPL sources noting gasoline vapour concentrations may be significantly greater than concentration assumed in the modeling (10 mg/L).

A significant limitation of modeling presented in US EPA (2013b) is the assumption of an impervious slab. In addition, while the model includes oxygen transport to below a depressurized building through soil gas advection, it does not include potential additional soil gas advection and resulting oxygen mass transport through wind or barometric-pressure induced gas migration.

5.2 Knight and Davis (2013) Study of Building Size

Knight and Davis (2013) present a 2D analytical solution for vapor diffusion, instantaneous biodegradation reaction, and sharp boundary interface for biodegradation assuming an impermeable slab. The solution enables prediction of the size of the foundation slab where detectable hydrocarbon vapour concentrations will just touch the centre of the slab. This is a conservative constraint because it does not mean significant vapour intrusion is occurring. The resulting relationship is shown in Figure B-3. Below the blue line, the hydrocarbon vapours do not touch the slab, and the entire vadose zone is oxygenated. Assuming a depth of 5 m and source hydrocarbon vapour concentration of 1E+04 ug/L (10 mg/L), a slab width of 20 m is required to create the beginning of an oxygen shadow. For a depth of 2 m and the same hydrocarbon concentration, a slab width of 8 m is calculated to create an oxygen shadow. The model is considered overly conservative with respect to prediction of an oxygen shadow because it does not include oxygen transport through the slab and a concern is identified when detectable hydrocarbon vapour concentrations are predicted to be present anywhere below the slab.

Davis *et. al.* (2021) updates the 2013 modeling study with modified analytical solutions that include different building dimensions and the effect of adjacent buildings and reduced open ground between buildings for oxygen ingress to occur. The modified model assumes an impervious slab.

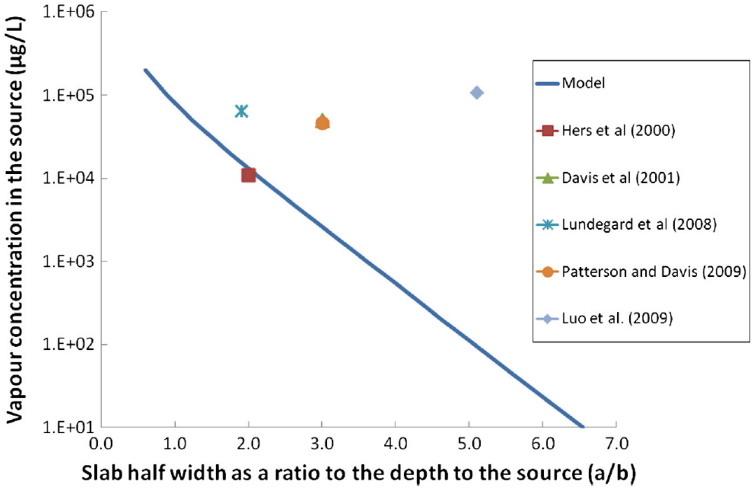


Figure B-3 Nomograph from Knight and Davis (2013)

5.3 Verginelli *et. al.* (2016) Study

Verginelli *et. al.* (2016) present the results of a study using an analytical method that estimates oxygen conditions beneath a building slab, for PVI scenarios with impervious or pervious building foundations. Modeling simulations were conducted for slab sizes of 10 m by 10 m, 15 m by 15 m and 20 m by 20 m, and vertical distances of 3, 5 and 10 m between the building slab and vapour source. For impervious slab scenarios the results are shown to be in good agreement with findings by previous studies.

The results for a pervious slab indicated for a reference TPH vapour concentration of 10 mg/L (10,000,000 µg/m^3), the lowest concentration simulated, no oxygen shadow (defined as less than 1% oxygen) formed directly below the slab regardless of the slab size or vadose zone thickness scenario. For a reference TPH vapour concentration of 100 mg/L (100,000,000 µg/m^3), no oxygen shadow formed directly below the slab regardless of the slab size or vadose zone thickness.

For a reference TPH concentration of 200 mg/L (200,000,000 µg/m^3), an oxygen shadow formed directly below the slab for a 3 m thick vadose zone for all building sizes. No oxygen shadow formed for vadose zone thicknesses of 5 m or greater, for all building sizes, and the depth to the aerobic/anaerobic interface was constant at 0.7 m for all building sizes. A limitation of the Verginelli *et. al.* (2016) study was that larger buildings were not evaluated.

5.4 Yao *et. al.* (2014) Study

In this study, Yao *et. al.* (2014) present the development and partial validation of an analytical model that predicts subslab PHC vapour concentrations that undergo aerobic biodegradation. Comparisons of this model with 3D simulations and another PVI screening tool (BioVapor) showed that the model is suitable for application in a scenario involving a building with an impermeable foundation surrounded by an open ground surface.

The modeling showed that the vertical screening distance recommended by US EPA (2015) is sufficient except when the TPH soil vapour concentrations at the vapour source exceed 50 to 100 mg/L. A concentration of 100 mg/L is characteristic of a weathered gasoline source. A limitation of the modeling is that transport through the foundation slab was not simulated.

5.5 Discussion

The modeling studies reviewed indicate that an oxygen shadow is unlikely to occur for a dissolved-phase PHC source for a 1.5 m source-building separation distance. Therefore, no precluding factor is considered warranted for a dissolved-phase PHC source, consistent with US EPA (2015) guidance.

The modeling studies reviewed indicate the potential for an oxygen shadow to develop for larger buildings and a LNAPL source. The modeling studies are limited in that the US EPA (2013b) study did not consider a sufficiently high vapour source concentration and assumed the concrete foundation slab was impervious. For the maximum TPH concentration considered, an oxygen shadow was predicted for a 30 m by 30 m building, but not for a 20 m by 20 m building, assuming a 4.6 m source-building separation distance.

The Verginelli *et. al.* (2016) study assumed a pervious slab, but the maximum building size assumed was 20 m by 20 m. No oxygen shadow was predicted for the maximum TPH concentration source assumed and 4.6 m source-building separation distance. There would be benefit in conducting modeling of larger buildings using the pervious slab model.

A limitation of all models was that soil gas advection and resulting oxygen transport through wind or barometric-pressure induced gas migration was not simulated. There are limited data upon which to derive a building size precluding factor for a LNAPL source based on the available studies, but a building dimension of concern may be between 20 m by 20 m and 30 m by 30 m. A complicating factor for the analysis is that a partial oxygen shadow below the centre of the building does not necessarily correspond to a significant reduction in the PHC vapour attenuation.

6.0 IMPLICATIONS FOR APPLICATION OF BAAD IN BC ENV *PROTOCOL 22*

The implications of the review conducted in this appendix for the application of the Biodegradation Attenuation Adjustment Divisor (BAAD) in BC *Protocol 22* is discussed. Issues that are addressed include site investigation for application of BAAD, identification of vapour source type and vertical distances, criteria for biologically active soil, precluding conditions for application of BAAD, definition of substantive surface cap and vertical screening distance approach.

6.1 Investigation to Support Application of BAAD

The application of a BAAD and/or vertical screening distance approach requires a robust CSM, well characterized sources and an evaluation of biologically active soil. The investigation requires assessment of the LNAPL *versus* dissolved-phase source extents. The source extents should be delineated and determined to be stable or shrinking following applicable BC ENV protocols and guidance.

The vertical distribution of LNAPL and dissolved-phase sources should be assessed through soil and groundwater sampling that provide sufficient spatial and temporal resolution to enable a representative estimate of the vertical separation distance between the source and building based on seasonal conditions. The vertical screening distance is taken from the top of the LNAPL source or seasonal high-water table for a dissolved-phase source. Accurate estimation of separation distances often requires relatively closely spaced samples in source zones and use of field screening and laboratory analyses of PHC concentrations. Additionally, the investigation of biologically active soil requires sampling and analysis of soil samples for indicator substances of PHC impact (such testing may not always be conducted for routine site investigations).

Soil gas data will generally improve the CSM and is a more direct measure of potential vapour concern. Under *Protocol 22*, soil vapour PHC concentrations used in an assessment of contamination where a BAAD is applied is required to be obtained within 1 m of the PHC source. As indicated in Technical Guidance 4, soil vapour concentrations may be estimated from soil and groundwater data, but soil vapour data generally provides for a more representative estimate of source or near-source concentrations.

The collection of additional soil gas data from vertical profiles and/or lateral transects (starting from sources and moving away) can provide information to support the CSM and assessment of vapour attenuation. Where possible, soil gas samples should be obtained below building slabs or asphalt surfaces if the goal is to investigate future building conditions.

Soil gas oxygen data may be useful to confirm conditions for aerobic biodegradation. Oxygen data should be considered when there is an existing larger building above the size threshold defined below for a substantive cap precluding condition.

Comprehensive guidance of investigation of PVI is provided in US EPA (2015) and ITRC (2014).

6.1.1 Identification of Vapour Source Type and Vertical Distances

BC ENV *Protocol 22* provides concentration criteria for volatile and extractable hydrocarbon ranges for identification of the presence and absence of NAPL (absence meaning there is a dissolved-phase source). The lines of evidence provided in ITRC (2014) (Table 3-1) could be considered as additional indicators of the likely presence and absence of NAPL. The vertical distances (2 m for dissolved-phase sources and 5 m for LNAPL sources) in *Protocol 22* for determination of when a BAAD may be applied are considered appropriate based on the data review. These distances are consistent with those recommended by US EPA (2015) for vertical screening distances for PVI pathway exclusion. A vertical distance screening approach is separately discussed below.

6.1.2 Criteria for Biologically Active Soil

Criteria for biologically active soil for assessment of PVI are addressed in ITRC (2014), US EPA (2015) and CRC Care (2013). US EPA (2015) recommends soil concentration thresholds of 100 mg/kg total petroleum hydrocarbon (TPH) (fresh gasoline) and 250 mg/kg TPH (weathered gasoline and diesel) to determine when LNAPL could potentially be present. US EPA (2013a) identifies a benzene concentration of 10 mg/kg as a threshold for LNAPL presence. These concentrations were estimated using the so-called “Csat” equation for equilibrium partitioning between soil, water and gas phases, where the water-phase concentration is set at the solubility limit. The equation represents the lowest concentration where potentially a separate phase is predicted in soil and is considered a conservative estimate. The oxygen demand from aerobic biodegradation of low ppm concentrations of TPH is considered insignificant.

According to USEPA (2015), certain geologic materials do not qualify as biologically active soil and vertical separation distances would not apply to such sites. Precluding geologic materials include:

- Coarse sand and gravel with a low content of silt, clay, and organic matter, and low moisture content that is less than 2 percent dry weight;
- Fractured, faulted, or jointed consolidated rock; and
- Consolidated rock with solution channels (*i.e.,* karst).

CRC Care (2013) include similar criteria for biologically active soil. ITRC (2014) does not specifically define criteria for biologically active soil but state criteria for “clean soil” may include volatile organic compound (VOC) or TPH analysis of subsurface soil adjacent to or beneath the building, or measurements of fixed gases (O_2), CO_2, CH_4) and other gases.

Currently, under *Protocol 22*, the criteria for biologically active soil include non-detect concentrations of CSR Schedule 3.3 substances and must be followed when applying a BAAD. As part of a detailed risk assessment approach, the US EPA (2015) definition of biologically active soil could be considered when applying a biodegradation attenuation adjustment where risk-based standards are being derived, with an additional precluding factor based on the absence of NAPL or hydrocarbon staining in soil.

6.1.3 Precluding Conditions for Application of BAAD

A range of precluding conditions are recommended by ITRC (2014) and US EPA (2015) for application of vertical screening distances. These precluding conditions are considered also generally applicable to a BAAD and are consistent with *Protocol 22*, although it is noted that the precluding conditions for a vertical distance approach are based on pathway exclusion while a BAAD is an adjustment factor. The precluding conditions in ITRC (2014) could additionally be considered for application of a BAAD. While not included in the ITRC (2014) guidance, a precluding condition for methane may be appropriate based on the analysis below.

High methane concentrations from biodegradation of PHC or biogenic sources represent a potential safety hazard, may cause soil advection, and may reduce biodegradation of PHC vapours because methane oxidation reduces available oxygen. It is noted that the US EPA (2013a) database did not indicate elevated methane resulted in reduced biodegradation or increased screening distances. This may be because methane concentrations must be highly elevated for there to be a similar oxygen demand compared to gasoline TPH vapours. On a stoichiometric basis, the oxygen demand for oxidation of methane is less than that for PHCs (*i.e.*, for methane 2 grams of oxygen are required for every gram of methane degraded while for many PHCs over 3 grams of oxygen are required). Assuming a TPH vapour concentration of 200 mg/L, an equivalent methane concentration of 30% v/v is calculated based on the oxygen demand. A conservative precluding condition for methane of 5% v/v is recommended based on the potential safety hazard. If methane concentrations exceed 5% v/v, an evaluation of the potential for soil gas advection may be appropriate, including pressure monitoring, where warranted.

In summary, science-based precluding conditions are considered to be the following:

- anthropogenic preferential pathways such as sewers or tunnels connecting a contamination source with the building (see Section 6.0);
- expanding or migrating LNAPL and/or dissolved-phase sources or plumes;
- fractured or karst media;
- greater than 10% v/v ethanol in gasoline;
- excessively dry soil (less than 2% moisture based on dry weight);
- excessively high organic content soil (greater than 4%); and
- Excessively high methane in soil gas (greater than 5% v/v) and/or soil gas under pressure such that soil gas advection is a more significant process than diffusion.

A surface cap condition is addressed below.

6.1.4 Definition of Substantive Surface Cap (Oxygen Shadow Concern)

The typical urban environment consists of buildings with adjacent surfaces such as asphalt pavement roads and parking lots, concrete sidewalks, and landscaped areas. There are utilities that penetrate the building foundation such as sewers, drains and sumps. Slabs may be constructed with expansion joints, which may or may not be sealed, and there are often cracks or other openings in slabs. In an outdoor environment, weathering of slabs will occur, and concrete and asphalt is subject to loading, which results in material degradation and cracking. Concrete and asphalt are porous materials and vapours diffuse through these materials.

The US EPA (2013a) empirical soil gas database suggests the potential for a slight oxygen shadow below asphalt pavement or building foundation slabs, although the data were inconclusive and there were inconsistent trends for the uncovered ground, paved and building foundation cases. An analysis of the empirical data indicates that the surface cover type did not affect the benzene vertical screening distances. The empirical data and modeling studies reviewed indicate that an oxygen shadow is unlikely to occur for a dissolved-phase PHC source for a 2 m source-building separation distance but could occur for larger buildings and a LNAPL source with high source vapour concentrations for a 5 m source-building separation distance.

A surface cap (cover) precluding condition is not considered warranted for a no NAPL (dissolved-phase) source as there is expected to be sufficient diffusion of oxygen through building foundations and hard surfaces in typical urban environments to support aerobic biodegradation of PHC vapours as indicated by measurement data and modeling studies reviewed regardless of the cap size. Where NAPL is present, a surface cap precluding condition is not considered warranted for hard surfaces adjacent to buildings in typical urban environments based on the above rationale. However, a surface cap precluding condition is considered warranted for larger buildings where there is the potential for a significant oxygen shadow below the building. There are limited data and uncertainty in available modeling studies on the oxygen shadow effect, which makes establishing a criteria for building size challenging. The available modeling studies suggest that an oxygen shadow may begin to form below buildings overlying LNAPL sources with a 5-m source-building separation when dimensions are greater than between 20 m and 30 m (*i.e.,* for a square building).

Currently, under *Protocol 22*, the criteria for no substantive surface cap indicates paved or other low permeability surfaces cannot represent more than 80% of the area surrounding the building, and must be followed when applying a BAAD. As part of a detailed risk assessment approach, the USEPA (2015) precluding condition for building size of 20 m on the shortest side could be considered for application of a biodegradation attenuation adjustment in the derivation of risk-based standards where supported by data. For buildings larger than 20 m, the recent science suggests that a biodegradation attenuation adjustment only apply if soil gas data are obtained below the building and the oxygen concentration > 2% v/v. For a future building condition, good practice is to obtain soil gas data within 1 m of the vapour source. An additional precluding condition to application of a biodegradation attenuation adjustment is considered an *impermeable* surface cap such as a geomembrane liner or concrete that is specifically treated or coated to create an impermeable barrier.

6.1.5 Vertical Screening Distance Approach

A vertical screening approach is supported by the CSM, empirical data and modeling studies that indicate rapid vapour attenuation over short vertical distances. Consequently, a vertical screening approach will generally provide for a more accurate representation of the attenuation that occurs at sites. This is because aerobic biodegradation results in a non-operable exposure pathway when vertical distances are sufficient (*i.e.,* there is much greater reduction than the 10-fold BAAD). ITRC (2014) and US EPA (2015) provide guidance on a vertical distance screening approach for PVI pathway exclusion for aerobically biodegradable PHCs, an approach that has been adopted by other regulatory jurisdictions. For example, the Ontario and Australia guidance describes a hybrid approach where initially site vapour concentrations are compared to generic standards. If the applicable standards are exceeded, there is an option to conduct a PVI assessment for UST sites using vertical screening distances adapted from US EPA (2015). A biodegradation attenuation adjustment factor larger than 10 (*e.g.,* 100) is also considered supported by the empirical data.

The assessment of sites for vapour contamination in BC must follow applicable regulatory standards and BCE ENV protocols (*e.g., Protocol 22*), and should follow guidance (*e.g.,* Technical Guidance 4). Hence, currently, a vertical screening distance may not be used as part of a generic standards approach in BC. As part of a detailed risk assessment, a vertical distance screening approach could be considered for screening of the PVI pathway or as an alternative approach to developing biodegradation attenuation adjustment factors as supported by the recent science. The risk assessment should include supporting rationale and applicable ENV approvals should be sought prior to use of such approaches where warranted.

The vertical screening distances recommended by US EPA (2015) are expected to generally apply in BC. Because the US EPA (2013a) database included sites in several northern US states with a similar climate to most areas of BC, the conditions for soil vapour transport and aerobic biodegradation are similar. A research study on cold climate vapour intrusion indicated that snow cover and cold temperatures did not significantly affect biodegradation rates at a site in North Battleford, Saskatchewan (Hers *et. al.* 2014). Consideration should be given to further evaluation of cold climate effects on biodegradation and, if required, a precluding condition could be very cold or permafrost conditions.

The US EPA (2015) vertical screening distances are based on assumptions for chemical toxicity that should be evaluated relative to BC standards. The driver for the US EPA (2015) vertical screening distances was benzene (*i.e.,* substance with the largest distance). The shallow benzene soil vapour criteria used in the US EPA (2015) analysis to determine vertical distances was 50 to 100 ug/m^3. A shallow soil vapour criteria for benzene based on the BC protocol is calculated as 75 ug/m^3 based on the BC Contaminated Sites Regulation residential vapour (air) standard of 1.5 ug/m^3 and an attenuation factor of 0.02. This initial evaluation suggests that the US EPA (2015) vertical screening distances would likely apply based on similar soil vapour criteria for benzene. Similar calculations could be performed for other PHC compounds. In addition, consideration could be given to obtaining data at sites in BC to validate a vertical screening distance approach.

APPENDIX C: UTILITIES LITERATURE REVIEW

Appendix C

This Appendix summarizes recent literature and guidance on preferential pathways for vapour intrusion and their assessment. The 2020 CSAP guidance on assessing the soil vapour to air pathway (ARIS and Golder, 2020), contains a review of much of the available literature up to 2020, and this is not repeated in detail herein. However, the information presented in this Appendix summarizes the available information, with emphasis on more recent studies, under five headings: Occurrence; Conceptual Models; Pathway and Risk Screening; Investigation; and Attenuation Factors.

1.0 OCCURRENCE OF VAPOUR INFILTRATION *VIA* PREFERENTIAL PATHWAYS

The assessment of vapour intrusion (VI) into buildings from volatile organic compounds (VOCs) present in subsurface soil and groundwater has historically focused on the ingress of soil gas through building foundations. The existence and role of alternative pathways in facilitating preferential subsurface vapour transport have been known for some time but have not been formally included in VI assessments until recently (Pennell 2020). Preferential pathways may be natural (*e.g.,* permeable soil units, fractured bedrock, karst features) or anthropogenic (*e.g.,* sewers, utility conduits, backfill, disturbed soils), but a growing body of evidence suggests that sewer lines, land drains and other conduits can be significant alternative VI pathways.

The occurrence of VI *via* sewer lines and utilities has been observed in a number of well-documented case studies and research projects, notably in Denmark (Riis *et al*. 2010; Loll *et al*. 2016; Nielsen and Hvidberg 2017) and in the United States (Pennell *et al*. 2013; Guo *et al*. 2017; Wallace and Friedrich 2017; Roghani *et al*. 2018; Beckley and McHugh 2020 and others). One recent landmark study was conducted by the US Department of Defense Environmental Security Technology Certification Program (ESTCP) on "*Sewers and Utility Tunnels As Preferential Pathways For Volatile Organic Compound Migration Into Buildings: Risk Factors And Investigation Protocol*" (ESTCP 2018).

Such studies have identified VOCs, in particular chlorinated solvents such as perchloroethylene (PCE) and trichloroethylene (TCE), in both sewer gas and indoor air, often at a considerable distance from any known source or contaminated groundwater plume. Observed points of entry to buildings include plumbing fixtures, such as toilets, uncapped pipes, dry or damaged p-traps and faulty seals (Beckley and McHugh 2020). Land drains connected to subslab granular fill have also been observed to contribute to VI through cracks and expansion joints in the building foundation (Guo *et al*. 2015). Sources of VOCs in sewer lines and other utilities include subsurface sources such as contaminated groundwater, nonaqueous phase liquids (NAPL) and vadose zone soil gas intersected by the sewers or utilities, as well as direct discharge (permitted or otherwise) of contaminated wastewater to the sewer system (Beckley and McHugh 2020). Vapours, contaminated groundwater and NAPL may penetrate sewer lines through cracks and loose joints caused by aging, degradation, settlement and/or root penetration. Evidence shows that conventional methods used to assess VI, such as groundwater and soil gas sampling outside a building, may not adequately represent the potential risk posed by VOCs when preferential pathways are present (CalEPA 2020).

2.0 CONCEPTUAL MODELS

Conventional conceptual models for VI consider vapour sources in groundwater, NAPL and vadose zone soils. Transport mechanisms to building foundations include diffusion and advection, and vapour ingress involves both pressure-driven flow (advection) and diffusion through foundation elements as shown in Figure C1.

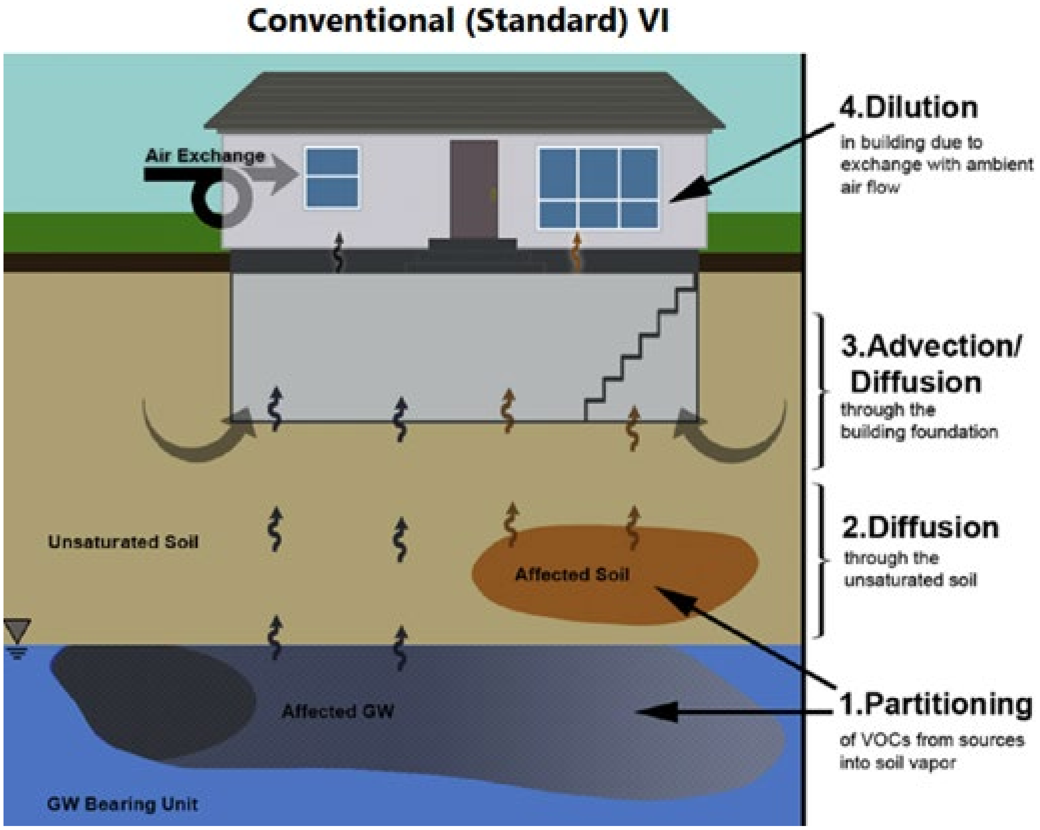


Figure C1 **Conceptual model of conventional vapour intrusion (from McHugh *et al.* 2017)**

Some sources of available guidance (*e.g.*, BC ENV Technical Guidance 4, Health Canada 2010, SABCS 2011, Indiana DEM 2019, CalEPA 2020 and others) suggest that preferential pathways should be identified and considered in developing conceptual site models (CSM), including both natural and man-made pathways. However, little guidance has historically been provided for CSM development other than identifying the presence of such pathways.

A preferential pathway is one that supports higher capacity transport of VOC vapours to a building foundation and into a building than that occurring through bulk soil. Vapour conduits are defined as a subset of preferential pathways that provide little to no resistance to vapour flow; when a conduit penetrates a building foundation, the pathway also serves as a vapour entry point (CalEPA 2020).

A number of recent studies provide guidance that addresses CSM development (*e.g.*, McHugh *et al*. 2017; ESTCP 2018; Ma *et al*. 2020) including identification of factors that contribute to preferential pathway migration such as drains connected to subslab fill, uncapped pipes, leakage through plumbing connections, dry or damaged p-traps, faulty seals, *etc.* (Beckley & McHugh 2020). An illustrative example of a CSM when a preferential pathway exists is shown in Figure C2.

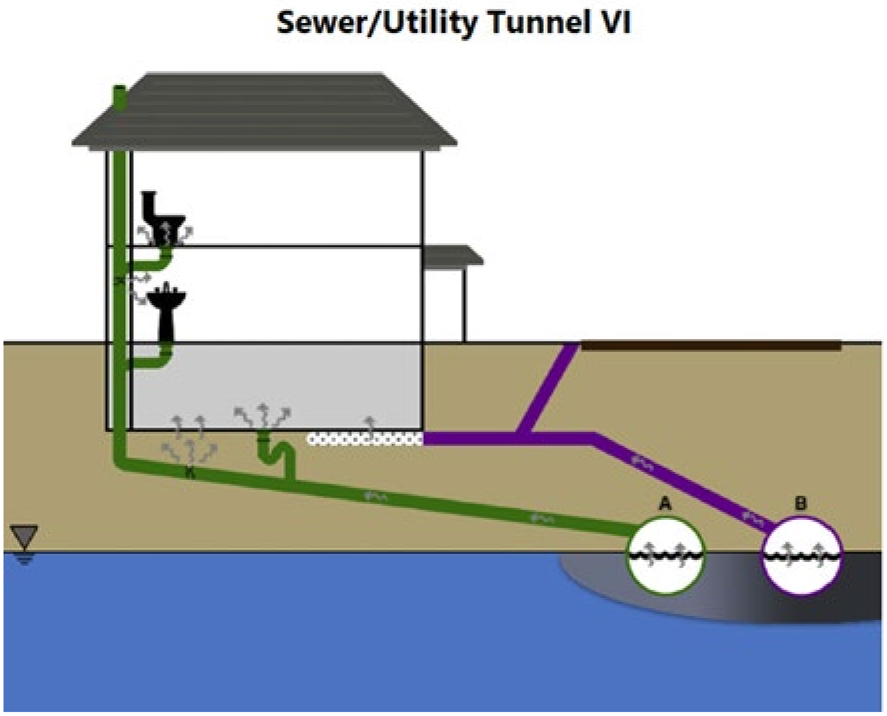
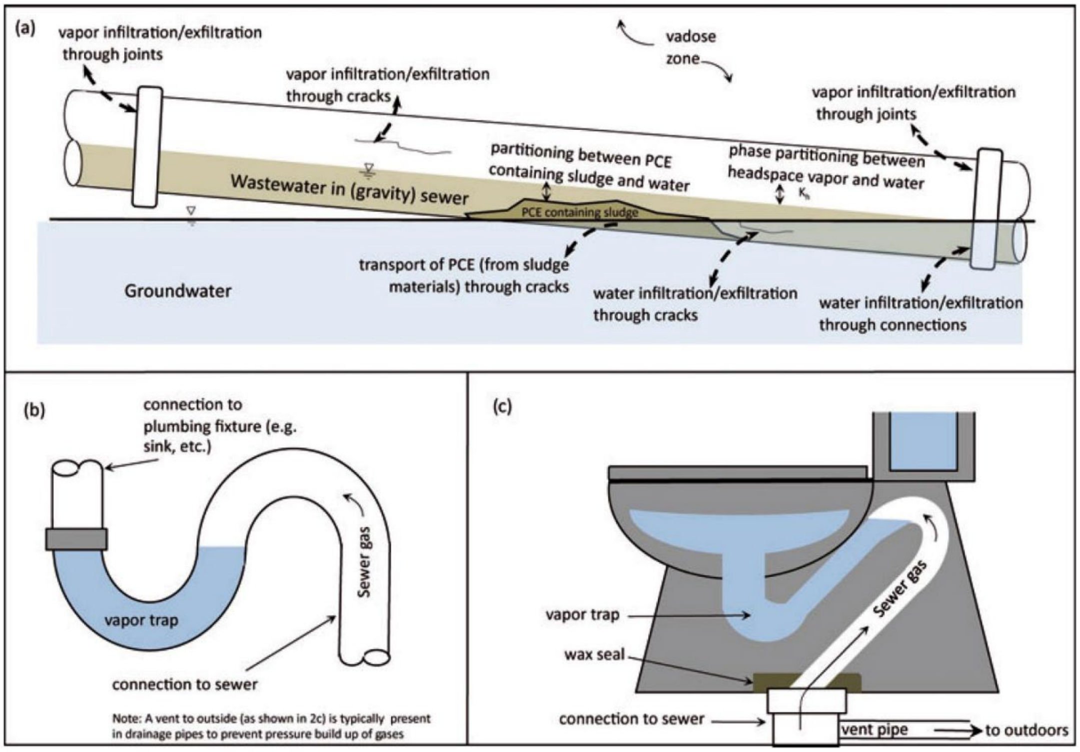


Figure C2 Conceptual model of vapour intrusion involving preferential pathway(s) (from McHugh *et al*. 2017)

Indications that sewers may be significant preferential pathways for VI include (Nielsen and Hvidberg 2017):

- higher concentrations in the upper floors in buildings;
- higher concentrations in indoor air than expected from soil gas measurements;
- higher concentrations in bathrooms/kitchen than in living rooms;
- chlorinated solvents in the sewer system; and
- a pressure gradient from the sewer system to indoor air.

Common mechanisms of entry to pipes and entry from plumbing fixtures to a building are illustrated in Figure C3.



Pennell et al 2013, GWMR

Figure C3 **Common mechanisms of VOC entry to sewers and into buildings *via* plumbing fixtures (from Pennell *et al*. 2013)**

A growing body of evidence has shown that migration through pipes and unfilled spaces is more important than migration through sewer line backfill or through the backfill of buried utilities not contained within a tunnel (McHugh *et al*. 2017; ESCTP 2018). However, the latter is still considered to be a potential preferential pathway in some cases (CalEPA 2020) and has been identified as a data gap (Ma *et al*. 2020).

3.0 PATHWAY SCREENING & RISK FACTORS

Studies have shown that the greatest risk for vapour intrusion *via* preferential pathways arises when the sewer line or utility tunnel directly intersects a potential contaminant source (Pennell *et al*. 2013; ESTCP 2018; Beckley and McHugh 2020). Based on this information, ESTCP (2018) has proposed a classification scheme for risk that can be used to guide the VI investigation strategy. Higher risk scenarios are defined as those where a sewer line or tunnel intersects contaminated groundwater, non-aqueous phase liquids (NAPL) or a vadose zone vapour source (such as residual NAPL within the vadose zone), or where there is direct evidence of VOC discharge to the sewer line (also referred to as direct interaction). A lower risk scenario is one in which the sewer or utility tunnel passes through the vadose zone directly above a groundwater or NAPL plume (also referred to as indirect interaction).

The high and low risk scenarios are illustrated in Figure C4.

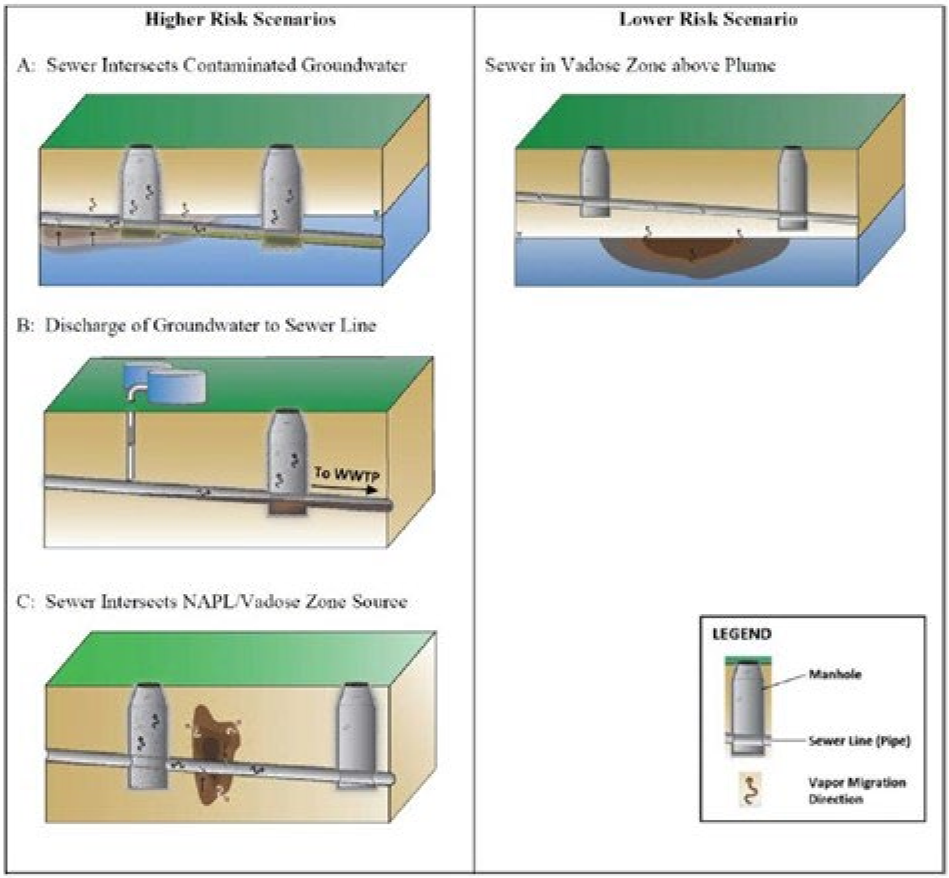


Figure C4 **Risk classification scenarios for sewer/utility tunnel vapour intrusion (from ESTCP 2018)**

Buckley and McHugh (2020) noted that the spatial area of possible vapour intrusion concern is potentially larger under the higher risk scenarios where the sewer line intersects the VOC source. This is illustrated schematically in Figure C5.

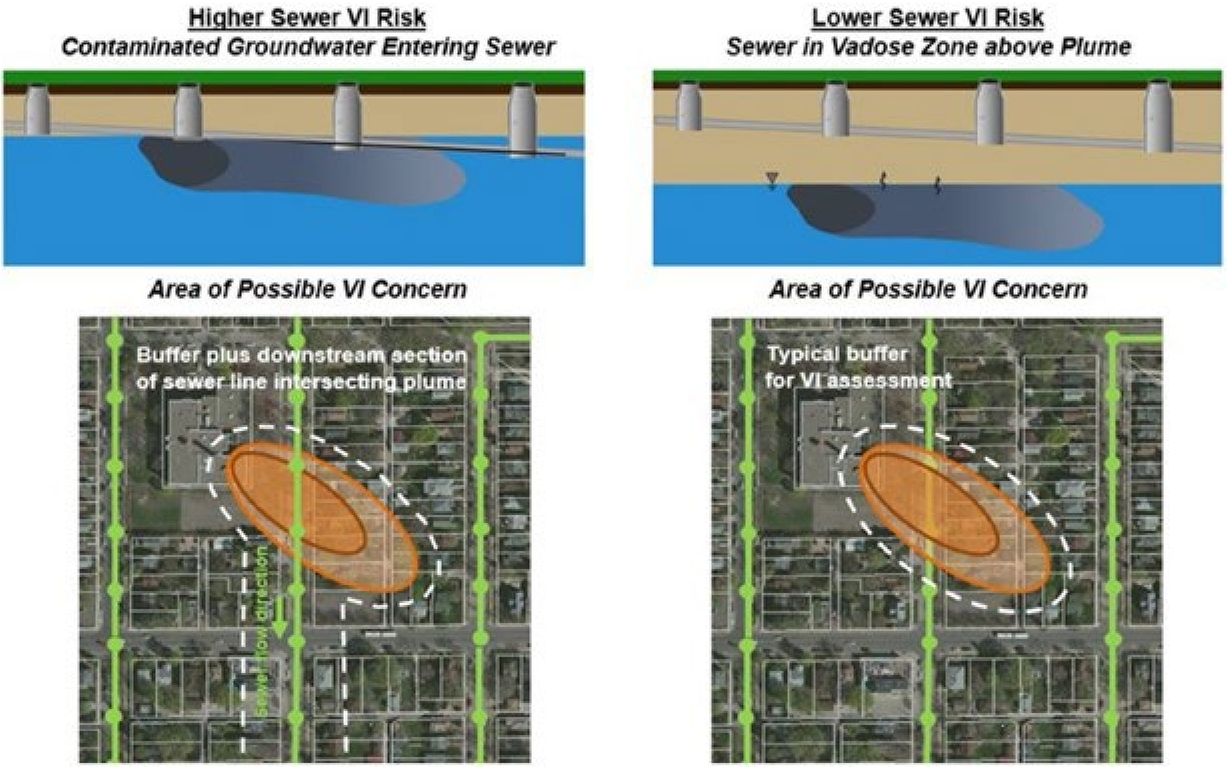


Figure C5 **Potential spatial areas of concern relative to risk scenarios (from Beckley & McHugh 2020)**

Note that the area of concern extends not only in the downstream direction, as suggested by Figure C5, but can also extend upstream relative to the source. Beckley and McHugh 2020 determined downstream and upstream. These are shown on Figure C6 normalized concentrations within the sewer system (manholes) as a function of distance both upstream and downstream.

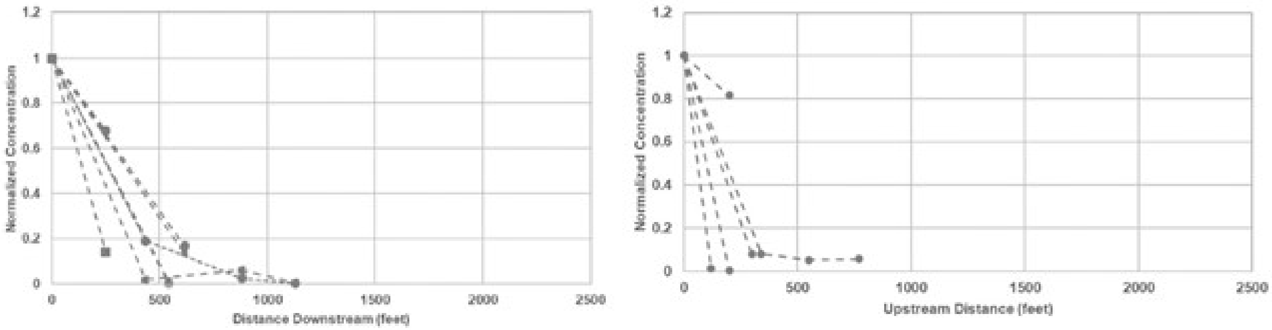
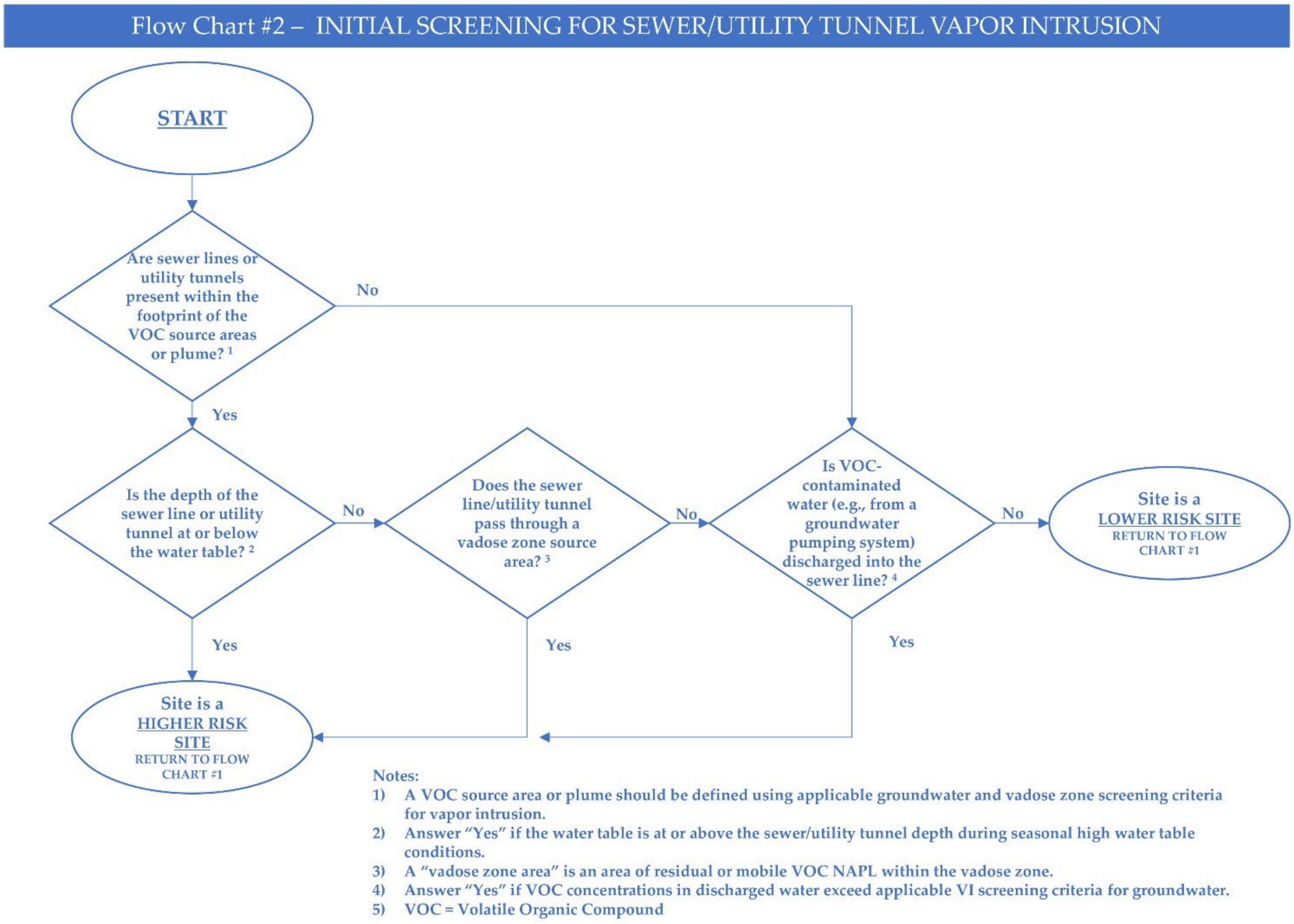


Figure C6 **VOC concentrations in sewer systems downstream and upstream of source (from Beckley & McHugh 2020)**

The risk classification system described above was used by ESTCP (2018) as the basis for a protocol to guide the investigation of preferential pathways. As part of this protocol, the flow chart presented in Figure C7 is used in initial screening to assess the relative risk level for sewer/utility line vapour intrusion.

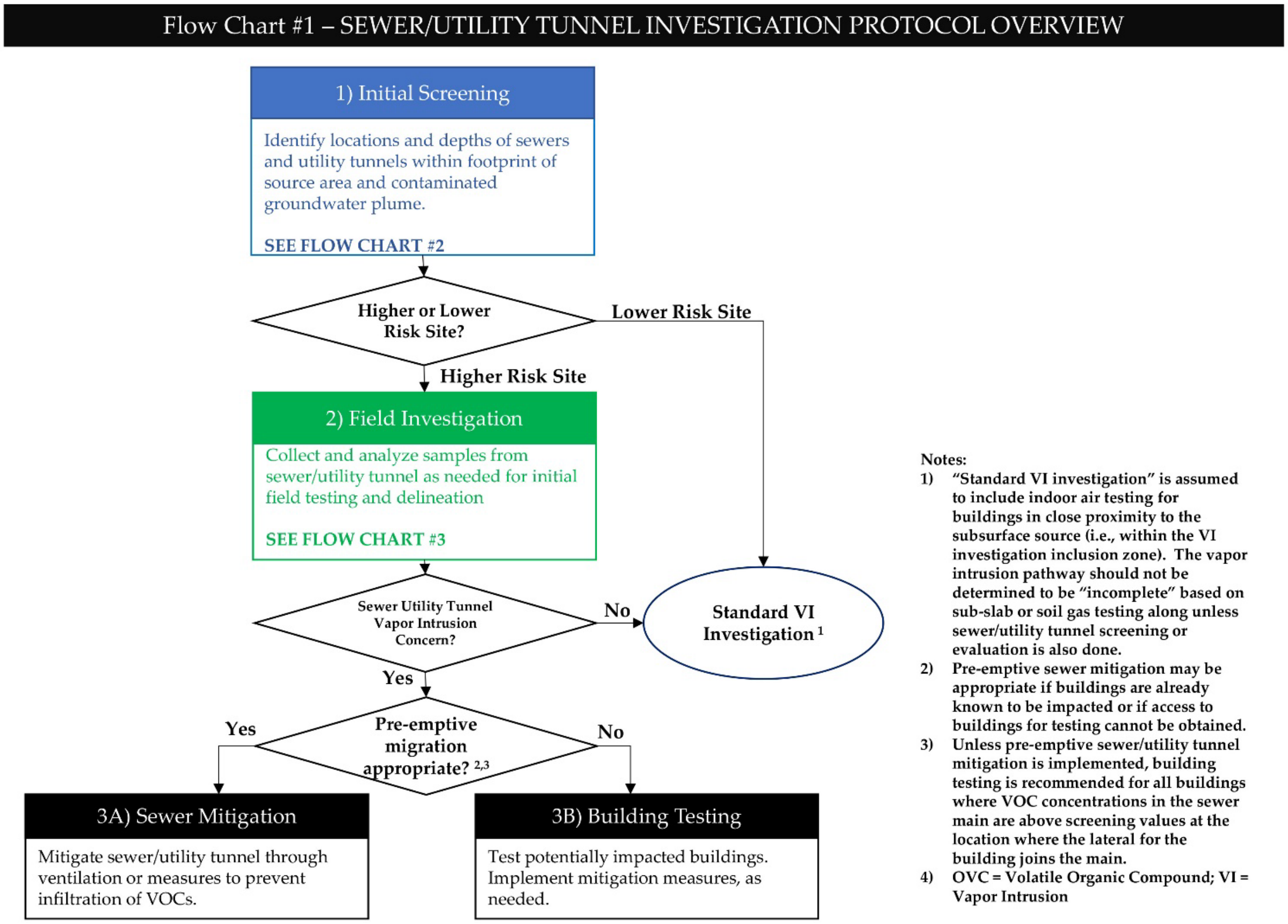

Flow Chart #2 – INITIAL SCREENING FOR SEWER/UTILITY TUNNEL VAPOR INTRUSION

Notes:
1) A VOC source area or plume should be defined using applicable groundwater and vadose zone screening criteria for vapor intrusion.
2) Answer "Yes" if the water table is at or above the sewer/utility tunnel depth during seasonal high water table conditions.
3) A "vadose zone area" is an area of residual or mobile VOC NAPL within the vadose zone.
4) Answer "Yes" if VOC concentrations in discharged water exceed applicable VI screening criteria for groundwater.
5) VOC = Volatile Organic Compound

Figure C7 Screening flow chart for risk classification for sites with preferential pathways (from ESTCP 2018)

4.0 INVESTIGATION AND SAMPLING

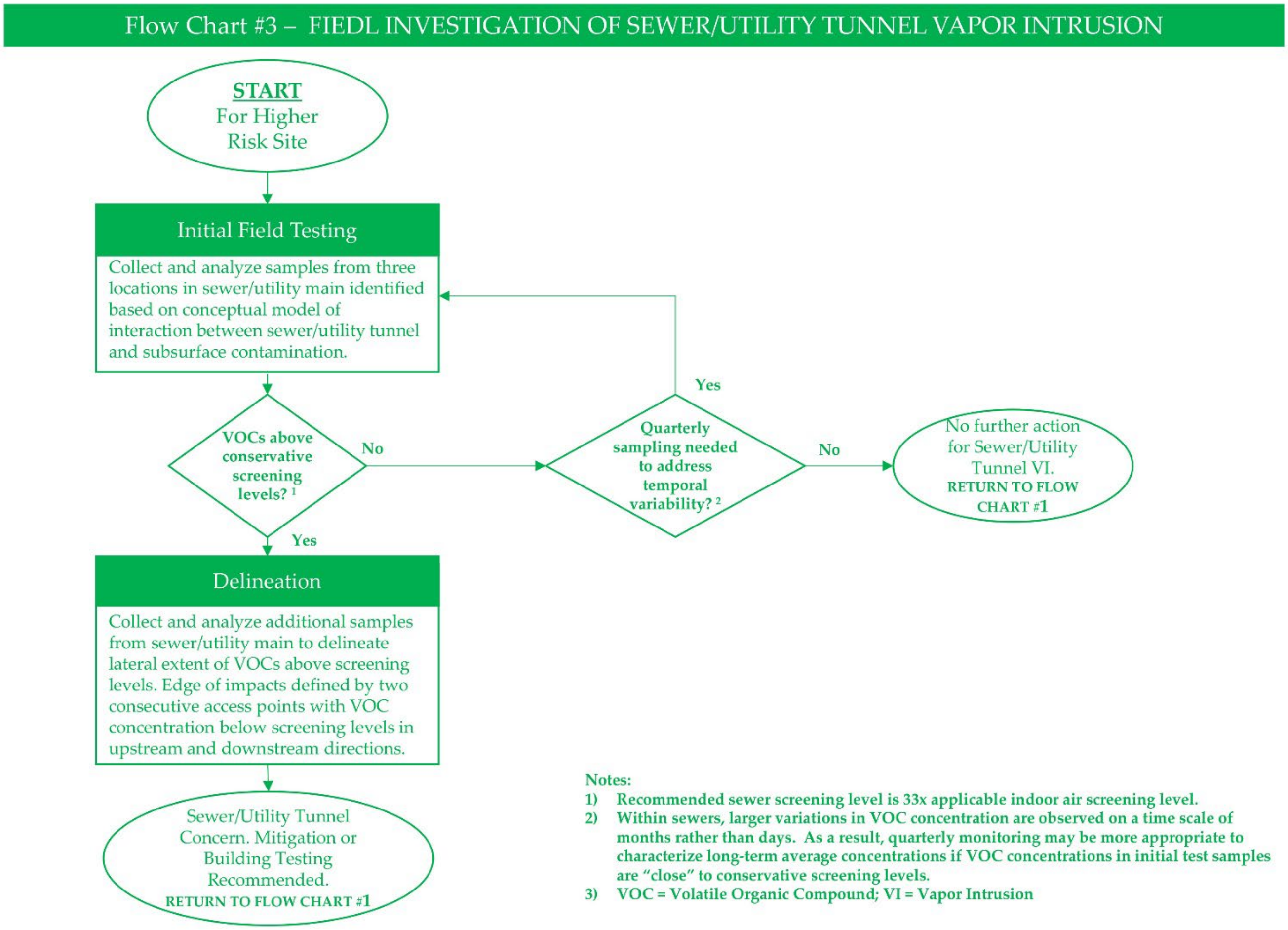
As noted above, ESTCP (2018) developed an investigation protocol to guide field investigation and sampling activities at sites with preferential pathways, depending on risk classification. An overview of the protocol is provided as a flow chart in Figure C8. The protocol references the screening process presented in Figure C7 to determine the risk classification of the site. Sites considered lower risk would undergo a "standard" vapour intrusion investigation. Sites considered higher risk would undergo additional investigation involving analysis of samples from the actual sewer or utility tunnel (or associated manhole); where vapours are encountered in excess of appropriate screening levels, calculated using appropriate conservative attenuation factors, mitigative measures and/or building testing would be implemented. Sites where vapours are within screening levels would proceed to a "standard" vapour intrusion investigation. Figure C9 presents a more detailed flow chart for the investigation process at a higher risk site.



Notes:

1) "Standard VI investigation" is assumed to include indoor air testing for buildings in close proximity to the subsurface source (i.e., within the VI investigation inclusion zone). The vapor intrusion pathway should not be determined to be "incomplete" based on sub-slab or soil gas testing along unless sewer/utility tunnel screening or evaluation is also done.
2) Pre-emptive sewer mitigation may be appropriate if buildings are already known to be impacted or if access to buildings for testing cannot be obtained.
3) Unless pre-emptive sewer/utility tunnel mitigation is implemented, building testing is recommended for all buildings where VOC concentrations in the sewer main are above screening values at the location where the lateral for the building joins the main.
4) OVC = Volatile Organic Compound; VI = Vapor Intrusion

Figure C8 Overview of investigation protocol (from ESTCP 2018)



Notes:
1) Recommended sewer screening level is 33x applicable indoor air screening level.
2) Within sewers, larger variations in VOC concentration are observed on a time scale of months rather than days. As a result, quarterly monitoring may be more appropriate to characterize long-term average concentrations if VOC concentrations in initial test samples are "close" to conservative screening levels.
3) VOC = Volatile Organic Compound; VI = Vapor Intrusion

Figure C9 Flow chart for initial field investigation (from ESTCP 2018)

The "standard" vapour intrusion investigation, applicable at lower risk sites where there is no evidence of a sewer/utility line as preferential pathway, would include source area and vadose zone sampling, together with subslab and indoor air sampling if warranted (*e.g.*, BC ENV Technical Guidance 4; ARIS and Golder 2020). The initial sewer/utility line investigation at higher risk sites, where there is evidence of a potential preferential pathway, would include sewer and/or manhole sampling from access points within or immediately downstream of the area where the sewer interacts with groundwater or NAPL, at appropriate times to assess temporal variability, in addition to the standard vapour intrusion investigation. Subsequent sampling would include delineation of sewer/utility line impacts, both upgradient and downgradient of the source, as well as testing of buildings including, potentially, sampling of indoor air and connected utilities (ESTCP 2018).

Additional investigation techniques could include tracer gas testing, which has been used effectively not only to confirm the vapour intrusion pathway into buildings but also to assess internal pathways within buildings (*e.g.*, Loll *et al*. 2010).

With respect to temporal variability, ESTCP (2018) found that short term variations (1 to 3 days) were typically less than 10x, and that longer term variations (quarterly sampling over 12 to 18 months) were up to 34x. They concluded that time average sampling over the short term offered little benefit compared to grab sampling, and that multiple quarterly events would be required to reduce uncertainty in estimating long term average concentrations.

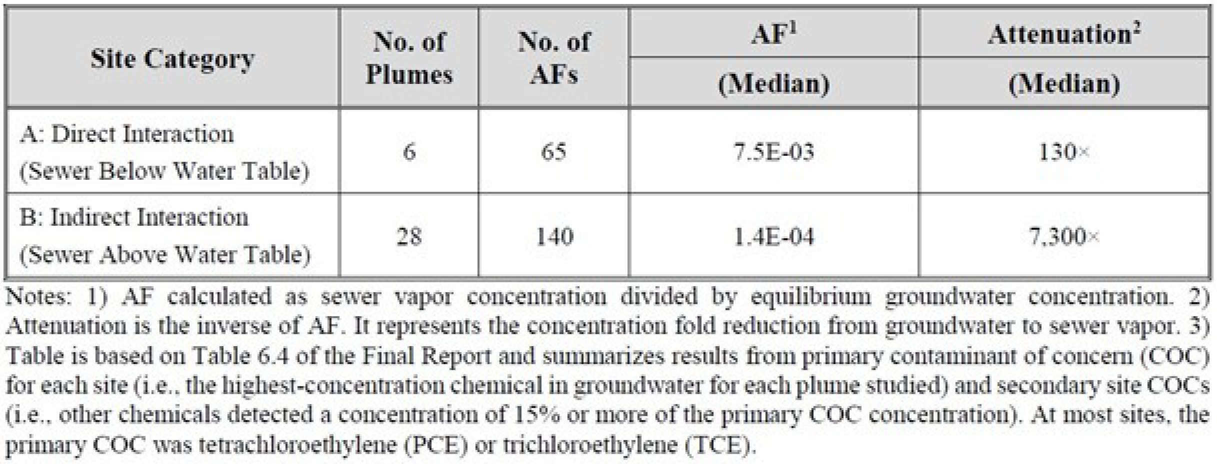
ESTCP (2018) made a number of recommendations regarding sewer line sampling, including:

- If groundwater elevations vary seasonally, sample during high water levels.
- Sample when the baseline sewer flow is low (typically between 9am-3pm), and not within 48 hours following significant rainfall (>0.25 cm (>0.1 in));
- Minimize venting of manholes;
- Collect grab vapour sample 0.3 m (1 ft) above bottom of pipe or water level;
- Compare initial field tests against conservative screening levels (use maximum VOC concentration measured in sewer);
- Collect delineation samples from access points both upstream and downstream of the source and delineate to screening levels (aim for two successive points that are below screening levels). Testing of sewer laterals should generally be conducted as part of the building investigation; and
- Existing protocols may be used for building testing; however, it is also recommended that building sewer laterals be tested if the sewer pathway is suspected. P-traps may be sampled if the laterals are inaccessible; in this case sample tubing would need to extend past the liquid barrier.

5.0 ATTENUATION FACTORS

The work described by ESTCP (2018) included the calculation of sewer attenuation factors (AFs) based on pairs of field data consisting of groundwater concentration (converted to an equilibrium vapour concentration) and sewer gas concentration for a number of demonstration projects. The data set was divided between sites where the sewer line interacted directly with the groundwater table and those where the sewer was located above the groundwater table (indirect interaction). The results are summarized in Table C1. Median AF values ranged from 7.5×10^{-3} (130x attenuation) for direct interaction to 1.4×10^{-4} (7300x attenuation) for indirect interaction.

Table C1. Groundwater to sewer median attenuation factors (AFs) (from ESTCP 2018)

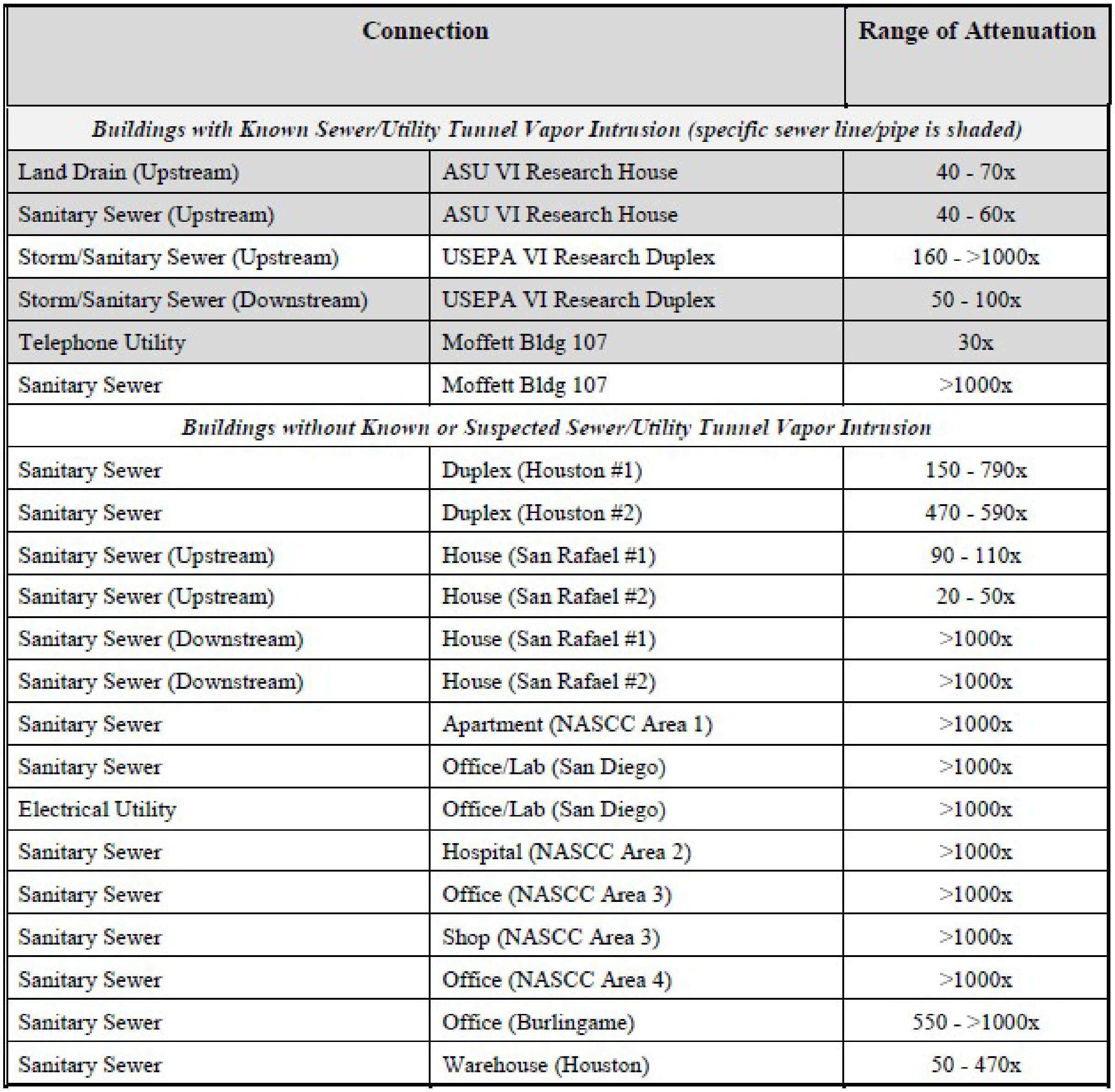


Site Category	No. of Plumes	No. of AFs	AF[1]	Attenuation[2]
			(Median)	(Median)
A: Direct Interaction (Sewer Below Water Table)	6	65	7.5E-03	130×
B: Indirect Interaction (Sewer Above Water Table)	28	140	1.4E-04	7,300×

Notes: 1) AF calculated as sewer vapor concentration divided by equilibrium groundwater concentration. 2) Attenuation is the inverse of AF. It represents the concentration fold reduction from groundwater to sewer vapor. 3) Table is based on Table 6.4 of the Final Report and summarizes results from primary contaminant of concern (COC) for each site (i.e., the highest-concentration chemical in groundwater for each plume studied) and secondary site COCs (i.e., other chemicals detected a concentration of 15% or more of the primary COC concentration). At most sites, the primary COC was tetrachloroethylene (PCE) or trichloroethylene (TCE).

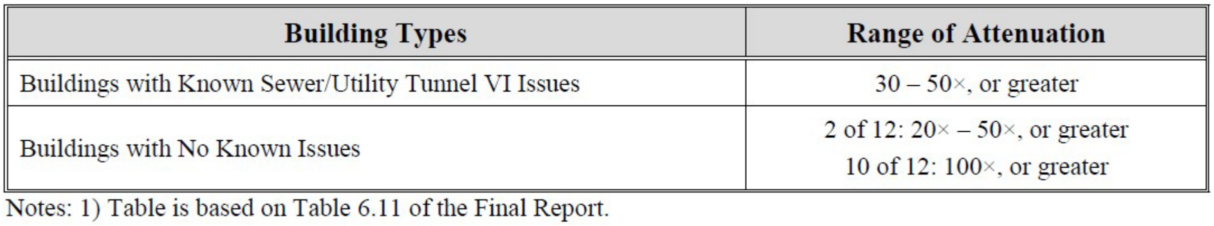
ESTCP (2018) calculated sewer to building AFs from the results of tracer studies and VOC measurements conducted at various sites, including test sites and sites where there were no known sewer vapour intrusion issues. The ranges of observed attenuation at several sites are presented in Table C2 and summarized in Table C3. Vapour concentrations decreased between sewers and building air by factors of 20x (AF = 5 x 10^{-2}) to more than 1000x (AF = 1 x 10^{-3}). At the majority of sites where there were no known sewer vapour intrusion issues the degree of attenuation exceeded 100x.

Table C2. Sewer to building air VOC attenuation at various sites (from ESTCP 2018)



Connection		Range of Attenuation
Buildings with Known Sewer/Utility Tunnel Vapor Intrusion (specific sewer line/pipe is shaded)		
Land Drain (Upstream)	ASU VI Research House	40 - 70x
Sanitary Sewer (Upstream)	ASU VI Research House	40 - 60x
Storm/Sanitary Sewer (Upstream)	USEPA VI Research Duplex	160 - >1000x
Storm/Sanitary Sewer (Downstream)	USEPA VI Research Duplex	50 - 100x
Telephone Utility	Moffett Bldg 107	30x
Sanitary Sewer	Moffett Bldg 107	>1000x
Buildings without Known or Suspected Sewer/Utility Tunnel Vapor Intrusion		
Sanitary Sewer	Duplex (Houston #1)	150 - 790x
Sanitary Sewer	Duplex (Houston #2)	470 - 590x
Sanitary Sewer (Upstream)	House (San Rafael #1)	90 - 110x
Sanitary Sewer (Upstream)	House (San Rafael #2)	20 - 50x
Sanitary Sewer (Downstream)	House (San Rafael #1)	>1000x
Sanitary Sewer (Downstream)	House (San Rafael #2)	>1000x
Sanitary Sewer	Apartment (NASCC Area 1)	>1000x
Sanitary Sewer	Office/Lab (San Diego)	>1000x
Electrical Utility	Office/Lab (San Diego)	>1000x
Sanitary Sewer	Hospital (NASCC Area 2)	>1000x
Sanitary Sewer	Office (NASCC Area 3)	>1000x
Sanitary Sewer	Shop (NASCC Area 3)	>1000x
Sanitary Sewer	Office (NASCC Area 4)	>1000x
Sanitary Sewer	Office (Burlingame)	550 - >1000x
Sanitary Sewer	Warehouse (Houston)	50 - 470x

Table C3. Summary of sewer to building air VOC attenuation (from ESTCP 2018)



Building Types	Range of Attenuation
Buildings with Known Sewer/Utility Tunnel VI Issues	30 – 50×, or greater
Buildings with No Known Issues	2 of 12: 20× – 50×, or greater 10 of 12: 100×, or greater

Notes: 1) Table is based on Table 6.11 of the Final Report.

ESTCP (2018) recommended the use of an AF of 3E-02 (33x attenuation) as a reasonable upper bound for the migration of VOC vapours from sewers to indoor air, for use in the calculation of screening values in connection with the investigation protocol discussed above and presented in Figure C9. A further upper bound AF of 3E-02 (33x attenuation) was recommended for groundwater (equilibrium vapour concentration) to sewer air, for an overall upper bound AF of 1E-03 (1000x attenuation), for calculating groundwater vapour to sewer to building air screening levels.