



**Report on:**

**Guidance on Site Characterization  
for Evaluation of Soil  
Vapour Intrusion into Buildings**

**Submitted to: Ministry of Environment  
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for Contaminated Sites in British Columbia**

**FINAL DRAFT REPORT**

**GUIDANCE ON SITE CHARACTERIZATION FOR  
EVALUATION OF SOIL VAPOUR INTRUSION  
INTO BUILDINGS**

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Submitted to:

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## PREFACE

This final draft report, prepared by Golder Associates Ltd. (Golder) for the Science Advisory Board for Contaminated Sites in British Columbia (SABCS), provides guidance on site characterisation for evaluation of soil vapour intrusion into buildings. As part of human health risk assessment, the soil vapour intrusion pathway is now commonly evaluated at contaminated sites where buildings are located near to subsurface volatile chemicals. The soil vapour intrusion pathway often requires that contaminant concentrations in soil vapour, and in some cases, indoor air be characterized as part of the risk assessment process.

The purpose of this guidance is to describe the framework, approach and methods for sampling, chemical analysis and data interpretation that should be considered when undertaking site characterization programs at contaminated sites where information obtained is used to evaluate potential human health risk from inhalation of soil vapour migrating into indoor air. Under the proposed framework for Screening Level Risk Assessment (SLRA) for Soil Vapour in British Columbia (Science Advisory Board (SAB), 2005), characterization of soil vapour will become an integral part of the risk assessment process; therefore guidance on soil vapour is warranted.

The guidance begins with an overview of the conceptual site model for soil vapour intrusion into buildings followed by approaches and methods for sampling and analysis of soil vapour and indoor air. While the focus of the guidance is characterisation of soil vapour and indoor air, the sampling and analysis of soil and groundwater media and collection ancillary data in the context of vapour intrusion studies are also addressed. The guidance concludes with recommendations for data interpretation and analysis, including consideration of quality assurance/quality control issues.

This guidance for soil vapour and indoor air characterization is based on the current state of the science. As the practice of site characterization and risk assessment advances, there will be new developments for protocols described in this guidance. These new advances should be incorporated in future updates to the protocol, as warranted.

This document was authored by Ian Hers, Ph.D. and Jeanette Southwood of Golder Associates Ltd. Valuable technical advice, input and external peer review was provided by Dr. Paul Johnson of Arizona State University, Mr. Matt Lahvis of Shell Research and Mr. Todd McAlary of Geosyntec Consultants. We also acknowledge the helpful review comments provided by the SABCS Review Task Group, comprised of the following individuals: Mr. Scott Hannam, ALS Environmental, Inc.; Dr. Jean Cho; Dr. Glenn Harris; BC Ministry of Environment and Mr. John Lambert (Roster Steering Committee representative).

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## **1.0 INTRODUCTION**

### **1.1 Purpose**

As part of human health risk assessment, the soil vapour intrusion pathway is now commonly evaluated at contaminated sites where buildings are located near to subsurface volatile chemicals. The soil vapour intrusion pathway, unlike other potential exposure pathways, often requires that contaminant concentrations in soil vapour, and in some cases, indoor air be characterized as part of the risk assessment process. The purpose of this guidance is to describe the framework, approach and methods for sampling, chemical analysis and data interpretation that should be considered when undertaking site characterization programs at contaminated sites where information obtained is used to evaluate potential human health risk from inhalation of soil vapour migrating into indoor air.

### **1.2 Soil Vapour Intrusion Pathway**

Soil vapour intrusion is the migration of volatile or semi-volatile chemicals from contaminated groundwater or soil into nearby buildings. When chemical releases occur near buildings, the subsequent volatilization of chemicals from the subsurface contamination can result in the intrusion of vapour-phase contaminants into indoor air. If the soil vapour intrusion pathway is complete, there may be the potential for unacceptable health risks to building occupants as a result of inhalation of vapours.

### **1.3 Scope**

The focus of this guidance is sampling and analysis of soil vapour and indoor air, although other media and ancillary data are also addressed. The guidance does not address characterization of soil and groundwater quality at contaminated sites. It is important that a sufficiently detailed investigation be completed such that an initial conceptual site model describing the soil vapour intrusion pathway can be developed prior to site characterization for soil vapour risk assessment purposes. While the context for this guidance is characterization of soil vapour intrusion, the concepts and methods described are applicable for any site assessment where soil vapour sampling is conducted.

The characterization methods described in this guidance are designed to provide the information needed to evaluate potential chronic health risks due to long-term exposure to vapours. The guidance does not address characterization to evaluate potential hazardous accumulation of gases and explosion or other safety risks. If the results of the soil gas sampling program indicate that there is an immediate safety concern, then emergency response or interim actions should be implemented as required under provincial or federal regulations.

## **1.4 Background and Need for Guidance**

Characterization of sites for evaluation of soil vapour intrusion can be relatively complex and may involve sampling of multiple media from different locations between the contamination source and the building. The development of technically defensible characterization programs requires an adequate conceptual site model, understanding of fate and transport processes, and knowledge of sampling methods and analytical protocols. The collection and use of soil vapour and indoor air data for evaluation of the soil vapour intrusion pathway is a relatively recent development and there is currently only limited guidance available. Under the proposed framework for Screening Level Risk Assessment (SLRA) for Soil Vapour in British Columbia (Science Advisory Board (SAB), 2005), characterization of soil vapour will become an integral part of the risk assessment process.

To meet these needs, comprehensive guidance on sampling design and methods, chemical analysis and data interpretation is provided in this document. To provide the context for sampling programs, a significant focus of the guidance is the background needed for understanding of fate and transport processes and conceptual site model development. The guidance attempts to balance prescription of methods, where appropriate and needed, with description of a range of approaches and methods, recognizing that soil vapour characterization is an emerging field and that there may be multiple methods that will yield acceptable results. Several checklists and exhibits are included to provide practical tools for practitioners working in this area.

## **1.5 Report Structure**

The report is organized as follows:

- Section 2 describes the conceptual site model for soil vapour intrusion and fate and transport processes for soil vapour; specific conceptual site scenarios are also provided for additional relevance respecting the range of possible site conditions;
- Section 3 provides guidance on soil vapour characterization, which includes sampling design, sampling methods and analytical protocols;
- Section 4 provides guidance on indoor air quality characterization, and includes specific aspects of the conceptual site model relevant to indoor air, preparatory tasks that are undertaken prior to indoor air sampling, indoor air sampling approaches and methods and analytical protocols, and;
- Section 5 describes the data organization, quality review and interpretation process.

## 2.0 CONCEPTUAL SITE MODEL FOR SOIL VAPOUR INTRUSION

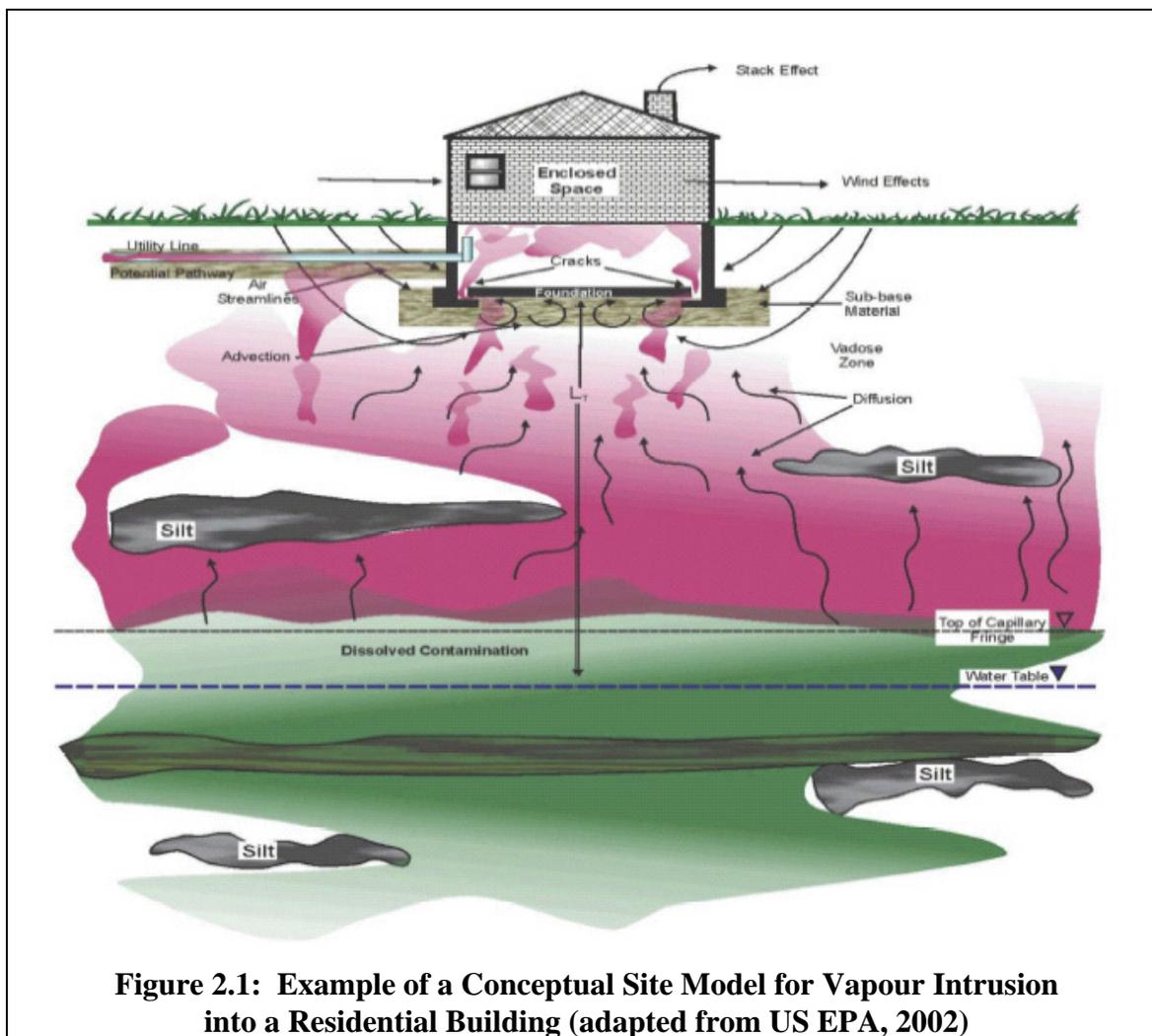
A conceptual site model (CSM) is a visual representation and narrative description of the physical, chemical, and biological processes occurring, or that have occurred, at a contaminated site. The CSM should be able to tell the story of how the site became contaminated, how the contamination was and is transported, where the contamination will ultimately end up, and whom it may affect.

A well developed CSM provides decision makers with an effective tool that helps to organize, communicate and interpret existing data, while also identifying areas where additional data is required. The CSM should be considered dynamic in nature and should be continuously updated and shared as new information becomes available (USEPA, 2002).

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

- The source and distribution of contamination (history of contamination, present conditions, and potential future conditions);
- The receptors that could be exposed to the contamination (under both present and future land use scenarios); and;
- The fate and transport pathways between the contamination and the receptors (under both present and future land use scenarios).

An example of a CSM for soil vapour intrusion is shown in Figure 2.1 below. The following sections present an overview of contamination sources and fate and transport processes, followed by specific CSM's of interest for vapour intrusion (Exhibit 1).



## 2.1 Contamination Sources

Contamination sources include non-aqueous phase liquid (NAPL), dissolved groundwater contamination or soil contamination. Common contaminants of potential concern for soil vapour intrusion comprise a range of organic chemicals including:

- Petroleum hydrocarbons, which can include fractions based on carbon chain length and hydrocarbon type (e.g., volatile petroleum hydrocarbon (VPH) and light extractable petroleum hydrocarbon (LEPH)), and specific chemicals of interest (e.g., benzene, toluene, ethylbenzene and xylenes (BTEX), hexane and decane);
- Light molecular weight polycyclic aromatic hydrocarbons associated with petroleum hydrocarbon, coal-tar or creosote contamination (e.g., naphthalene); and

- Chlorinated solvents and associated breakdown products of biodegradation (e.g., tetrachloroethylene or perchloroethylene (PCE), trichloroethylene (TCE), cis- and trans-1,2-dichloroethylene (cis-1,2-DCE), 1,1-dichloroethylene (1,1-DCE), vinyl chloride, 1,1,1-trichloroethane (TCA)).

Inorganic chemicals such as mercury may also pose a potential vapour inhalation risk. A screening process for determination of chemicals of sufficient toxicity and volatility is provided in the British Columbia Soil Vapour SLRA Guidance (SAB, 2005).

Soil vapour intrusion can also result from naturally occurring radon sources, landfills (e.g., methane), and other subsurface vapour sources (e.g., a leaking natural gas line). However, for the purpose of this guidance, only soil vapours arising from sites contaminated with organic chemicals are addressed.

## 2.2 Chemical Transfer to Vapour Phase (Volatilization)

Source contamination zones associated with spills of petroleum fuels, which are typically lighter-than-water NAPLs (LNAPLs), may consist of LNAPL within the unsaturated zone in the area of the release and a more laterally extensive LNAPL zone at the water table. Source contamination zones associated with spills of chlorinated solvents, which are typically denser-than-water NAPLs (DNAPLs), may consist of DNAPL within the unsaturated zone in the area of the release. DNAPLs are often also found below the water table, where they may form pools above soil layers of low permeability. Both LNAPL and DNAPL zones are sources of dissolved contaminant plumes in groundwater.

Equilibrium partitioning models are typically used to estimate the distribution of chemicals between different phases. Where NAPL is present above the water table, a two-phase model based on the vapour pressure of the chemical is used to estimate the soil vapour concentration. Raoult's Law is used to account for partitioning for a multi-component mixture of chemicals, which is a function of the mole fraction and vapour pressure, as follows:

$$C_v = 1000 * MW * X * VP / (R * T) \quad (1)$$

where  $C_v$  is the soil vapour concentration ( $\text{mg}/\text{m}^3$ ),  $MW$  is the molecular weight ( $\text{g}/\text{mole}$ ),  $X$  is the mole fraction (dimensionless),  $VP$  is the vapour pressure ( $\text{atm}$ ),  $R$  is the gas constant ( $\text{m}^3\text{-atm}/\text{K}\text{-mole}$ ) and  $T$  is the temperature ( $\text{K}$ ).

For dissolved chemicals in groundwater, the Henry's Law constant is typically used to estimate the vapour concentration in equilibrium with water, as follows:

$$C_v = C_g * H' \quad (2)$$

where  $C_g$  is the groundwater concentration (ug/L) and  $H'$  is the dimensionless Henry's Law constant. Since it is not possible to obtain a soil gas sample at the water table (i.e., due to the capillary transition zone), the measured soil vapour concentration should be lower than that predicted using the Henry's Law constant. This is because there will be attenuation of chemical concentrations by diffusion (and possibly biodegradation) within the capillary fringe and transition zone between the water table and region where there are continuous gas-filled soil pores. The attenuation within the capillary zone has implications for soil vapour intrusion modeling and comparison of measured and predicted soil vapour concentrations.

Where there is soil contamination, but no NAPL, a three phase model<sup>1</sup> for partitioning between sorbed, aqueous, and vapour phases can be used to estimate the soil vapour concentration, as follows:

$$C_t = C_w (K_d + (\theta_w + \theta_a * H' / \rho_b)) \quad K_d = K_{oc} * f_{oc} \quad (3)$$

where  $C_t$  is the total soil concentration (mg/kg),  $C_w$  is the soil-water concentration (mg/L),  $K_{oc}$  is the organic carbon-water partition coefficient (L/kg),  $f_{oc}$  is the fraction organic carbon (dimensionless),  $\theta_w$  is the water-filled porosity (dimensionless),  $\theta_a$  is the air-filled porosity (dimensionless),  $H'$  is the Henry's Law constant (dimensionless) and  $\rho_b$  is the bulk dry density (kg/L). If, under equilibrium, the three phases become saturated by the chemical, then the remainder of the chemical will be in its pure form (i.e., NAPL). Guidance on calculation of the soil saturation (" $C_{sat}$ ") concentration for NAPL is provided in USEPA (1996).

For non-ionizing organic chemicals, a linear equilibrium partitioning model is widely used to predict absorption of organics into native organic carbon. Studies have shown that the sorption of organics by soils is highly correlated with the  $f_{oc}$  (e.g., Chiou et al. 1979, Hassett et al. 1980), provided the  $f_{oc}$  is above a critical level. USEPA (1996) suggests that when  $f_{oc}$  is below about 0.001, adsorption to inorganic mineral surfaces becomes important. For most non-ionic organics, the sorbed phase is a linear function of equilibrium solution concentration up to 60 percent to 80 percent of its water solubility (Hassett and Banwart, 1989). While soil partitioning models are well established, the accuracy of such models to predict soil vapour concentrations is poor.

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<sup>1</sup> A four-phase model for partitioning between the sorbed, aqueous, soil-air and NAPL phases has recently been developed and applied to the vapour intrusion pathway (Park and San Juan, 2000). The four-phase model better accounts for mass and volume conservation between all four phases and may enable more accurate estimation of mole fraction in the NAPL phase, for a multi-component mixture.

## 2.3 Vadose Zone Fate and Transport Processes

Fate and transport processes in the vadose zone that influence the movement of chemicals from a contamination source toward a building include: diffusion; advection; dispersion; partitioning between soil, water and gas phases; and biodegradation reactions. Several of the fate and transport processes that influence soil vapour intrusion are conceptually shown in Figure 2.1. In this example, volatilization is occurring just above the top of the capillary fringe to create soil vapours. These vapours are subsequently transported upwards toward the ground surface via diffusion. Closer to the building, if the building is depressurized relative to atmospheric pressure, advective soil gas transport may be the dominant process. The rate of volatilization at the contamination source is controlled by the mass flux rate for chemical migration away from the source. This will vary temporally as a result of fluctuations in various factors such as moisture content, temperature and elevation of the water table.

### 2.3.1 Diffusion

Diffusion is the movement of molecules from an area of higher concentration to an area of lower concentration, as influenced by their kinetic energy. The rate that a chemical will diffuse is a function of the concentration difference, or gradient, and the compound- and temperature-dependent diffusion coefficient. Diffusion coefficients in air are about four orders-of-magnitude higher than in water; therefore, diffusion is much faster through the air-filled soil pores, than through water-filled soil pores.

The diffusion rate is slower in soil than in a gas-filled volume as a result of the tortuosity or non-linear migration path for diffusing gas species. Mathematically, this is expressed as the effective diffusion coefficient where the free-air diffusion coefficient ( $D^{\text{air}}$ ,  $\text{cm}^2/\text{sec}$ ) is multiplied by a tortuosity factor ( $\tau$ ), which is less than unity. A common empirical relationship for the tortuosity factor is the Millington-Quirk relationship (1961):

$$D^{\text{eff}} = \tau * D^{\text{air}} \quad \text{where } \tau = \theta_a^{3.33} / \theta^2 \quad (4)$$

When contamination is limited to dissolved chemicals in groundwater, diffusion through the capillary fringe is often the rate-limiting process because the moisture content in the capillary fringe is high, and may even be completely saturated. The thickness of the capillary fringe increases with decreasing soil grain size. Diffusion rates can also be highly sensitive to the presence of fine-grained, high moisture content soil layers within the vadose zone.

### **2.3.2 Sorption**

As soil vapours migrate away from contamination source zones, the transport of soil vapours will be retarded due to sorption to the soil matrix and transfer of chemicals into soil water. Soils with higher native organic carbon will tend to have a greater sorption capacity. While partitioning into soil water will occur rapidly, for some chemicals biodegradation may occur simultaneously to reduce the concentration in soil water. This allows for the continuous partitioning of the chemical into the soil water, thus reducing the concentration in the vapour phase.

### **2.3.3 Biodegradation**

Different organic compounds will biodegrade at different rates, and with various oxygen demands. For example, the aerobic biodegradation of volatile petroleum hydrocarbons in the vadose zone (e.g. BTEX) has been demonstrated through several investigations (Ostendorf and Campbell, 1991; Ririe et al., 1998; Roggemans et al., 2002; Hers et al., 2002). Several of these studies indicate significant bioattenuation can occur over short distances within the vadose zone. There is little information on vadose zone transformations of chlorinated solvent chemicals, although in groundwater environments, it has been demonstrated that TCE and PCE do not readily degrade under aerobic conditions but do degrade under anaerobic conditions (Wiedemeier et al., 1999).

### **2.3.4 Vadose Zone Advection**

Gas-phase advective transport can occur as a result of fluctuations in atmospheric pressure (e.g., barometric pumping), water movement, water table fluctuations, and density gradients due to composition and temperature variations (soil gas advection due to building depressurization is discussed in Section 2.4). For most geologic environments, diffusion is the dominant vadose zone transport process; however, soil gas advection can be important where there are high permeability, relatively deep unsaturated zone deposits (i.e., tens of metres deep) and/or methanogenesis is significant. Choi and Smith (2005) through a modeling study found that pressure-driven advective flux increased for deep, drier, permeable deposits; nevertheless, for all combinations of scenarios, the diffusive flux was at least one order-of-magnitude greater than the advective flux. They also found that daily water-table fluctuations with an amplitude of 0.1 m induce advection fluxes as large as those by barometric pumping. Where there are relatively high soil gas advection rates, dispersion may also be important. Dispersion is a mixing process that is caused by small-scale variations in air velocities in soil. The effects of these velocity variations are similar to the effects of diffusion (Auer, 1996).

## 2.4 Near-Building Processes for Soil Vapour Intrusion

The primary process for soil vapour intrusion into buildings is typically soil gas advection, although vapour migration will also occur as a result of diffusion through the building foundation. Model sensitivity analyses suggest that soil gas advection will be the dominant mechanism when the building depressurization (relative to ambient air) is greater than about 1 pascal (Hers et al., 2003; Johnson, 2005), which will be exceeded at many residential buildings.

Soil gas advection can occur through untrapped floor drains, edge cracks at the building wall and floor slab interface (shown in Figure 2.1), unsealed entry points for utilities, expansion joints and other cracks and openings, if present. Field research programs that include pressure data for soil adjacent to the building foundation indicate that most of the soil gas flow occurs within 1 to 2 m of the foundation (Garbesi *et al.* (1993); Hers et al, 2002). Therefore, the properties of the backfill surrounding the foundation are important, as well as any nearby utility corridors. Field measurements and model simulations indicate that for most sites, the permeability of soil near the building will control the rate of soil gas flow, as opposed to the permeability of the building foundation.

Depressurization of the building airspace relative to the ambient (outdoor) air pressure can be caused by a number of factors including temperature differences between indoor and outdoor air (i.e., “stack effect”), wind-loading and operation of the building heating, ventilation and air-conditioning (HVAC) systems. The operation of HVAC systems can cause a building to be depressurized through insufficient combustion air for furnaces or unbalanced heating and ventilation systems where the exhaust air flow rate exceeds the intake flow rate. For commercial buildings, HVAC systems are designed to control the pressure inside buildings. Buildings may be either positively or negatively pressurized depending on HVAC system design, operation and environmental conditions. Diffusion through the building foundation will readily occur through cracks and openings in the foundation. Diffusion rates through intact building materials are relatively low, but will depend somewhat on material type (e.g., poured concrete slab, concrete block wall, plastic moisture vapour barrier).

## 2.5 Summary

Diffusion is the dominant process for soil vapour transport in many geologic settings, although aerobic biodegradation of hydrocarbon vapours can be an important mechanism for vapour attenuation. Closer to a building, advective processes may be dominant. Soil vapour intrusion is influenced by building characteristics, geologic setting and anthropogenic features. There can be significant temporal variation in soil vapour intrusion due to environmental and building related conditions (Exhibit 2.1). Long-term transient effects may be important if there is depletion of the contamination source through volatilization, leaching and/or biodegradation.

## **2.6 CSM Information Requirements**

Information gathering is an important step in the development of the CSM. The data that should be obtained in order to support CSM development is summarized in the checklist provided in Appendix I. While often the focus of the site investigation is subsurface conditions, it is also important to evaluate building conditions. Information on commercial buildings may be obtained from design drawings and through discussions with mechanical and HVAC engineers. Additionally, if land use may change, the potential influence of future buildings and surface features on soil vapour intrusion should be considered.

**EXHIBIT 2.1. CONCEPTUAL SITE SCENARIOS**

**FRESH-WATER LENS**

For chemicals present only in groundwater (i.e., dissolved phase sources), their distribution below the water table will determine their potential to volatilize and migrate to indoor air. If volatile chemicals are present near the surface of the water table, volatilization will readily occur. In contrast, if there is a layer of “clean” groundwater above contaminated water, then the rate of volatilization will decrease since mass transport is controlled by diffusion and dispersion in groundwater. At some sites, the layer of clean water has been observed to increase in thickness with increasing down-gradient distance from a contamination source (i.e., “fresh-water lens formation”). If water table fluctuations are large compared to the amount of infiltration, the fresh water lens may not develop or may not be sustained. Vertical gradients may also affect the formation of a fresh water lens.

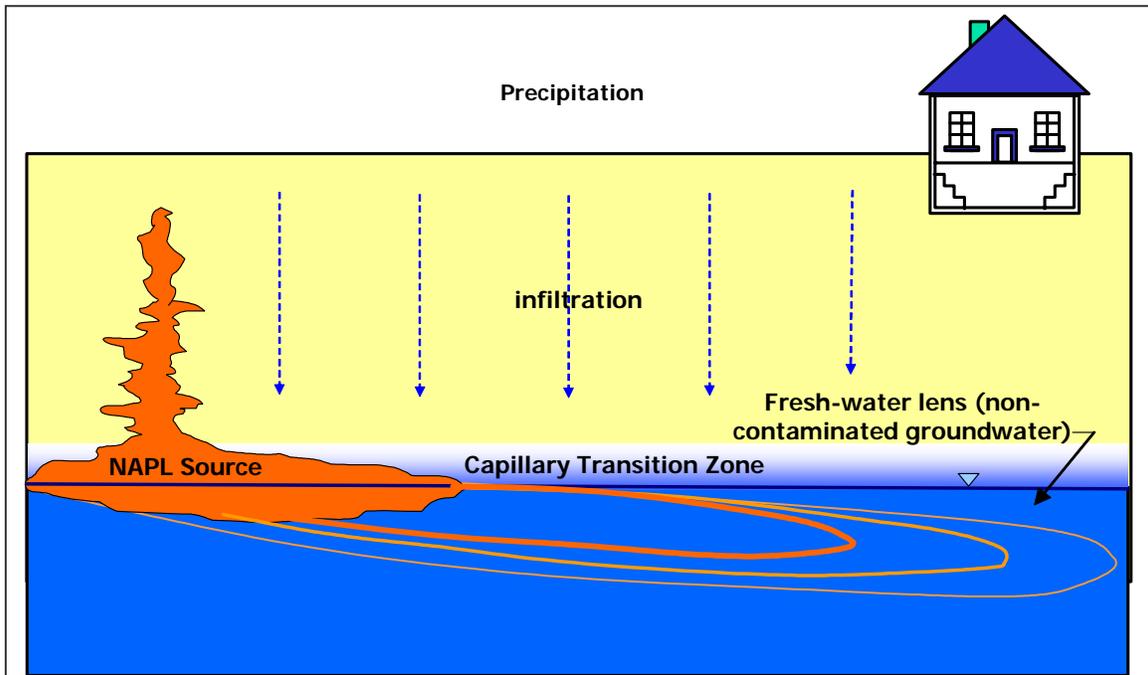
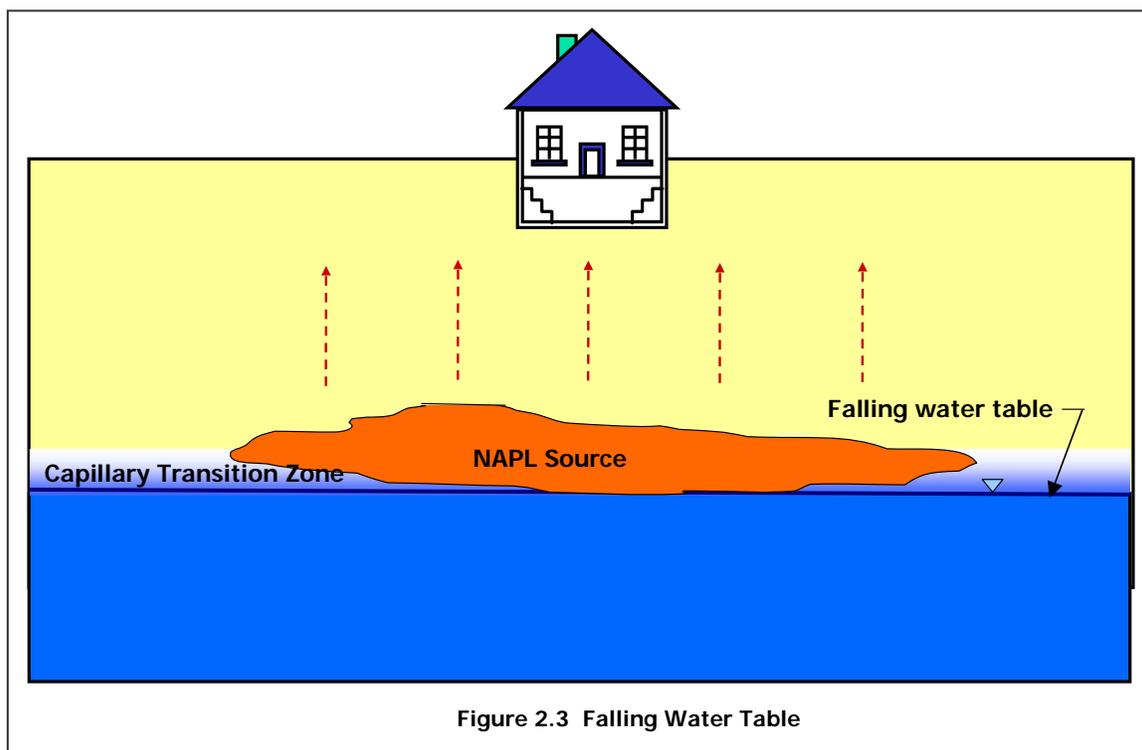


Figure 2.2 Fresh Water Lens

## FALLING WATER TABLE

If there is a water table decline of sufficient extent, higher levels of dissolved contamination or NAPL, if present, will become exposed to soil gas. This will result in increased volatilization rates. In addition, the beneficial effect of a fresh water lens may be lost if there is a significant drought, and the water table drops by a distance larger than the thickness of the fresh-water lens. Long-term water level data should be reviewed where available to assess the potential significance of water table fluctuations on volatilization rates and when to sample soil gas.



## LATERAL SOIL VAPOUR DIFFUSION

Organic chemicals released near ground surface may result in a contamination source in the unsaturated zone, which can potentially diffuse laterally toward adjacent buildings. For unsaturated zone sources, vapour diffusion in all directions will occur, which tends to result in a rapid decline in soil vapour concentrations with increasing lateral distance from the source, particularly for smaller contamination sources. In contrast, vertical profiles of soil vapour concentrations for some source geometries may be relatively consistent.

The presence of anthropogenic features such as paved surfaces, concrete slabs and fine-grained fill materials can reduce soil vapour flux to the atmosphere and may promote lateral diffusion of soil vapour. There will also tend to be greater lateral than vertical diffusion due to depositional history and soil layering, although the effect for most soils is relatively minor.

For the SAB SLRA soil vapour guidance, buildings more than 30 m from contamination were excluded from the screening process partly based on modeling studies that included lateral diffusion and which indicated a significant decline in predicted vapour concentrations over this distance (Mendoza, 1995; Abreu, 2005; Lowell and Eklund, 2004). A semi-logarithmic chart of concentration versus log of distance may help estimate the distance where soil vapour concentrations fall below levels of potential concern.

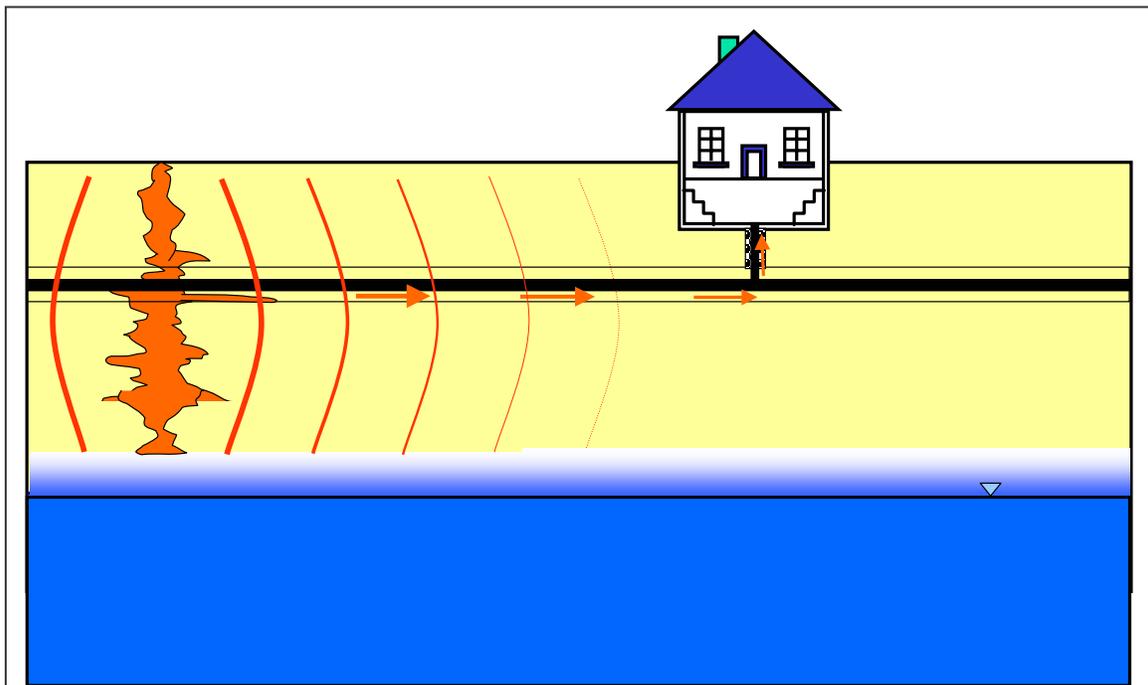


Figure 2.4 Lateral Diffusion and Preferential Pathways

## TRANSIENT SOIL VAPOUR MIGRATION

After a spill has occurred, sorption into native organic carbon will initially cause concentrations to be transient as soil vapour migrates from the source. After a period of time, an approximate steady state vapour profile will develop after sorption sites are filled (assuming no biodegradation). There are also transient effects through partitioning into soil moisture, which may be significant for soluble chemicals such as MTBE. The time for a steady state profile to develop will depend on chemical and soil properties and the thickness of the uncontaminated soil layer. The time for steady state conditions can be estimated through an analytical solution for one-dimensional steady-state diffusion and sorption based on linear partitioning into native organic carbon. For example, based on solutions to this equation provided by Johnson et al. (1998), for trichloroethylene, the approximate time required for a steady state diffusion profile to develop would be approximately 0.5 years, for a depth to contamination of 3 m, and 5.7 years, for a depth to contamination of 10 m.<sup>2</sup> The time to steady state has implications for design of soil gas sampling programs (i.e., sampling location and when to sample).

## HYDROCARBON VAPOUR BIODEGRADATION

The biodegradation of hydrocarbon vapours depends on site specific conditions. Aerobic biodegradation rates will depend on several factors including chemical-specific biodegradation kinetics, oxygen availability, presence of requisite microbes, moisture content, availability of nutrients and pH. Vertical soil gas profiles of the hydrocarbon of interest, oxygen and carbon dioxide can provide information on where, and to what extent, biodegradation is occurring. Since several studies suggest that hydrocarbon vapour biodegradation readily occurs in the presence of oxygen, the main issue for vapour intrusion is whether there is sufficient oxygen below the building for attenuation of vapours to occur prior to migration to the building. Factors affecting oxygen levels below the building include source vapour concentrations, soil properties including organic matter content, building size relative to depth to the vapour source, ability of oxygen to migrate through surface materials adjacent to the building and building foundation itself, and processes such as barometric or diurnal pumping, which may serve to increase transfer of air (oxygen) to below the building. Conceptually, there is greater opportunity for the significant oxygen levels below buildings when the depth to the vapour source is large, the building is small, and the surface cover besides the building is permeable.

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<sup>2</sup> The input parameters for this calculation are water-filled porosity equal to 0.1, total porosity of 0.3 and organic carbon fraction of 0.006.

## **BAROMETRIC PUMPING**

A potentially important mechanism for soil gas advection is “barometric pumping,” caused by cyclic changes in atmospheric pressure. These changes create a “piston-like” force on soil gas, causing compression of soil gas when the air pressure increases, and expansion when it decreases. This may result in a cyclic up and down movement of contaminant vapours in the affected interval. Typically, the maximum variation in barometric pressure is about three percent over a 24-hour period (Massman and Farrier, 1992). Assuming gas compression according to the ideal gas law, atmospheric air will be pushed into surface soil to a depth up to about three percent of the total depth of the unsaturated zone. For a 10 m thick homogeneous unsaturated soil column, this means that the top 0.3 m of soil would be affected by the complete barometric flushing of soil gas.

The magnitude of the pumping effect decreases with increasing depth, and also is affected by pressure dampening and time-lag in the pressure response, which can be significant for finer-grained deposits. There are unpublished accounts of barometric pumping causing significant movement of soil gas in deep (greater than 100 m), unsaturated, fractured bedrock deposits where a “breathing” phenomena has been observed (i.e., air flowing in and out of wells).

Close to a building, barometric pumping may result in the movement of atmospheric air in and out of foundation subsoils. Barometric pressure fluctuations may also result in episodic soil gas intrusion. If there is a low permeability surface seal adjacent to buildings, cross-foundation slab pressure gradients may be generated when the barometric pressure decreases. One study reported measured transient cross-slab differential pressures of up to 500 Pascals (Adomait and Fugler, 1997).

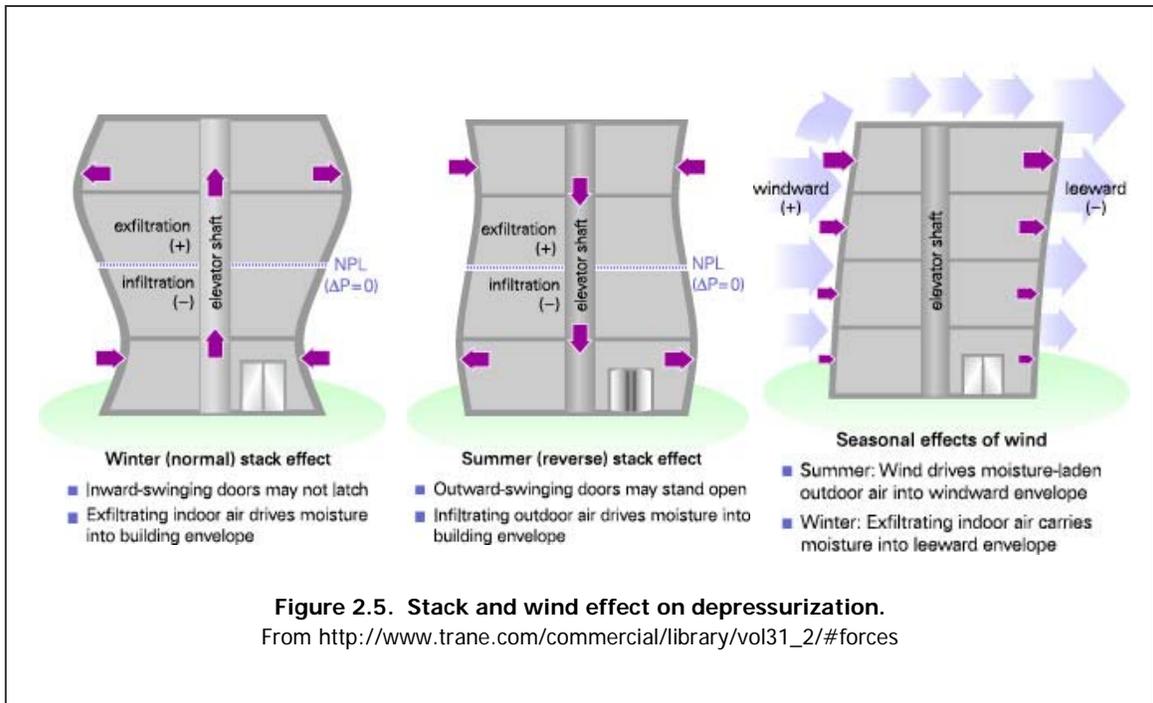
## **PREFERENTIAL PATHWAYS**

The presence of preferential pathways such as utility conduits with granular backfill, which intersect a contamination source and connect to the building, may result in enhanced soil vapour intrusion. Since most buildings have subsurface utility penetrations, their presence alone is not typically of concern. Of relevance are pathways that facilitate enhanced movement of soil vapour toward and into a building.

**STACK EFFECT**

The heating of a building, either by furnace, radiator, or other sources (i.e. sunlight on the roof) creates a “stack effect” as warm air rises in the building. This causes an outward air pressure in upper storeys and inward air pressure near the base of the building. Warm air that escapes is replaced by air infiltrating through doors and windows and soil gas migrating through the foundation. The magnitude of the depressurization at the base of the building is proportional to the height of the building, although tall buildings are designed with features to minimize cross-floor leakage of air and excessive depressurization.

Elevator shafts may represent both a preferential pathway for soil gas intrusion at the base of the building (a drain is often present in the elevator pit) and for upward movement of air within the building.



## FOUNDATION CONSTRUCTION

Conceptually, different foundation construction could lead to different processes for soil vapour intrusion. For example, higher soil gas advection rates would be expected for houses with basements, due to higher depressurization and larger subsurface foundation surface area for intrusion. For houses with crawlspace foundations, the degree to which the crawlspace is ventilated by outside air and the influence of cross-floor mixing and leakage between the crawlspace and main floor could affect soil vapour intrusion rates. Although working hypotheses have been developed, the influence of foundation type on soil vapour intrusion is still poorly understood. However, there is empirical data indicating that soil vapour intrusion can be significant for several different types of building foundations including basements, crawlspaces and slab-at-grade construction.

## TEMPORAL AND SEASONAL CONSIDERATIONS

Potential temporal factors influencing soil vapour intrusion are complex. Higher building depressurization and soil gas intrusion rates would be expected during the heating season. Winter frost or higher soil moisture in near surface soils may limit the surface flux of volatiles to the atmosphere. As a consequence, the migration of soil vapour toward drier soils below the building may be enhanced. In some cases, intensive rain and wetting fronts can induce advective movement of soil gas, which may, in turn, cause nonequilibrium mass transfer of the contaminants between the water and the gas phases (Cho *et al.*, 1993).

Surface soils with high moisture content may also reduce migration of atmospheric oxygen into soil, which may reduce aerobic biodegradation of hydrocarbon vapours. An off-setting factor is that during summer, near surface ground temperatures may be higher leading to slightly higher volatilization rates, since the Henry's Law Constant is temperature dependent. The amplitude in seasonal temperature variation decreases with increasing depth below ground surface, and at many sites, temperature effects will be insignificant.

The influence of seasonal factors on building ventilation, which acts to dilute vapours, is difficult to predict. While natural ventilation through open doors or windows may be reduced in winter, there may be increased air exchange through building depressurization and operation of a furnace. There can also be significant short-term variability unrelated to seasonal factors caused by diurnal temperature fluctuations, occupant use (e.g., opening windows and doors), wind, and barometric pressure variations. On balance, the above factors suggest that in British Columbia, soil vapour intrusion would tend to be greatest during winter months based on climatic conditions.

**BUILDINGS AND TANKS AS SOIL VAPOUR SOURCES**

While the usual paradigm for soil vapour transport is upward migration from a contamination source located at or near the water table, if there is a surface contamination source, vapours will migrate in all directions, including downwards. Indoor air that is affected by contamination sources within a building may affect subsurface vapour concentrations if the building is positively pressurized (McHugh et al., 2006). In this case, air will move downwards through the foundation. Once below the building, vapours could diffuse away from the building, thus creating a zone of impacted soil vapour. While it would be rare for buildings to have a significant effect on subsurface soil vapour concentrations, a dry cleaner is one possible example of where this could occur. Leaking underground storage tanks also represent potential soil vapour sources.

### **3.0 SUBSURFACE CHARACTERIZATION FOR EVALUATION OF SOIL VAPOUR INTRUSION**

#### **3.1 Overview**

This chapter describes methodologies for completing site characterization programs at sites where the information obtained is used to evaluate soil vapour intrusion into buildings. The focus of this chapter is investigation methods for characterization of soil vapour, since at many sites soil vapour measurements are an important component of a technically defensible assessment of soil vapour intrusion. This chapter also provides a brief summary of considerations for sampling and analysis of other media (soil and groundwater), and describes ancillary information that may assist in the interpretation of soil vapour data and evaluation of soil vapour intrusion.

Soil vapour is generally considered to be the most reliable medium for evaluation of the soil vapour intrusion pathway since it provides a direct measure of the contaminant phase that may migrate into indoor air. While the use of soil vapour is preferred for risk assessment purposes, it is critical that an appropriate sampling approach and methods be followed to avoid invalid conclusions being drawn from the data collected. Measured soil and groundwater concentrations may also be used for evaluating the vapour intrusion pathway through estimation of the chemical partitioning from soil or groundwater to soil vapour. However, there are limitations and uncertainties associated with the use of soil data, and to a lesser extent groundwater, for evaluating soil vapour intrusion, as subsequently discussed in this chapter. While the context of this chapter is guidance on methodology for evaluation of soil vapour intrusion, the concepts and techniques described are applicable for any site assessment where soil vapour sampling is proposed.

There are three basic steps in the design of a soil vapour characterization program (API, 2005):

1. Develop a conceptual site model (CSM), with specific consideration of factors that influence soil vapour, and update the CSM as new data is collected.
2. Develop site characterization objectives to address the questions that need to be answered, recognizing regulatory requirements and the purpose of the assessment.
3. Develop a detailed sampling plan that begins with the sampling approach and strategy, and then provides details on sampling locations, frequency and methods.

Since soil vapour characterization programs are highly influenced by site specific conditions and project-specific objectives and potential constraints, it is not possible to provide a standardized template for sampling design and methods. However, the key principles and factors that should be considered in developing a sampling strategy are outlined and a range of methods are described to provide the practitioner with the necessary approaches and tools to investigate this pathway. A checklist to assist with the development of a soil gas sampling and analysis program is also provided in Appendix I.

## **3.2 Development of Soil Vapour Investigation Approach and Design**

### **3.2.1 Define Study Objectives**

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

- Compare measured soil vapour concentrations to risk-based generic or site-specific soil vapour criteria;
- Provide soil vapour data needed for input into models used for site-specific risk assessment;
- Evaluate hydrocarbon vapour biodegradation through collection of soil vapour samples from vertical profiles or lateral transects;
- Evaluate cross-media transfer (chemical partitioning and attenuation through the capillary fringe) through comparison of measured concentrations in groundwater and soil vapour, at nearby sampling points;
- Evaluate models used to simulate soil vapour transport through collection of soil vapour samples at various points along the migration pathway and comparison to model-predicted soil vapour concentration profiles; and
- Evaluate the influence of background chemical sources on indoor air samples through concurrent collection of subslab vapour and indoor air samples.

The study objectives should be well defined prior to developing a sampling plan, as the sampling plan could vary substantially depending on the type of data required and how that data is intended to be used. The type, number, locations and frequency of samples obtained may all vary depending on the study objectives.

### 3.2.2 Develop Investigation Approach

In developing the investigation approach, consideration should be given to the following key concepts for soil gas characterization programs. Typically, multiple samples from different locations should be tested to characterize variability in soil gas concentrations and improve confidence in the results and conceptual site model. A phased sampling program, beginning with characterization of soil vapour near the contamination source followed by sampling closer to the buildings of potential concern, may be needed to meet the site characterization objectives. Depending on the site conditions and initial results, repeat testing over different time periods to capture possible seasonal variations may be warranted.

There are often significant spatial and temporal variations in soil vapour concentrations. Contamination source zones are variable and, as a consequence, there are often large differences in near-source vapour concentrations. A large reduction in soil vapour concentrations over small distances may result when there are soil layers with high moisture content (e.g., fine-grained layer) or aerobic biodegradation of hydrocarbon vapours (Fischer et al., 1996, Hers et al., 2000). There may also be significant lateral concentration gradients over short distances as evidenced by large concentration differences for probes situated on either side of houses (Sanders and Hers, 2006). The variability in soil vapour concentrations will tend to increase as the distance from the contamination source increases.

The number and spacing of probes will depend on the heterogeneity and anticipated variability in soil gas concentrations. When determining investigation locations consideration should also be given to utility corridors, particularly where they intersect confining layers.

### 3.2.3 Define Soil Vapour Sampling Locations

An important consideration for the design of a soil vapour study is the sampling location. Possible options for sampling locations (Figure 3.1) include:

- Deep soil vapour sample near the vapour contamination source obtained beside (external to) a building;
- Shallow soil vapour sample obtained beside (external to) a building; and
- Subslab soil vapour sample obtained below the building;

Soil vapour sampling may also be required if currently there is no building, but future development is planned.

The factors affecting deep, shallow and subslab soil vapour concentrations and potential advantages and disadvantages with each type of sampling location are summarized in Table 3.1 and discussed below.

### Deep Soil Vapour

Soil vapour samples obtained from near the vapour contamination source will tend to be stable seasonally and are relatively unaffected by near-surface processes (i.e., building, weather conditions). Deeper soil vapour concentrations are also less influenced by biodegradation or biotransformation processes and will reach steady state conditions relatively quickly. When there is bioattenuation, the use of deep soil vapour concentrations will typically result in a more conservative estimate of indoor air concentrations and health risk, compared to use of shallow soil vapour. Soil vapour characterization should generally begin with testing of deeper soil vapour samples collected from close to the vapour contamination source. If near-source vapour concentrations are above levels of potential concern, a subsequent investigation phase could include collection of shallow or subslab vapour samples.

When the objective is to initially obtain deep soil vapour samples above a groundwater contamination source, it is important to recognize that soil vapour samples cannot be obtained until there is a continuous interconnected network of gas-filled pores, which is a function of the capillary transition zone height above the water table. The height above the water table where the transition to continuous gas-filled pores begins can be approximated using a water retention model (e.g., Van Genuchten model). Using model input parameters for US Soil Conservation Service (SCS) soil texture classifications, the predicted height of this transition point is approximately 17 cm for sand and 38 cm for loam. When a small additional allowance is included for water table fluctuations, these transition height estimates would suggest that soil gas probes should generally be installed about 0.5 m to 1 m above the water table. Additional information on the water retention modeling is provided in Golder (2004).

The lateral spacing of deep soil gas probes needed to characterize soil vapour source zones is highly dependent on site conditions and the number and size of buildings where soil vapour intrusion is of potential concern. For large disperse groundwater plumes, a soil gas probe spacing of several tens of meters may be adequate. For smaller plumes and areas where steep concentration gradients are expected in groundwater, more closely spaced probes are warranted (e.g., 10 m to 20 m, or spacing similar to the size of a house). Where there are steep concentration gradients, a minimum of two soil gas probes on opposite sides of a building would generally be warranted, with one probe located in the direction of highest concentrations.

### Shallow Soil Vapour (External to Building)

Shallow soil vapour samples are more likely to be affected by surface characteristics (e.g., paved versus non-paved) and changes in near-surface conditions such as barometric pressure or temperature fluctuations. Near a building, soil gas advection, caused by building depressurization, and variation in foundation subsoils can cause variability in soil vapour concentrations.

Bioattenuation is an important process for aerobically biodegradable chemicals (e.g., petroleum hydrocarbon compounds such as BTEX) that should be taken into account when considering where to locate soil gas probes. As discussed in Chapter 2, for some sites, soil vapour concentrations below a building may be significantly higher than the vapour concentrations beside a building (i.e., at the same elevation) due to oxygen transport limitations and drier soils below the building. The use of non-representative soil vapour concentrations external to the building could lead to non-conservative predictions of indoor vapour concentrations.

To address the above issues, the SLRA guidance for soil vapour developed by the SAB requires that external soil vapour samples used for input in risk assessment be constrained as follows:

- Vertically, a minimum of 1 m below the elevation of the foundation slab base and 1 m below ground surface.
- Laterally, close to the building but beyond the zone of disturbance and fill beside a building (generally 1 to 2 m from the foundation wall). This distance may also depend on whether access agreements can be obtained.

Samples constrained to the above criteria will tend to be beyond the advective zone of influence associated with barometric pumping and building depressurization, and of sufficient depth to minimize the potential for atmospheric air to be drawn into the sample. For non-degrading chemicals, samples from these locations should provide for reasonably representative soil vapour concentrations. For chemicals which undergo aerobic biodegradation, there is still debate as to where external soil gas samples should be obtained for risk assessment purposes, and there is little field data comparing soil vapour concentrations from beside and below buildings. A conservative approach would be to obtain soil vapour samples from just above the contamination source, since these samples would be least affected by bioattenuation. However, this approach limits flexibility in terms of sampling (deep samples are required) and incorporation of bioattenuation in risk assessments.

This guidance allows for the use shallow (up to 1 m below foundation) external soil gas samples for biodegradable chemicals, if through a detailed sampling program and lines-of-evidence evaluation it can be reasonably demonstrated that shallow external soil vapour data is likely representative of below building conditions, as described in Section 3.2.7.

### Subslab Soil Vapour

Characterisation of subslab soil vapour below a building foundation may be warranted when deeper soil vapour tests indicate potentially unacceptable health risk. Subslab soil gas testing can also be advantageous in that subslab vapour concentrations are typically much higher than typical background indoor air concentrations where vapour intrusion is occurring; therefore, the ratio of subslab to indoor air concentrations can be used to evaluate potential background sources of VOCs. It is noted that, with barometric pressure fluctuations and positively pressurized buildings, it is also possible for indoor air to move from the building into the subslab soil gas. If indoor air contains elevated VOC concentrations (e.g., as seen at some dry cleaner sites), this could confound interpretation of subslab data. The reverse intrusion phenomenon is likely to be rare for most residential buildings because of the lack of sustained positive pressure.

There are potential drawbacks associated with subslab sampling that should be recognized. It requires an access agreement from the building owner, and is intrusive in that drilling or coring equipment must be used inside the building and floor coverings may be damaged, which may be disruptive or unpleasant for owners and occupants. It may also be difficult to determine subsurface utility locations below slabs, although geophysical techniques (e.g., ground penetrating radar) can be used for this purpose.

There are limited data on spatial variability in subslab vapour concentrations or how subslab concentrations vary over time as a result of barometric pressure fluctuations or other environmental factors. The following factors should be taken into account when designing a sampling program that includes the collection of subslab soil vapour:

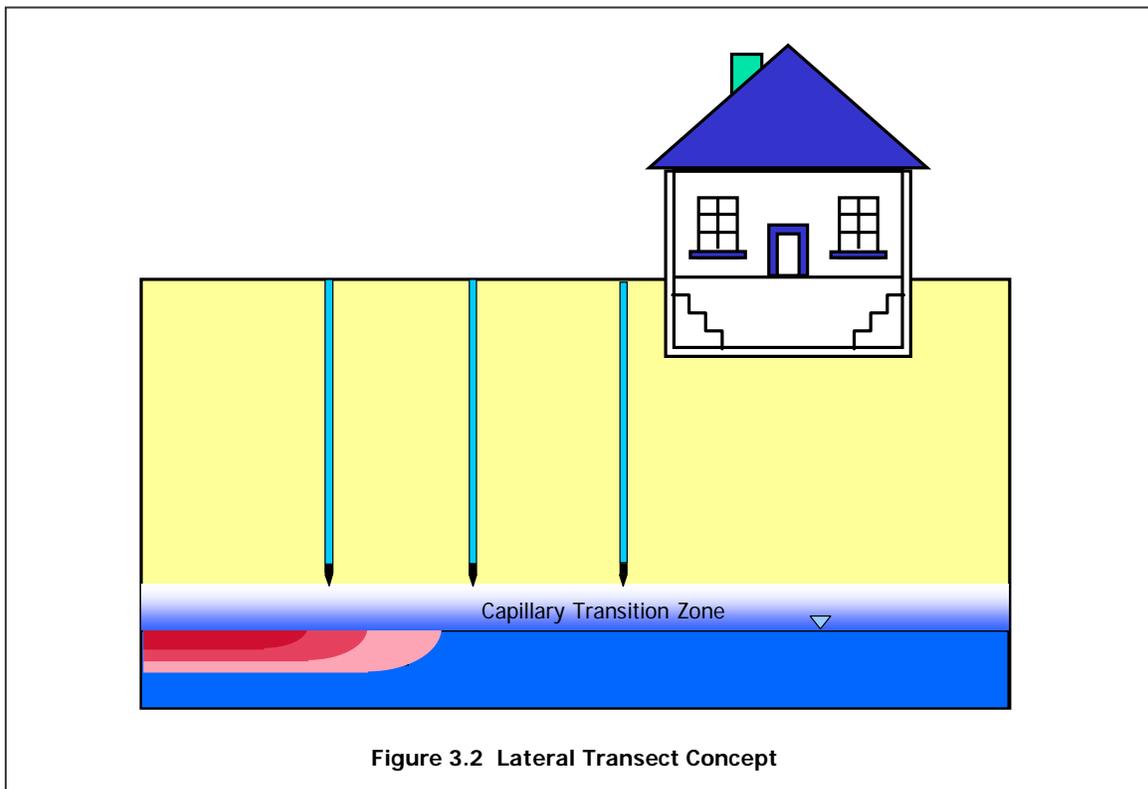
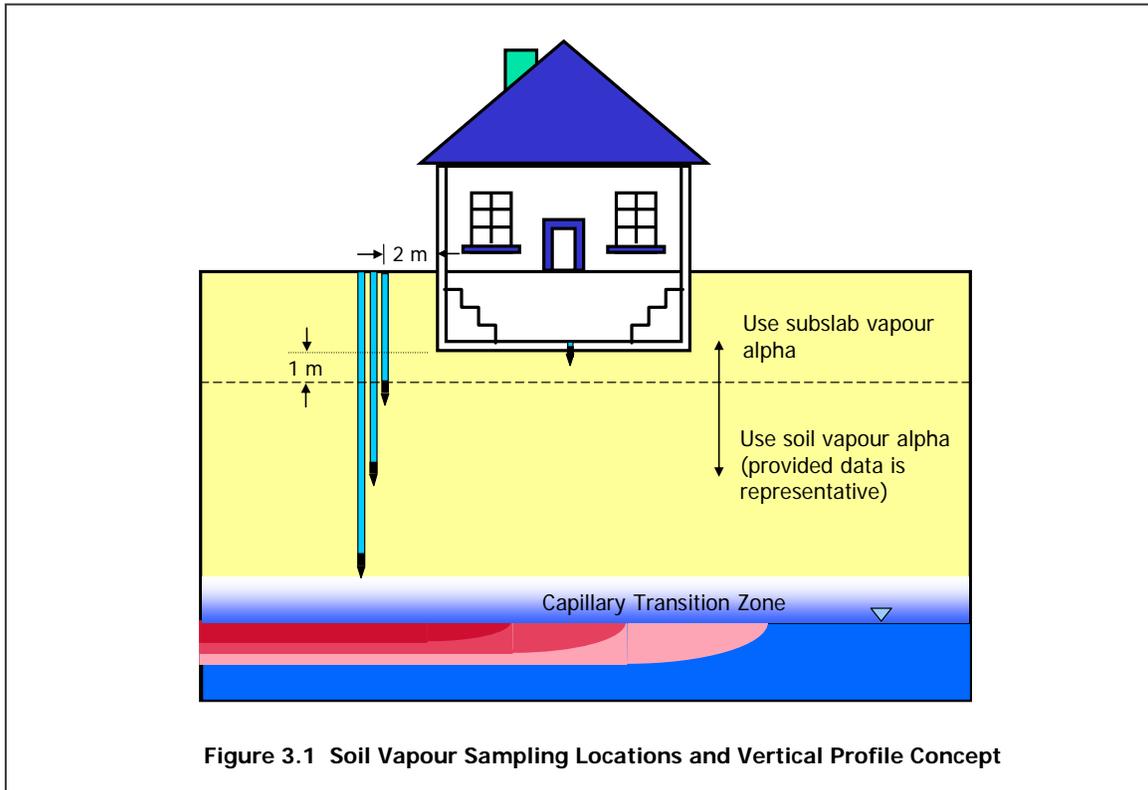
- A coarse-grained soil layer below a building foundation, or small crack or void below the foundation slab due to settlement will tend to promote advective soil gas transport, lateral mixing and uniformity of vapours immediately below the slab;
- There may be spatial or temporal variations in subslab vapour concentrations as a result of source concentration variability, biodegradation of hydrocarbon vapours or advective pumping of soil gas caused by barometric pressure changes; and
- Subslab vapour concentrations may be highest near the centre of a building for a uniform contamination source; however, the soil gas advection rates into a building may be greatest at a perimeter crack, which may be present along the interface between the floor slab and foundation wall.

Subslab soil vapour sampling protocols are just now being developed by various agencies. Some advocate a minimum of three subslab samples below a typical single-family residence (USEPA, 2002) (although this may be more than needed), so sub-slab sampling costs are not insignificant, especially if the vapour intrusion assessment includes a neighbourhood of residences and temporal monitoring is required.

The number and location of subslab soil vapour samples that should be tested will depend on site-specific conditions. For small to moderate sized houses, one subslab sample, preferably located in a central location away from the foundation footings, is considered reasonable for screening purposes. It is recognized that practical considerations (e.g., homeowner access) will often dictate the location of subslab soil vapour samples. For larger buildings, multiple samples are recommended to investigate the variability in subslab soil vapour concentrations and for some buildings, it may be desirable to install sufficient probes to delineate areas with elevated subslab vapour concentrations. It is expected that future updates of this guidance will include a more definitive recommendation on the appropriate number of subslab samples as additional experience is gained in this area.

**Table 3.1. Comparison of Soil Vapour Measurement Locations**

<b>Type of Soil Vapour Data</b>	<b>Where Obtained</b>	<b>Characteristics</b>	<b>Use of Data and Cautions</b>
Deep Soil Vapour (external)	As near to water table as practical, subject to considerations relating to capillary fringe and depth limitations for drilling (e.g., 15 m)	<p>Concentrations reach near-steady conditions quickly, tend to be stable seasonally and are relatively unaffected by near surface changes</p> <p>Least affected by biodegradation</p> <p>Should represent the highest concentrations of soil vapour</p>	<p>If deep vapour concentrations are below target levels, vapour to indoor pathway likely not significant</p> <p>For future development scenario, only deep vapour concentrations should be used</p>
Shallow Soil Vapour (external)	Close to the building, but outside perimetric area Minimum 2 m laterally from building Minimum 1 m below base of foundation and ground surface	<p>More likely to be affected by changes in near-surface conditions including barometric pumping, temperature changes, moisture content and variability in near building soils</p> <p>May be affected by bioattenuation depending on chemical</p> <p>Greater potential for non steady state conditions depending on distance from vapour source to measurement point.</p> <p>Shallow soil vapour concentrations should be lower than deep concentrations</p>	If there is significant bioattenuation beside but not below building, use of shallow soil vapour may result in non-conservative indoor vapour
Subslab Soil Vapour	Immediately below foundation slab Generally, central location away from the foundation footings preferred	<p>Higher temporal and spatial variability expected as samples are affected by changes in near-surface conditions such as barometric pumping, temperature changes, HVAC systems and variability in foundation subsoils</p> <p>If bioattenuation is occurring, may provide for more representative prediction of indoor vapour concentration since empirical vapour attenuation factors typically used already reflect the effect of biodegradation between the vapour source and the building.</p> <p>Greater potential for non steady state conditions depending on distance from vapour source to measurement point.</p>	<p>Logistical issues associated with sample collection</p> <p>Depending on where subsurface vapours enter a building through the building foundation, subslab sample location may or may not be representative of the vapour concentrations entering the building</p> <p>May be affected by subslab utilities</p>



### **3.2.4 Lateral Transects and Vertical Profiles**

The soil vapour sampling design may employ transects or vertical profiles to characterize spatial variation in concentrations (Figures 3.1 and 3.2). Lateral transects or vertical profiles can provide useful information for more in-depth analysis of the effect of biodegradation or fine-grained soil layers on soil vapour transport and pathway evaluation. Transect or vertical profile data can increase the level of confidence in the CSM for soil vapour transport and data quality.

Lateral transects are generally used when the contamination source is laterally removed from the building. Generally, a minimum of three samples should be used as part of a transect, consisting of soil gas samples from (i) the edge of contamination source nearest to building, (ii) the mid-point between source and building, and (iii) the edge of building (API, 2005). While three sampling locations are likely sufficient for many sites, consideration could be given to additional intermediate probes if the distance between the contamination source and building is greater than 30 m.

Vertical profiles are generally used when the contamination source is below the building. Again, three or more samples should be obtained from (i) just above the contamination source, (ii) mid-point between upper and lower sampling point, and (iii) a sampling point located near the building. The upper sampling point is obtained 1 m below the base of the building foundation. Therefore, vertical profiles can only be installed when the contamination source is at least 2 to 3 m below the building foundation. When the contamination source is within 1 m of the building foundation, subslab soil gas probes should be installed.

Additional probes are recommended where there are changes in lithology, where changes in concentrations are expected, where the pathway is uncertain, or where the distance between the source and building is sufficiently large. The soil vapour sampling design should also consider the potential implications of subsurface utilities for sampling locations since utilities may represent preferential pathways for soil vapour migration.

### **3.2.5 Biodegradation Assessment**

At some sites, more detailed monitoring of soil vapour may be warranted to evaluate the biodegradation of petroleum hydrocarbon vapours and to determine whether the soil vapour transport to indoor air pathway is complete (i.e., are hydrocarbon vapours biodegraded to negligible concentrations before reaching the building). When evaluating biodegradation in the context of the vapour intrusion pathway, it is important to recognize that the building may influence local conditions for biodegradation below and near to the building.

The recommended biodegradation assessment consists of sampling of vertical profiles adjacent to the buildings of potential concern, or lateral transects if the contamination source is offset from the building. Since there are often significant lateral concentration

gradients at hydrocarbon-contaminated sites, it is critical that sufficient soil vapour samples be analyzed to evaluate concentration variability and that the soil vapour profile used for bioattenuation assessment be obtained in the direction of highest source vapour concentrations. In addition, if possible, the probes should be situated below a surface cover of similar permeability and size compared to the building (concrete or asphalt of reasonable quality). Probes should be installed below the middle of such surface slabs. To provide for delineation of biodegradation effects, four vertical probes are generally recommended, although three may be sufficient if the distance between the building and source is small. The shallowest probe used for risk assessment input should be a minimum of 1 m below the base of the building foundation. The deepest probe should extend to near to the contamination source. Bioattenuation assessments should also include careful assessment of the contamination source zone distribution through collection of soil samples and field headspace vapour testing (e.g., using a photoionization detector) and laboratory analysis of selected soil samples. A continuous soil core is recommended so that the lithology can be examined. Fine-grained soils with high moisture content can act as diffusive barriers, which give the appearance of bioattenuation. Since soils below a building will tend to be drier, there may be less attenuation through diffusion below the building.

Soil gas samples should be tested for the hydrocarbon vapours of potential concern, and as a minimum, for oxygen, carbon dioxide and methane. These gases provide an indication of microbial activity occurring through aerobic or anaerobic processes. For example, depleted oxygen and elevated carbon dioxide levels are indicators of aerobic biodegradation of hydrocarbons. Consideration should be given to the analysis of certain hydrocarbon compounds (e.g., cyclohexane, 2,2,4-trimethylpentane) that are more volatile than the BTEX compounds, and potentially less biodegradable, and which serve as useful tracers for hydrocarbon vapour transport (Sanders and Hers, 2006).

The assessment of bioattenuation should consider the potential for reduced biodegradation below buildings and non-representative soil vapour conditions external to the building. The key factors affecting bioattenuation below buildings include source vapour concentration, the depth to vapour source below the building, the building size, the connection between ground surface beside building and foundation subsoils, and lateral uniformity of contamination below the building. The conditions leading to non-representative external soil vapour concentrations (subslab concentrations that are higher than external concentrations) and representative external soil vapour concentrations (similar concentrations) are evaluated in Table 3.2.

**Table 3.2. Evaluation of Factors Affecting Below Building Hydrocarbon Vapour Bioattenuation and Soil Vapour Data Representativeness**

<b>Conditions that Limit Below Building Bioattenuation and Lead to Non-Representative External Soil Vapour Data</b>	<b>Conditions that Enhance Below Building Bioattenuation and Lead to Representative External Soil Vapour Data</b>
<ul style="list-style-type: none"> <li>▪ <i>Higher source vapour concentrations</i> (e.g., LNAPL above water table): Greater oxygen demand.<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>▪ <i>Lower source vapour concentrations</i> (e.g., dissolved groundwater plume): Less oxygen demand.<sup>3</sup></li> </ul>
<ul style="list-style-type: none"> <li>▪ <i>Shallow depth</i> to vapour contamination source and <i>larger building</i> size: Less opportunity for oxygen migration to below the building.<sup>1</sup></li> </ul>	<ul style="list-style-type: none"> <li>▪ <i>Deeper depth</i> to vapour contamination source and <i>smaller building</i> size: Greater opportunity for oxygen migration to below the building.<sup>1</sup></li> </ul>
<ul style="list-style-type: none"> <li>▪ <i>Foundation subsoils</i> that are <i>not well connected</i> to ground surface: Less opportunity for oxygen migration to below the building due to near-building capping effect (e.g., low permeability soils or high soil moisture).</li> </ul>	<ul style="list-style-type: none"> <li>▪ <i>Foundation subsoils</i> that are <i>well connected</i> to ground surface: Greater opportunity for oxygen migration to below the building through barometric pumping and wind-induced advection.</li> </ul>
<ul style="list-style-type: none"> <li>▪ <i>Contamination below entire building</i> (laterally uniform concentrations): Greater oxygen demand.<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>▪ <i>Contamination below part of building</i> (lateral concentration gradients): Less oxygen demand.<sup>2</sup></li> </ul>

## Notes

1. The combined influence of the depth to contamination and building size can be captured through a depth to building size ratio.
2. When there are lateral concentration gradients, the external soil vapour samples should be obtained in the direction of highest concentrations.
3. There may also be biodegradation through other electron acceptors.

The above qualitative factors should be reviewed when evaluating the use of external soil vapour data. If conditions suggest shallow data may not be representative, then it is recommended that deep soil vapour data be used for assessment purposes. Alternately, consideration could be given to sampling and analysis of subslab soil vapour samples to confirm that bioattenuation is also occurring below the building. If multiple buildings are potentially affected, testing below a subset of building(s) in the highest source concentration area may be sufficient to demonstrate bioattenuation is occurring.

Hydrocarbon vapour biodegradation is an area of active research. It is expected that more quantitative guidance on how to apply the above factors will be developed over the next few years.

### 3.2.6 Define When to Sample and Sampling Frequency

Investigation of the soil vapour intrusion pathway will often require more than one round of soil vapour sampling since there can be significant temporal variability in soil vapour concentrations due to changes in source contamination concentrations, seasonal variations in the water table and conditions for hydrocarbon vapour bioattenuation. For example, if the water table level decreases, soil contamination, which previously was submerged by groundwater, could be exposed to soil gas thus resulting in increased volatilization. For soil vapour samples collected near to the building, there may be weather or building related sources of variability. In general, the sampling frequency should coincide with seasonal patterns for factors affecting soil vapour such as the water table elevation (i.e., high and low levels) and precipitation (soil moisture) (i.e., wet and dry season).

One sampling event may sometimes be sufficient depending on the results of initial soil vapour testing. For example, if soil vapour concentrations are significantly less (i.e., greater than one order-of-magnitude) than concentrations of potential concern, and if vapour concentrations are unlikely to change significantly over time, one monitoring event may be sufficient. Alternately, if soil vapour concentrations are close to levels of potential concern, repeat testing is likely warranted.

Soil vapour sampling should be avoided during and after heavy rainfall events since collection of a representative sample is difficult. In addition, infiltration of water into soil can result in negative bias in soil vapour concentrations due to partitioning of vapour into soil moisture and, in some cases, can induce advective movement of soil gas. The time for moisture to drain from soil pores will depend on the soil type. Coarse-grained soil (sand or gravel) will drain to field capacity within a few hours (from complete saturation) while fine-grained soil will take longer to drain (Hillel, 1980). Field capacity is the soil water content after water drainage by the force of gravity is mostly complete. Based on drainage data, we recommend that you wait at least one day after a heavy rainfall event (defined here as 1 cm) for coarse-grained soils (sand or gravel), and several days for fine-grained soils.

The design of a soil gas sampling program should consider the possible effect of barometric pressure fluctuations. These fluctuations could influence shallow soil vapour concentrations when there are thick coarse-grained unsaturated zones. A conservative approach would be to collect soil vapour samples when the barometric pressure is decreasing. However, it is generally not practical to schedule soil gas sampling events to target the desired barometric pressure. However, barometric pressure data for several days before and after sampling should be obtained, when available.

Frost cover can also reduce soil gas flux through ground surface, increase pressure gradients, and affect subsurface soil vapour concentrations. Consideration should be given to repeat sampling when frost cover is not present.

### **3.2.7 Future Land Use Considerations**

If the objective of the risk assessment is to predict exposure under future conditions, the soil vapour sampling design should consider how land use changes will affect soil vapour measurements and data interpretation. Changes to surface conditions and development would tend to have the greatest effect on shallow vapour concentrations and the least effect on soil vapour concentrations near to the contamination source. Therefore, it is recommended that soil vapour characterization programs for the future use scenario focus on sampling of deep soil gas.

### **3.3 Soil Gas Probe Construction and Installation**

Soil gas probes can be constructed of a variety of materials and installed using several techniques. Critical aspects to probe construction include (i) probes should be constructed from materials that are relatively inert and non-sorptive, (ii) techniques should be used to minimize the potential for short-circuiting of atmospheric air to the probe soil gas collection point, and (iii) the probe should remain sealed between sampling events. The main options for installation of soil gas probes include:

1. Probes installed in boreholes or coreholes through a concrete slab;
2. Probes installed via direct push technology; and
3. Driven probes.

Further discussion on the probe materials and installation methods for each of the above probe types is described below. For all of these probe types, it is important that prior to installation, subsurface utilities be located. Multiple options for probes are described to provide the practitioner with alternatives to accommodate site-specific conditions and constraints.

#### **3.3.1 Probes Installed in Boreholes**

Probes installed in boreholes are constructed in a similar fashion to groundwater monitoring wells; however, there are important differences in design. Generally short screens (0.15 to 0.3 m length) should be used for probes since typically the objective is to characterize local soil gas concentrations (i.e., over a small volume). The screened portion of the probe can consist of slotted polyvinyl chloride (PVC) pipe or a steel-mesh screen. The diameter of the probe should be relatively small (less than 25 mm) to minimize the volume of air needed to purge the probe and to minimize the surface area for adsorption of VOCs on probe surfaces. For probes constructed of continuous PVC pipe to ground surface, the recommended diameter is 12.5 mm (1/2 inch) to 19 mm (3/4 inch). For probes consisting of a steel-mesh screen (e.g., implants), smaller diameter tubing (6 mm, 1/4 inch) is typically used to connect the screen to ground surface.

Coarse sand or fine gravel should be placed surrounding the screened portion of the probe, and a bentonite seal should be constructed above the screened portion of the probe. Since soil gas probes are installed in the unsaturated zone where soil moisture may be relatively low, careful consideration should be given to the hydration of the bentonite seal. A competent seal can be constructed through use of dry granular bentonite (16 mesh), as opposed to powder, chips, or pellets, and addition of distilled water to the bentonite during installation. Granular bentonite has a texture much like the sand used for a filter-pack, and so it will settle effectively within the borehole, but hydrates instantaneously. An effective method of sealing the remainder of the borehole annulus is to use a thick slurry of powdered bentonite and water (“volclay grout”).

If multiple probes are installed in a borehole, the borehole above and below each probe should be sealed with bentonite. Soil gas probes should be completed with an air-tight valve or stopcock at surface to prevent atmospheric air from entering the probe, and protected using a well cover or other similar protective casing for security and weatherproofing. If multi-level probes are used, each probe should be tagged with a permanent label, using no glues, or markers. In general, a similar or higher level of care and quality control to that employed for monitoring wells should be followed when installing a soil gas probe.

Potential advantages of permanent probes installed in boreholes are that temporal variability can be assessed through repeat sampling and there is greater installation flexibility (i.e., deep probes, dense soils). In addition, the filter pack that surrounds the screen provides for more open area for drawing a soil gas sample than a driven probe. A potential disadvantage of probes installed in boreholes may be access restrictions for drill rigs.

Soil gas samples can also be obtained from groundwater monitoring wells screened across the water table provided the well screen extends above the capillary fringe. Larger purge volumes are required for monitoring wells. In addition, if the screened interval is relatively long, soil gas samples from wells may not provide the desired level of vertical discretization. Since groundwater wells may be vented at surface, an air-tight cap and valve should be used when sampling soil gas.

Soil samples should be collected during drilling of boreholes for soil gas probes. Consideration should be given to testing of soil samples for soil moisture content and grain size distribution and the soil lithology and stratigraphy should be carefully logged. Soil samples should also be evaluated for possible contamination, including sources that may be located above the water table (see Section 3.6)

### **3.3.2 Probes Installed Using Direct Push Technology**

Direct-push techniques can be used to install a single soil gas implant in a borehole. Direct push rods are pushed to the desired depth, and implants are installed post-run after the desired depth is reached by lowering the implant down the hollow rods and attaching

it to a detachable anchor drive point. A sand pack and bentonite seal should be installed through the push rods as they are removed to minimize the potential for short-circuiting of atmospheric air from ground surface to the sampling point. The position of the filter pack and seal should be confirmed using a tamping rod. It is noted that past practice has been that installers often relied on the natural collapse of the formation around the probes; however, this technique will not provide a competent seal.

There is also direct push equipment that enables collection of multiple depth samples during a single push where soil gas samples are collected through a screen located within a retractable protective sleeve. This technology may be useful in characterizing soil vapour concentrations above source contamination zones; however, due to the potential for cross-contamination, it should not be used within or below source contamination zones.

A potential advantage of using direct push technology to install a probe is that implants can be rapidly installed with minimal disturbance. A potential disadvantage is short-circuiting of atmospheric air from surface to the sampling point, if the borehole above the screen is not well sealed. In addition, the presence of gravel or cobbles may hinder or preclude the use of direct-push technology.

### **3.3.3 Driven Probes**

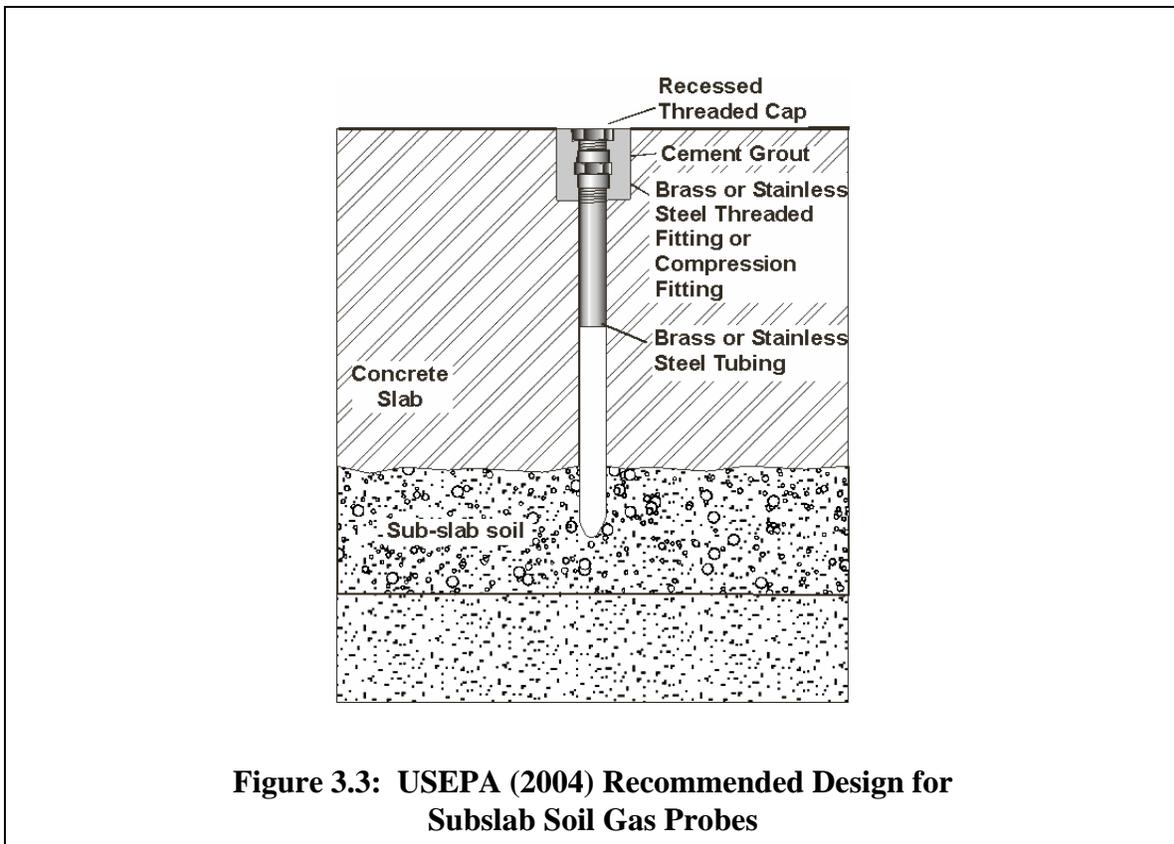
Driven probes in their simplest form are hollow steel rods with an internal diameter typically ranging between 9 mm and 25 mm (sometimes referred to as ground probes). The probes can be driven by hand, or with the aid of direct push equipped vehicles. The rods include a loosely fitting conical tip that is pushed a short distance further into the formation using an inner rod, once the probe is driven to its desired depth. Several holes may also be drilled near the tip of the probe to increase the open area through which soil gas is drawn into the probe. Driven probes are often temporary installations in that the probe is removed after the sample is obtained.

Driven probes may be advantageous in terms of flexibility of installation and cost. Another potential advantage is that when field analytical capabilities are available, multiple soil gas samples may be collected and analyzed from a single driven probe installed to varying depths enabling near real-time evaluation of vertical vapour profiles. One disadvantage is that driven probes can be difficult to install in coarse-grained or dense soil, especially at greater depths. The use of driven probes is discouraged in low permeability soils as it is difficult to ensure the absence of annular leakage, which is more likely to become a path of least resistance in low permeability soils. When driven probes are used in such geologic materials, the use of tracer tests to evaluate possible leakage is recommended, as described in Section 3.4.4.

### 3.3.4 Subslab Soil Gas Probes

Prior to drilling or coring through concrete slabs, relevant structural and utility information should be reviewed to evaluate whether drilling or coring could adversely affect the integrity of the building envelope, foundation slab or subsurface utilities, and whether there are any potential health and safety issues with drilling or coring. As warranted, geophysical techniques should be used to identify the location of re-bar within concrete slabs prior to drilling. After drilling the hole and prior to installation of the probe, the hole should be temporarily sealed (e.g., using rubber stopper) to minimize disturbance to subslab vapour concentrations.

Typically, the objective of subslab soil gas sampling is to characterize vapour concentrations in foundation subsoils immediately below the slab. Therefore, permanent probes typically consist of stainless steel or brass inserts installed within a corehole that are sealed with concrete grout (USEPA, 2004). The concrete grout should consist of Portland cement, aggregate and water, and should not contain any additives that could contain VOCs. A subslab probe design by USEPA (2004) is shown in Figure 3.3.



An alternate design for installation of a temporary soil gas probe involves drilling of a smooth-walled small hole that is slightly smaller than the outer diameter of the metal insert to be used (e.g., suggested diameter is about 12.5 to 19 mm). Teflon™-tape is wrapped around the outside of the metal insert, which is then forced through the hole to the base of the concrete slab. Another method of sealing the probe within the corehole is to use a rubber stopper with tubing inserted through a hole in the stopper. Both of the above methods are acceptable provided that care is taken to ensure an adequate seal.

### **3.3.5 Probe Materials**

Relatively inert and non-porous materials are preferred for soil gas sampling. While probes constructed of stainless steel are desirable, based on practical considerations, PVC probes are often installed. There is little quantitative information on the best type of sample tubing to use. Teflon™ is sometimes cited as the plastic of choice, but others indicate that Teflon™ is porous and is a poor choice of tubing material for vapour sampling (Kreamer, 2001). Some practitioners indicate that nylon (Nyla-Flow™) and high density polyethylene (HDPE) have reasonable sorption characteristics compared to other types of plastic. Silicon and tygon tubing are highly sorptive and should not be used. Glue, tape or other materials that could emit volatiles should not be used as part of probe construction.

In general, the probes and tubing should be selected to minimize the overall internal volume of the sampling train to minimize potential negative bias through sorption and to minimize purge volumes. Tubing external to the probe should be kept as short as possible.

### **3.3.6 Short-Circuiting Considerations**

Short-circuiting of atmospheric air to the probe can occur between the probe and soil, and leakage of soil gas and/or atmospheric air can occur at probe joints. Prevention of short-circuiting and leaks is particularly important for low permeability soil deposits.

For finer-grained soils, the process of driving a steel probe may cause movement and cracking of soil around the probe, and hence the potential for short-circuiting during sampling. For driven probes, the surface surrounding the probe should be sealed with bentonite prior to sampling, or suitable alternate material that is inert (e.g., modeling clay).

As discussed in Section 3.4.4 and Appendix 2, the probe surface seal integrity may be tested by introducing a tracer gas around the probe at the contact with the ground surface and then analyzing the collected soil gas samples for the tracer gas. Avoid the lateral or vertical movement of probes once installed to minimize any separation between the soils and the outside of the probes.

### **3.4 Soil Gas Sampling Procedures**

Soil gas sampling procedures addressed in this section are soil gas equilibration, sampling containers, decontamination, methods to detect leaks and short-circuiting, and purging and sampling. The methods used should be documented throughout the sampling process. A more detailed discussion of sampling procedures is provided in API (2005).

#### **3.4.1 Soil Gas Equilibration**

Soil gas should be allowed to equilibrate after probes are installed prior to sampling. The time required for equilibration will depend on the disturbance caused during installation. The least disturbance is caused by driven probes, or probes installed using direct-push technology. Moderate disturbance is caused by auger drilling while the greatest disturbance is caused by air rotary drilling, since air is introduced into the formation during drilling. For driven probes or probes installed using direct-push technology, a few minutes to hours is likely sufficient for equilibration of soil vapour concentrations. For probes installed in auger boreholes, a few days may be sufficient. For air rotary boreholes, it may take several weeks for equilibration of soil vapour concentrations since air is used as a drilling fluid. For probes installed using air rotary drilling, it is recommended that repeat monitoring be conducted over several weeks to evaluate whether soil vapour concentrations surrounding the probe have recovered.

#### **3.4.2 Sampling Container or Device**

Sample collection devices can include evacuated steel canisters, sorbent tubes, glass cylinders and Tedlar bags<sup>3</sup>. The selection of a collection device is influenced by investigation objectives, analytical requirements and detection limits. For field screening using hand-held detectors, soil gas samples are often collected using Tedlar bags. Gas-tight syringes are often used for on-site analysis using mobile laboratories. Soil gas samples collected for analysis by a fixed laboratory for VOCs should generally be obtained using sorbent tubes or stainless steel or glass-lined (e.g., Summa) canisters. Glass cylinders or Tedlar bags may be appropriate for light gas analysis (oxygen, carbon dioxide, methane). Sampling devices are compared in Table 3.3.

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<sup>3</sup> Tedlar™ is a proprietary plastic with properties similar to Teflon™.

**Table 3.3. Soil Gas Sample Collection Containers and Devices**

<b>Tedlar™ Bags</b>	<ul style="list-style-type: none"> <li>• Tedlar bags are available in volumes ranging from 10 ml to 10 litre; typically a 0.5 to 1 litre bag is used for soil gas sampling.</li> <li>• Tedlar bags can be filled using a: 1) small battery-powered electric pump, 2) peristaltic pump or 3) vacuum chamber. Electric pumps can become contaminated and thus cross-contamination is possible. At higher vacuums, pumps do not function well and may leak. An advantage of peristaltic pumps is that soil gas does not pass through the pump. The vacuum chamber method involves placing a Tedlar bag in a sealed chamber that is evacuated, which in turn, causes the bag to fill with soil gas. The vacuum chamber method is advantageous in low permeability soils.</li> <li>• Studies indicate significant leakage of Tedlar bags over the first 24 to 48 hours after sampling (Wang <i>et al.</i>, 1996; Andiro and Butler, 1991).</li> <li>• Tedlar bag samples should be analyzed as quickly as possible. Although reported analytical holding times are up to seven days, analysis of bags within 24 and 48 hours is recommended.</li> </ul>
<b>Glass Cylinders</b>	<ul style="list-style-type: none"> <li>• Glass cylinders are available in a range of volumes; typically a 0.5 to 1 litre cylinder is used for soil gas sampling;</li> <li>• The glass cylinder is placed in-line between the probe and pump.</li> <li>• Glass cylinders are typically supplied by the analytical laboratory filled with high-purity nitrogen.</li> <li>• Once purging is completed, the cylinder should be inserted into the sampling train. An additional five cylinder volumes should be purged through the cylinder before simultaneously closing both stopcocks.</li> <li>• Glass cylinders should be analyzed as quickly as possible. Although reported analytical holding times are up to seven days, analysis of cylinders within 24 and 48 hours is recommended</li> </ul>
<b>Gas-Tight Syringes</b>	<ul style="list-style-type: none"> <li>• Gas-tight syringes are used to collect small volume gas samples (typically 5 to 60 ml).</li> <li>• Gas-tight syringes are typically used for on-site GC analysis.</li> <li>• Samples should be analyzed within a short time (30 minutes) of collection.</li> </ul>
<b>Sorbent Tubes</b>	<ul style="list-style-type: none"> <li>• A wide range of sorbent materials are available. Tubes are selected based on the types and concentrations of volatile chemicals expected in soil gas.</li> <li>• Sorbent tubes are placed in-line between the probe and pump.</li> <li>• Sorbent tube sampling rates are typically 100 to 200 ml/min; the flow rate supplied by the sampling pump must be accurately determined.</li> <li>• The sampling duration will depend on the expected concentration, flow rate, chemical type, sorbent and desired detection limit.</li> <li>• For quality control purposes, sorbent tubes often have a “front” and “back” section, or two tubes are placed in series to evaluate possible chemical breakthrough.</li> </ul>

<p><b>Stainless Steel or Glass Canisters (Summa Canisters)</b></p>	<ul style="list-style-type: none"> <li>• Canisters have a relatively inert, passivated interior surface.</li> <li>• Available volumes range from 400 ml to 6 litres.</li> <li>• Canisters are supplied under vacuum. The vacuum is measured prior to shipping by the laboratory, immediately prior to and after sampling using a gauge supplied by the laboratory, and by the laboratory upon receipt. Significant differences in laboratory and field vacuums (beyond the range of accuracy of the gauge) indicate possible leakage during shipping.</li> <li>• There should be a residual vacuum left in the canisters; otherwise, the sample will not represent the entire planned sampling interval.</li> <li>• The sampling rate is typically controlled by flow regulator.</li> </ul>
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**3.4.3 Decontamination of Sampling Equipment**

Clean equipment and sample containers should be used for soil gas sampling. This can be implemented through decontamination of equipment or through the use of new, unused equipment. Care should also be taken when handling equipment since sampling equipment could be contaminated through dirty containers, hands, vehicle exhaust, etc. The level of decontamination may depend on the objectives of the soil gas survey and detection limits for analytical testing.

If the soil gas survey is limited to testing of soil gas samples using a field photoionization detector (PID) or flame ionization detector (FID) measuring to part-per-million levels, it may be appropriate to re-use the soil gas probes, tubing and sampling containers (e.g., Tedlar bags). However, prior to installing a probe and collecting each sample, a field blank sample comprised of ambient air should be collected through the entire sampling train and tested using the field PID or FID. If concentrations in the field blank are elevated above background ambient levels, the equipment should be cleaned or new equipment should be used.

If the soil gas survey involves collection of soil gas samples for field PID or FID analysis at part-per-billion levels or for laboratory analysis, greater care must be taken with respect to decontamination and verification of clean sampling equipment and containers. It is recommended that the analytical laboratory be required to demonstrate that the containers and flow controllers, if applicable, are clean prior to shipment to the site and that new sample tubing in all cases be used for each soil gas probe. Field blanks should be obtained using certified zero gas as opposed to ambient air. If steel probes are to be re-used, they should be thoroughly washed with a hot-water soap solution and rinsed with distilled-deionized water.

#### **3.4.4 Testing of Equipment for Leaks and Short Circuiting**

There are several ways in which the sampling train can be tested for leaks. A simple method is to pressurize the sampling train and to monitor pressure over time to confirm that the pressure does not dissipate. A soapy-water solution can be used to identify any couplings that may be leaking. A alternate method, described by API (2005), involves testing of sampling equipment for potential leaks using a tracer gas (e.g., diluted helium) of known concentration that is drawn through the sampling equipment at the approximate vacuum anticipated during sampling. The API method is described in Appendix 2.

Potential short-circuiting of atmospheric air during sampling can also be indirectly evaluated through careful examination of oxygen and carbon dioxide data. For example, if oxygen concentrations at a probe installed within a petroleum hydrocarbon source zone or landfill under methanogenic conditions are at atmospheric levels, further investigation should be conducted to determine if the soil gas sample was representative (see Section 5 for additional discussion).

#### **3.4.5 Sample Probe Purging and Sampling**

##### Use of Direct Reading Instruments

Following equilibration, the sampling equipment should be connected to the sampling probe, and then checked for possible leaks before purging the probe. The purpose of purging is to ensure a representative soil gas sample is collected. The use of direct reading instruments during the purging process can be used to evaluate purging effectiveness since approximately stable readings should be obtained after two to three purge volumes, although slowly increasing concentrations could indicate a higher soil gas concentration zone laterally removed from the probe. Direct reading instruments can be affected by flow rate restrictions and high water vapour levels and therefore should be used with caution.

##### Number of Purge Volumes

The purpose of purging is to remove stagnant air from the probe; however, over-purging should be avoided since the objective is generally to characterize soil gas in the immediate vicinity of the probe. Over-purging also increases the potential for short-circuiting when soil-air permeability is low. Cody (2003) evaluated purge volumes on the basis of a differential equation for the sequential and complete mixing of VOCs over each time step within the entire volume under consideration (probe and tubing). On the basis of this equation, the estimated concentration within the probe volume reaches 90 percent of the input concentration after purging about three volumes. For narrow diameter tubing, fewer purge volumes are likely needed to obtain a representative sample due to reduced mixing resulting from more a “plug flow” phenomena. The removal of three purge volumes prior to sample collection is recommended.

### Sampling Flow Rate

The sampling flow rate recommended by others ranges between about 1 L/hour and 1 L/minute (API, 2005). Some practitioners recommend that the sampling rate should be tied to the vacuum generated during sampling, and that the vacuum should not exceed 10 inches of water (Lahvis, 2002). The concern with higher flow rates and vacuums is the increased potential for leakage of air into the soil gas probes and probe tubing. Some practitioners also suggest that high vacuums enhance the volatilization of the more volatile compounds in a chemical mixture (API, 2005). A flow rate between 20 and 200 ml/min and a vacuum that is less than 10 inches of water is recommended for soil gas purging and sampling. The vacuum can be easily measured using a T-junction connected to a digital manometer.

### Sample Collection

Once purging is complete, soil gas samples from conventional soil gas probes should be collected using the same sampling flow rate as for purging. For subslab soil gas probes, it may be desirable to collect a subslab gas sample concurrently with an indoor air sample. Indoor air samples are typically obtained over a 24-hour period. The soil gas sampling rate for a 6-litre Summa sample collected over 24 hours is about 6 mL/minute. Sampling of probes at a site should be completed over a relatively short time period (e.g., within one week) to provide an internally consistent data set (Lahvis, 2002). If measurements with a portable multi-gas detector are to be made (e.g., oxygen, carbon dioxide), measurements should be conducted after collection of the soil gas sample for VOC analysis. If any water is drawn in the sample container, re-collect the sample after taking measures to eliminate water.

### Sample Handling and Storage

Soil gas samples obtained using syringes, steel canisters or glass cylinders should not be placed in a chilled cooler for transport since volatiles may condense out the vapour phase at lower temperature (Hartman, 2002). Samples should not be subjected to excessive heat.

Tedlar bags and glass cylinders should be placed inside a container immediately after collection to avoid possible photo-oxidation reactions.

For sorbent tubes, cool storage (approximately 4°C) in sealed containers is recommended. Sorbent tubes should be stored in a sealed plastic container containing a bed of activated carbon to minimize the potential for adsorption of ambient VOCs. All soil gas samples should be transported in separate containers from soil and groundwater samples.

### **3.5 Soil Gas Analytical Methods**

#### **3.5.1 Selection of Method**

Analytical testing methods appropriate for analyzing soil gas samples will be dependent on risk assessment objectives, sampling method and data quality objectives. Soil gas programs often consist of a combination of field testing of soil gas samples using hand-held detectors and laboratory analysis of selected soil gas samples for specific chemicals of potential concern. Since analytical testing is a broad topic, only an overview of the key issues is provided below. Common analytical methods for soil vapour are summarized in Table 3.4, with a detailed list provided in Appendix III.

It is important to understand procedures and potential limitations associated with different testing methods. Since soil vapour and air methods are not as well defined as groundwater methods, adequate consultation with the laboratory is essential. The types of information that should be discussed include optimal sampling flow rate and duration, detection limits, laboratory QA/QC requirements and considerations, and the optimal handling and transport of samples. Communication with the laboratory at the early stages ensures that important analytical considerations are taken into account during the development of the sampling plan.

#### **3.5.2 Field Detectors**

Field detectors commonly used are photoionization detectors (PID), combustible gas detectors or explosimeters, and multi-gas detectors for compounds such as oxygen, carbon dioxide and methane, which are important for studies evaluating biodegradation. Photoionization detectors will respond to most organic vapours as well as some inorganic vapours (hydrogen sulphide, ammonia) depending on the ionization lamp energy. The sensitivity of a PID varies depending on the compound, and excessive moisture can bias readings; therefore care should be taken when conducting soil gas surveys, particularly when connecting a PID directly to a soil gas probe. Combustible gas detectors are typically calibrated to methane in air, but also readily respond to heavier hydrocarbon (e.g., gasoline) vapours. Filters can be used to enable light (methane) and heavier organic vapours to be quantified, if desired. It is important to document the type of combustible gas detector and mode of operation. Photoionization detectors, which measure hydrocarbon vapour concentrations to ppm, or even ppb levels, are generally more sensitive than combustible gas detectors.

While field detectors are valuable for site screening, the limitations associated with these instruments, including non-specificity to compounds of possible interest and the effect of environmental factors and sampling methods, should be clearly understood (Robbins et al., 1990). Field detectors should generally not be directly connected to sampling probes when taking measurements, unless it can be demonstrated that possible sampling flow rate constrictions and vacuums generated by sampling will not affect the field detector response. Samples should generally be obtained in Tedlar bags to facilitate readings taken using field detectors.

**Table 3.4. Summary of Common Soil Vapour Sampling and Analysis Methods**

	Compound Class	Collection Device	Methodology	Method No.	Comments
Field Screening Methods	VOCs	Tedlar Bag	PID/FID		<ul style="list-style-type: none"> <li>• Real time results, equipment is simple to use</li> <li>• Generally ppm detection limits (except light gases, which may be % level)</li> <li>• Lower cost</li> <li>• Not compound specific</li> <li>• Some detectors, such as those for landfill gases, are designed to sample against vacuum, whereas others instruments are sensitive to vacuum and flow rate constrictions</li> </ul>
	Light Gases (O <sub>2</sub> , CO <sub>2</sub> , CH <sub>4</sub> )	Tedlar Bag	Infrared (CO <sub>2</sub> , CH <sub>4</sub> ), electrochemical (O <sub>2</sub> )		
	Combustible Gases	Tedlar Bag	Platinum catalyst		
Field Laboratory Methods	VOCs (e.g., BTEX)	Glass syringe, Tedlar Bag	GC/PID	Modified USEPA 8021B	<ul style="list-style-type: none"> <li>• Near real time results</li> <li>• May need to analyze sub-set of samples using fixed laboratory methods</li> <li>• Higher cost than field screening</li> </ul>

	Compound Class	Collection Device	Methodology	Method No.	Comments
Fixed Laboratory Analysis	VOCs	sorbent tube, solvent extraction	GC/FID <sup>1</sup>	OSHA 7 / NIOSH methods	<ul style="list-style-type: none"> <li>• Lower detection limits (except some NMOC &amp; TVOC methods)</li> <li>• More rigorous QA/QC</li> <li>• Higher cost</li> <li>• Depending of chemical, may be issues for sorbent tube analysis (e.g., recovery, breakthrough)</li> <li>• High humidity can cause problems for analysis</li> </ul>
	VOCs	sorbent tube, thermal extraction	GC/MS	USEPA TO-17	
	VOCs	Specially-treated (eg. Summa) canister	GC/MS	USEPA TO-14A /TO-15	
	PAHs	Polyurthane foam (PUF)	GC/MS	USEPA TO-13A	
	TVOC & Hydrocarbon Fractions <sup>2</sup>	sorbent tube, solvent extraction	GC/FID	NIOSH 1550	
	TVOC & Hydrocarbon Fractions	Canister (Summa or non specially-treated), Tedlar Bag	GC/FID (Cryotrap)	USEPA TO-3	
	NMOC	Canister or on-line	FID	USEPA TO-12	
	Light Gases (e.g., O <sub>2</sub> , CO <sub>2</sub> , CH <sub>4</sub> , CO, H <sub>2</sub> )	Canister, Tedlar Bag, Glass syringe	GC/TCD	ASTM D1945-03	

## Notes:

1. MS is also used by commercial labs but is not part of the reference method.
2. Hydrocarbon fractions can consist of both ranges (e.g., TVOC (C6-10), TVOC (C10-19)) and aromatic and aliphatic fractions (e.g., CCME CWS-PHC approach)
3. GC = gas chromatograph, PID = photoionization detector, FID = flame ionization detector, TCD = thermal conductivity detector, MS = Mass Selective detector
4. USEPA = US Environmental Protection Agency
5. NIOSH = National Institute for Occupational Safety and Health (USA)
6. OSHA = Occupational Safety & Health Administration (USA)
7. NMOC = non-methane organic compounds
8. CCME = Canadian Council for Ministers of the Environment
9. CWS-PHC = Canada Wide Standards for Petroleum Hydrocarbon Compounds

### 3.5.3 Field Laboratory Analysis

Field laboratory methods are used when a greater degree of precision or component-specific information is required than that provided by a field screening method. The advantage of field laboratory methods are near real-time results, which can be used to modify programs while in progress, and potentially lower costs. Also ability to collect repeat samples can be advantage to assessing sampling, temporal, and spatial variabilities. The disadvantage of field laboratory methods are higher detection limits than fixed laboratory methods based on U.S. EPA TO- protocols (see below). Possible regulatory requirements for soil gas analytical protocols should also be reviewed when evaluating field laboratory analysis.

Field laboratory methods include the use of portable gas chromatographs (GCs) that are brought to the site to analyze grab samples on an on-going basis. Soil gas air is usually collected using gas-tight syringes and is injected into the GC (or purge-and-trap apparatus) for analysis. The portable GC usually analyses data through photo ionization, flame ionization or electron capture detectors (e.g., modified USEPA Method 8021B). The precision of the results can vary depending on the equipment used. Portable mass spectrometers (MS) are also being introduced to the market, which provide greater certainty for compound identification (e.g., modified USEPA Method 8260).

### 3.5.4 Fixed Laboratory Analysis

For risk assessment studies, low detection limits and more rigorous quality control requirements typically require that soil gas samples be collected using either active sorbent tubes (i.e., air is drawn through tube using pump) or Summa canisters, and quantified by GC/MS methods. The use of GC/FID analysis is generally not recommended due to non-specificity of detection.

Sampling using a sorbent tube is an indirect method of estimating the soil vapour concentration in that volatile chemicals are initially trapped on the sorbent, and then thermally desorbed (e.g., USEPA TO-17) or extracted using a solvent (e.g., modified OSHA 7 or NIOSH 5515 methods). The test measures the mass of chemical trapped. The air concentration is estimated by dividing the mass by the total volume of air drawn through the tube.

The Summa canister method involves collection of a “whole air” sample enabling direct analysis of the soil vapour sample. The analytical protocols for the Summa method are USEPA TO-14A (non-polar compounds) (USEPA, 1999a) and USEPA TO-15 (polar and non-polar compounds) (USEPA, 1999b).

### Sorbent Tube Method

Thermal desorption involves rapidly heating the sorbent to desorb the VOC, while passing an inert carrier gas through the tube. The VOCs are carried by the gas and concentrated on a smaller downstream trap, which usually is cryogenically cooled. For thermal desorption, the whole sample is analyzed at one time without the possibility of replicate analyses. Solvent extraction involves use of a solvent such as carbon disulphide to extract the sample. In contrast to thermal desorption, replicate analyses can be performed on the extract. While chemical extraction methods are adapted from industrial hygiene practice and are typically not as sensitive as thermal desorption, higher detection limits may not be an issue for soil vapour analysis (but may be problematic for air analyses).

### Sorbent Types and Issues

Sorbents used for VOCs commonly used consist of charcoal, polymeric and/or carbonaceous resins. Some tubes contain multiple compartments containing materials with differing sorptive properties (e.g., graphitized carbon black, carbon molecular sieve), designed to optimize the collection process. There are wide variations in sorbent properties. Since soil gas typically has a relative humidity of close to 100 percent, hydrophobic sorbents are preferred since sorbed water reduces the retention of VOCs, and because water vapour can affect the GC analysis (Harper, 1994). Polar VOC compounds can also partition into the water phase reducing recovery. Elevated ozone levels (150 to 300 ppm) have been reported to result in reduced recovery for certain VOCs such as styrene and aldehydes (McClenny et al., 2002). Other issues for sorbent sampling include sorbent pore size and uniformity, possible reactions between the sorbent and adsorbed molecules, and slow breakdown of certain polymeric sorbents and release of aromatic hydrocarbons (Harper, 1994).

Sorbents used for semi-volatile (PAH) analysis (naphthalene and heavier molecular weight compounds) often consist of Teflon™-impregnated glass fibres followed by a resin (XAD) and polyurethane (PUF) foam cartridge (USEPA Method TO-13A).

### Sorbent Selection and Handling

The selection of the sorbent should be based on VOC type, desired detection limit, and data quality objectives. Sorbents designed to perform well under conditions of high humidity should be selected. For some chemicals and depending on detection limits, newer sorbents such as processed synthetic carbon (e.g., Anasorb 747) or molecular sieve materials should be used in place of older sorbent materials such as coconut shell charcoal. Special attention should be paid to sorbents selected for analysis of highly volatile chemicals such as vinyl chloride, which are difficult to trap using sorbent media.

Appropriate measures should be taken to mitigate the effects of high humidity or cold weather when sampling using thermal tubes, which may not always be practical to avoid. Reducing the sampling air flow or sampling with varying volumes of air (using multiple samples) may be a good approach under this circumstance. When the ambient temperature is greater than the ground temperature, water vapour may condense on the sampling media. This can be prevented by heating or insulating the sorbent tube, as appropriate.

#### Sorbent Sampling Volume:

The sampling volume should be carefully determined through consideration of the expected VOC concentration and mass, the sorption capacity and required detection limits. When available, the results of field PID analyses of soil vapour should be communicated to the laboratory analyst prior to sorbent sampling to guide selection of a sampling duration and flow rate that would minimize the potential for chemical breakthrough. An option is to collect two samples over different time durations to avoid the possibility of re-sampling. Since the concentration is sensitive to the flow rate, pumps must be accurately calibrated and provide a constant flow rate throughout the sampling duration.

#### Summa Canister Method

Summa canisters are constructed of passivated electropolished stainless steel<sup>4</sup>, a relatively inert material, and are supplied under vacuum. Low detection limits can be achieved utilizing this method and, in general, the accuracy and precision of analytical results generated are high. For soil vapour sampling, a one-litre canister is typically a sufficient volume. Depending on the sampling duration, either a critical orifice alone or critical orifice with flow regulator is used to fill the canister over the desired time interval. Particulate filters consisting of sintered steel with 2 to 7 micron pore sizes or deactivated glass frit are placed before the fore the critical orifice.

Experience has shown that even for stainless steel canisters, there is the potential for contaminant carry over in the canister, regulator, filter or inlet tube, particularly when the sampling train is subjected to high VOC concentrations. Therefore, batch testing and certification that canisters are clean is recommended. It is also important that the critical orifice or flow regulator be appropriately calibrated and that all fittings are tight during sampling. Flow regulators are temperature and altitude dependent; therefore, the sampling location must be communicated to the laboratory so that appropriate adjustments can be made.<sup>5</sup> For heavier molecular weight compounds (trimethylbenzene

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<sup>4</sup> Silcosteel canisters are a different type of canister where steel is coated with an inert fused silica layer that is non-reactive with sulphur compounds or compounds that react with metal surfaces

<sup>5</sup> Laboratories typically conduct performance studies to verify that flow regulator's provide for an uniform sampling rate over the sampling duration, within an acceptable tolerance. If warranted, flow rates can be verified in the field using an extra canister using an electronic mass flow meter or rotometer, calibrated for vacuum conditions.

and heavier), sorption onto metal tubing and filter has been shown to result in reduced compound recovery (Entech Application Note 902).

Similar to sorbent tubes, high humidity can create challenges for sample recovery and cryogenic focusing prior to analysis, although an alternate method of multiple focusing using non-cooled sorbent tubes can reduce problems associated with water vapour.

### **3.5.5 Quality Assurance / Quality Control Considerations**

#### Data Quality Objectives

Data quality objectives should be established as part of the sampling plan in conjunction with the overall study objectives. In broad terms, the data quality objective is to ensure that data quality is acceptable and that data can be relied upon for decision-making purposes. Specific objectives may be developed in terms of accuracy, precision, data representativeness, data completeness and detection limits.

The development of a QA/QC plan will help to ensure that the desired data quality is achieved. Standard operating procedures should be used for sampling and analytical procedures, including the use of chain of custody records and identifying sampling locations. Systematic data collection and planning helps provide for defensible results and increased credibility.

#### Detection Limits

For risk assessments, the measured vapour concentrations are often used to predict indoor air concentrations. Required detection limits can be back-calculated using risk-based target indoor air concentrations combined with minimum expected dilution factors between soil vapour and indoor air. A lower bound dilution factor for the soil vapour to indoor air transport pathway of 100 may be used to estimate the required detection limit. An additional adjustment factor should be applied to reflect increased uncertainty near to the detection limit. The maximum detection limit is calculated as follows:

$$DL_{\max} = DF * C_{\text{air}} / AF$$

Where DL is the analytical reporting (detection) limit, DF is the dilution factor (100),  $C_{\text{air}}$  is the target indoor air concentration, and AF is adjustment factor (5).

### Testing and Certification that Sampling Device is Clean

For all methods, it is recommended the analytical laboratory demonstrate that the sampling device (canister, sorbent tube) is clean to below the required detection limits prior to sampling and analysis, for either a representative subset or all of the sampling devices. Depending on the project requirements, either batch or individual certification of the sampling device may be warranted.

### Quality Control Samples

Analysis of duplicate samples is required to assess the precision of the method and variability of the sampling process. The field duplicate samples should be obtained from the same soil gas probe using identical sampling procedures and submitted blind to the laboratory. Duplicate samples can either be obtained simultaneously (i.e., using a splitter) or in sequence. When duplicate samples are collected in sequence, variability due to temporal changes is introduced. For indoor and ambient air sampling, the typical approach is to use side-by-side sampling to collect duplicate (collocated) samples.

The frequency of field and laboratory duplicate sample analyses, while often each set at 10 percent of the samples analyzed, may depend on the total number of samples analyzed and analytical method. When only a small number of samples are tested, it may be desirable to increase the frequency of testing or pool QC results from multiple programs before drawing conclusions about data quality. For tubes that are thermally desorbed, collection of a greater frequency of duplicate samples can be advantageous for another reason; since the analysis is destructive, any re-analysis that may be required can only be done if a second tube is available.

While not a duplicate analysis, for sorbent tube analysis, both the front and back sections of sampling tubes (or two tubes in series) should be analyzed separately to evaluate for chemical breakthrough.

Depending on project requirements, other quality control samples that may be analyzed include transport blanks, method blanks and spike samples, as described below:

- Field transport blanks are sample containers that are shipped with the other samples, but which are not used for collecting a sample. While it is possible to analyze transport blanks for sorbent tubes and canisters, resources may be better spent by ensuring the laboratory certifies the sampling device as clean through testing of blanks. For Summa canisters, testing a field transport blank would involve filling the canister with ultra high purity air or nitrogen, which may practically be difficult to do in the field.
- A field method blank may be collected by drawing atmospheric air or high purity inert gas through the sampling train and probe to be sampled, prior to installation. This can provide useful data on whether the sampling train is clean.

- 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 type of test is normally performed by the analytical laboratory.

All data should be clearly reported, including blanks, and any suspect results should be flagged. The interpretation of quality control data is discussed in Section 5.

### 3.6 Other Media

As described previously, it is preferable to evaluate the soil vapour intrusion pathway using directly measured soil vapour concentrations. However, soil and/or groundwater data are critical for developing the CSM that is used to guide the development of the soil vapour characterization program. Soil data can be used to evaluate contamination source zones, including possible sources that are located above the water table. Shallow groundwater data and predictions of deep soil vapour concentrations along with measured deep vapour concentrations can be used to evaluate the degree to which volatilization from groundwater and migration through capillary fringe occurs, or the degree to which it may be inhibited through infiltration or geologic barriers. In some cases, it may not be possible to collect a representative soil gas sample due to low permeability deposits; therefore, the use of soil and/or groundwater data alone may be required for evaluation of the soil vapour intrusion pathway.

#### 3.6.1 Groundwater Data

Groundwater characterization for evaluation of soil vapour intrusion should provide information on concentrations in groundwater near to the water table. This is because cross-media transfer from groundwater to soil vapour occurs when chemicals in pore-water volatilize into soil gas, which occurs in the capillary transition zone above the water table. Since there can be significant vertical concentration stratification, the use of relatively short monitoring well screens situated across the water table or depth discrete sampling methods such as the Geoprobe™, Waterloo Profiler™ or Hydropunch™ methods are recommended when evaluating the soil vapour intrusion pathway.<sup>6</sup> Depth discrete samples can also be obtained from existing monitoring wells using Passive Diffusive Bag Samplers (Vroblesky and Hyde, 1997; ITRC, 2002). Diffusive Bag Samplers can also be used to measure VOC concentrations in pore-water within the capillary transition zone.

As well screen lengths increase, there is increased blending of groundwater across the screened interval. This may result in either over-estimation or under-estimation of concentrations at the top of the aquifer, depending on the contamination scenario. At

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<sup>6</sup> Another potential option may be to install small diameter implants (e.g., 15 cm long) at several depths near the water table, which can be used to sample either soil gas or groundwater depending on water table fluctuations.

locations where LNAPL is present or where there is an interface plume from fluctuating water table and interaction between soil gas and the water table, longer well screens may under predict concentrations near the top of the aquifer. Where there is a fresh-water lens or contamination source below the water table (e.g., DNAPL), longer well screens may over predict concentrations near the top of the aquifer.

Groundwater well installation, well development and purging prior to sampling should be conducted according to current standards of practice. For vapour intrusion assessments, a saturated screen length of 1 to 2 m is recommended. Low flow purging and sampling methods that minimize disturbance, aeration and/or de-gassing of groundwater are recommended (Puls and Barcelona, 1996). Particular attention should be given to groundwater samples collected from submerged screens or wells with long screen intervals. The concentrations from these wells may be of limited value for vapour intrusion assessments.

While the appropriate focus of groundwater investigations for vapour intrusion studies is shallow groundwater quality, in some cases, it may also be important to assess the deeper groundwater quality. This is because contaminants at depth within groundwater systems could pose future vapour intrusion potential for hydrogeologic systems that undergo changes, due to natural seasonal fluctuations of the water table elevation and/or through human activities. The vertical concentration variability can be investigated either through the use of nested wells (at different elevations) or vertical profiling using a Geoprobe or similar groundwater sampling technique.

While in general shallow groundwater quality data should be used for vapour intrusion assessment, deeper data should be used if deeper groundwater concentrations are higher than shallow concentrations, and if significant future changes to groundwater systems are possible that would result in shallow data being non-representative.

### **3.6.2 Soil Data**

There are a number of uncertainties associated with use of soil data for evaluation of soil vapour intrusion as a result of losses of volatile contaminants during soil sampling, handling and chemical analysis. Depending on the contaminant type and geologic conditions, there may be significant spatial variation in soil concentrations, which may be difficult to detect based on conventional sampling programs. Finally, there are uncertainties associated with soil partitioning calculations and predicted soil vapour concentrations are sensitive to the partitioning coefficient between water and organic carbon, and the fraction organic content in soil, a parameter that can be difficult to accurately determine. If soil analyses results are to be used for the vapour pathway, it is recommended that the soil samples be field preserved (e.g., using methanol), where possible (e.g. US EPA SW-846 Method 3035). Multi-functional sampling devices (MFSDs), which act as a coring tool and airtight storage container, can also be used to collect soil samples for volatile analysis (e.g., EnCore™ Sampler). The storage chamber is completely soil filled with zero headspace and is then capped to form an airtight seal.

### 3.7 Passive Soil Gas

Passive diffusion samplers contain an adsorbent material that collects organic compounds over time. The adsorbed compounds are removed from the adsorbent by thermal desorption or solvent extraction, and typically analyzed using GC/MS methods. The passive soil gas method provides the mass of vapours adsorbed to the media, but currently can not reliably be used to estimate soil vapour concentrations. Passive soil gas samples are typically deployed for a few days to weeks, and therefore provide a time-integrated sample. The extended sampling duration also provides for high sensitivity. The adsorbent material should be hydrophobic to minimize water vapour uptake. In the context of soil vapour intrusion studies, passive soil gas sampling methods could be useful in mapping the location of subsurface plumes and identifying areas of potential concern. Passive samplers can be beneficial for identifying pathways (in particular when placed in or along utility corridors) for determining locations for permanent probe placement when the CSM is not well understood. However, the current passive soil gas methods can not be reliably used to provide concentration data needed for risk assessment purposes.

Passive diffusive samples can be used to estimate VOC concentrations in air and are described in Section 4.4.

### 3.8 Ancillary Data

In addition to measured soil vapour concentrations, the supplemental data below may assist in understanding the vapour intrusion pathway. This information may have been collected as part of an environmental site assessment. However, supplementary data collection may be required if sufficient information was not collected during investigations completed prior to the soil vapour sampling program.

**Physical Properties:** The properties of significant soil layers of the vadose zone, including soil moisture, bulk density, air-filled porosity, water-filled porosity and total organic carbon content may be important in evaluating vapour intrusion. Care should be taken to minimize re-distribution of soil moisture or drying of soil during drilling, sampling and storage of samples. Water retention tests on samples compacted to approximate *in situ* density can provide useful data on the likely range of water-filled porosity that could be expected in soil. Although not commonly performed, consideration can also be given to *in situ* tests to provide estimates of tortuosity (effective diffusion coefficient) (Johnson et al., 1998; Lahvis et al., 1999) and soil-air permeability (Baehr et al., 1991).

**Hydrogeological Properties:** The groundwater elevation during sampling and during an appropriate period prior to sampling is important when evaluating possible seasonal influence on volatilization. The hydraulic conductivity and gradient are fundamental parameters required to evaluate groundwater flow systems.

***Meteorological Data:*** There are an increasing number of weather stations (government, private) for which meteorological data (temperature, barometric pressure, wind speed and direction, relative humidity and precipitation) can be readily down-loaded. If there is a weather station near the site, meteorological data should be obtained. Barometric pressure and precipitation data for a few days prior to sampling should be obtained to enable trends to be evaluated. Frost cover should be noted. Meteorological data may be useful in interpretation of soil vapour intrusion particularly if there were severe weather conditions during sampling (e.g., rapid change in barometric pressure, strong winds).

***Building Pressure Data:*** Highly sensitive manometers (sensitivity less than 1 Pa (1/250 inches of water)) can be used to measure the differential pressure between the building and outdoor air, and building air and subslab soil gas. Information on pressure gradients can be useful in assessing soil gas intrusion potential, for example, soil gas intrusion potential would be low if the pressure in the building is higher than in soil below the building. When measuring pressures, consideration must be given to the potential influence of wind and other environmental variables on the measurements.

***Building Ventilation Tracer Test:*** Inert tracers such as carbon dioxide can be used to evaluate building ventilation characteristics and to estimate air change rates (ASTM E741-00). The ventilation test involves release of tracer gas (carbon dioxide) within the enclosed space followed by monitoring of the concentration decay over time. The concentration decay rate is used to estimate the air exchange rate. There are also tracer test methods that use sulphur hexafluoride (ASTM Method E 741). For commercial buildings, it may be possible to estimate the ventilation rate from HVAC system design. The air exchange rate should be calculated from the make-up volume, and not the total air handling volume.

***Radon Tracer Test:*** Naturally-occurring radon can be used as a tracer to evaluate sub-slab to indoor air attenuation, although results may be somewhat biased by radon emissions from concrete itself. The potential advantages of using radon, compared to analyses for VOCs, are potentially lower analytical costs, there are no common sources of indoor radon, and less bias is caused by non-detect values.

## **4.0 INDOOR AIR QUALITY TESTING FOR EVALUATION OF SOIL VAPOUR INTRUSION**

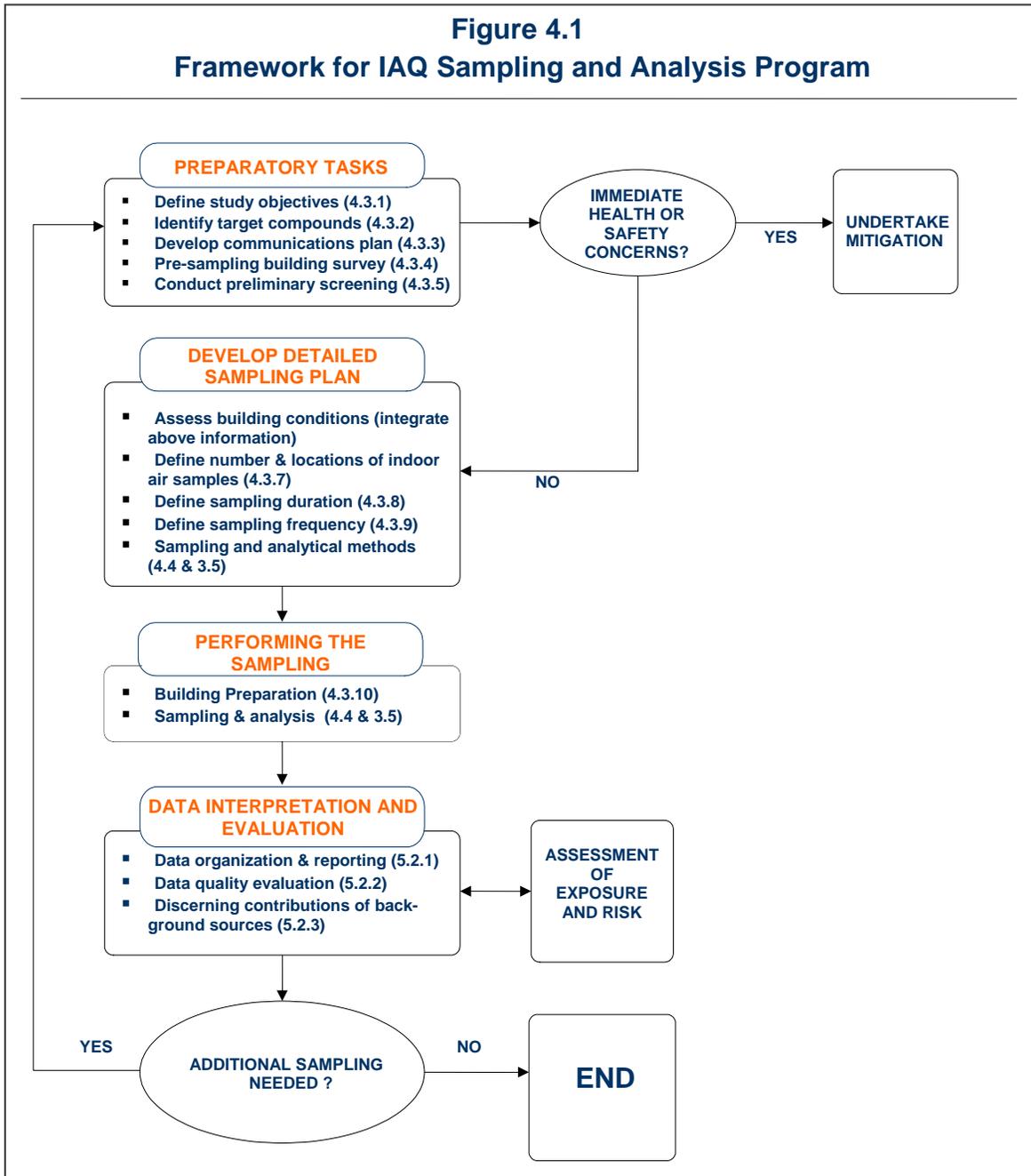
### **4.1 Overview**

This chapter describes methodology for completing indoor air quality (IAQ) testing for evaluation of soil vapour intrusion. The use of IAQ measurements to evaluate potential health risk associated with vapour intrusion is an option for a current exposure scenario (existing building). While indoor air testing can provide a direct measurement of potential inhalation exposure, there are a number of issues that can complicate a risk assessment based on indoor air measurements, and which should be taken into consideration. These issues include background sources of the chemicals of interest and often significant variability observed in indoor vapour concentrations due to building or weather related factors. An IAQ testing program is also a relatively intrusive activity that particularly for a residential or institutional setting requires appropriate communication of program objectives and results.

The basic steps for design of an IAQ program are similar to those described for soil vapour characterization and consist of (1) development of a conceptual site model (CSM), with specific consideration of factors that influence IAQ based on site conditions, (2) development of IAQ study objectives, and (3) preparation of a sampling plan. As indicated for soil vapour characterization, it is not possible to provide a standardized template for IAQ program design, and instead key principles and factors that should be considered in developing a sampling strategy are discussed below. A detailed flow chart of the framework for a IAQ study is provided in Figure 4.1.

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

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



**4.2 Conceptual Site Model for Indoor Air**

The CSM for soil vapour transport and intrusion into buildings was described in detail in Chapter 2. The purpose of this section is to describe specific aspects of the CSM that could influence indoor air quality (excluding subsurface factors), which are background sources of VOCs in indoor air, building foundation construction, building ventilation, building depressurization and weather conditions, and vapour depletion processes within buildings.

#### 4.2.1 Background Indoor Air Concentrations

When evaluating the impact of subsurface vapour sources on IAQ, it is paramount that background sources of VOCs in indoor air be considered, since many subsurface contaminants of concern are also common “background” VOCs. Common background sources of VOCs include household products, off-gassing from building products (i.e., carpeting, shower curtains, building insulation, pressed wood products, fabrics), home heating (i.e., heating oil storage, combustion emissions), tobacco smoke, attached garages (i.e., vehicle emissions, stored products), volatilization from water (particularly when heated) as well as through activities occurring in the home or workplace. A list of dominant indoor air sources and associated volatile contaminants is provided in Table 4.1. Due to these and other indoor air sources, contaminant concentrations in indoor air are frequently higher than in outdoor air. Other background sources of contaminants include outdoor sources such as vehicle or industrial air emissions that enter the building through air leakage or ventilation.

**Table 4.1 Dominant Sources of VOCs in Residential Indoor Air**

Source	Contaminants
Latex Paints	Benzene, Toluene, TMBs
Alkyl Paints	PCE, CBs
Carpets	Benzene, Toluene, Styrene, TMBs, CBs, Decane
Wood Burning	Toluene, Xylenes, Styrene, TMBs, Naphthalene
Foam Board	CBs
Paint Removers	Toluene
Spray Products	Xylenes
Adhesives/Tapes	Toluene, Styrene, TCE, Decane
Room Deodorizers	CBs
Tobacco Smoke	Benzene, Toluene, Ethylbenzene, Xylenes, Styrene
Gasoline/Driving	Benzene, Toluene, Xylenes, Styrene, TMBs
Solvents	Toluene, Ethylbenzene, Trichloroethanes
Dry Cleaning	PCE

Notes:

Adapted from Hers et al. (2001)

TMBs: Trimethylbenzenes; TCE: Trichloroethylene; PCE: Tetrachloroethylene; CBs: Chlorobenzenes

As a consequence of the large variations in building design, use, and environmental setting, IAQ data is also highly variable. A number of studies have been completed in the United States, but fewer studies have been undertaken in Canada examining background IAQ in residential homes. Table 4.2 provides a summary of VOC data from key Canadian studies including a Health Canada Study conducted in 1991 and 1992 across Canada, a study conducted in the Greater Toronto area in 1996 and a study completed in Saskatchewan and Ontario in 1991 and 1999. These studies demonstrate that background concentrations are highly variable, but also show that a large number of compounds can be expected to be found in residential buildings. Although background IAQ can be expected to vary between buildings, regions and time frames, the data from these and other studies can be used to help interpret the results of IAQ investigations (refer to Section 5 for further discussion).

**Table 4.2 Compilation of Indoor Air Quality Data from Canadian Studies**

Contaminant	Ontario Ambient Air Quality Criteria		Health Canada 1991,1992 <sup>a</sup>		Greater Toronto, 1996 <sup>b</sup>		Saskatchewan and Ontario, 1991,1999 <sup>c</sup>	
	Annual	24-hour	Mean	Max	Mean	Max	Mean	Max
Benzene	-	-	5.4	67.9	3.42	45.8	15	42.3
Toluene	-	2000	40.8	5730	15.2	186	23.9	110.5
Ethylbenzene	-	1000	8.2	540	1.58	20.9	9.6	32.9
m,p-Xylene	-	2300	20.7	1470	-	-	21.6	74.2
o-xylene	-	2300	5.6	320	-	-	5.7	20.3
Styrene	-	400	0.3	130	-	-	4.1	11.3
1,3,5-TMB	-	-	2.7	640	0.53	1.47	5.1	15
Naphthalene	-	22.5	-	-	4.81	83.4	7.2	30
1,2-Dichloroethane	-	-	<0.1	1.7	-	-	7.4	25
TCE	2.3	12	0.5	165	-	-	2.3	6.5
PCE	-	360	2.7	313	1.59	9.55	8.2	30
DCBs	-	95	18.9	1390	53.4	1600	12.8	337.5
n-hexane		12000	1.2	124	5.24	108	14.5	99.4
n-decane	-	-	31.4	6450	6.85	91.9	-	-
n-dodecane	-	-	-	-	-	-	14.7	91.9

Notes:

Concentrations in units of  $\mu\text{g}/\text{m}^3$

a: Davis, C.S. and R. Otson. 1996.

b: Otson, R. and J. Zhu. 1997.

c: Saskatchewan Research Council. 1992.

TCE: Trichloroethylene; PCE: Tetrachloroethylene; DCBs: Dichlorobenzenes; TMB: Trimethylbenzene

As a result of these background sources, particular care must be taken in the collection, review and interpretation of IAQ data. For instance, it is important to understand, as well as minimize, the effects of indoor sources through an assessment of building conditions and proper building preparation prior to sampling (Exhibit 4.1), and in certain cases, include sampling to evaluate representative background air concentrations at the site.

#### 4.2.2 Building Foundation Construction

The building foundation construction will influence soil vapour intrusion rates into the building. For example, soil vapour can migrate through relatively small cracks or openings in the foundation or through utility penetrations. Soil vapour intrusion rates may vary depending on type of foundation, which include basement, slab-on-grade, crawlspace or earthen floor construction. For houses, there is often a perimeter edge crack between the foundation wall and slab for concrete floor slab construction. Compared to houses, construction methods for commercial buildings may be different including some buildings where measures are taken to seal concrete foundations, which would tend to reduce (but perhaps not eliminate) soil vapour intrusion. Utilities represent potential entry points for soil vapour intrusion regardless of building type.

#### 4.2.3 Building Ventilation

The building ventilation and exchange with fresh air, vapour concentrations in indoor air are diluted. Building ventilation or air exchange vary depending on climate, construction and season. A review of approximately 2,800 building ventilation measurements in houses across the U.S. grouped the results according to regions (defined by heating degree-days) and four seasons (Murray and Burmaster, 1995). The average yearly air change per hour (ach) for the four regions ranged from 0.4 to 0.98 hr<sup>-1</sup>. For the north central to eastern part of the US (which most closely approximates most regions in Canada), the average ach in summer was 0.82 hr<sup>-1</sup>, the average in fall was 0.25 hr<sup>-1</sup>, the average in winter was 0.36 hr<sup>-1</sup> and the average in spring was 0.44 hr<sup>-1</sup>. In Canada, air exchange rates in high energy efficient (“R-2000”) homes can be quite low based on tight construction. In an Ontario study, air exchange rates from 70 houses ranged from 0.06 to 0.77 ach, with the lowest air exchange occurring in summer with closed windows in R-2000 houses (Walkinshaw, 1987). In a study completed in Saskatchewan and Tilsonburg, Ontario, the average measured air exchange rate from 44 houses was 0.34 ach (SRC, 1992), while in a study completed in the Greater Toronto area, the average air exchange rate from 44 houses was 0.45 ach (Otson and Zhu, 1997).

For commercial buildings, design air exchange rates must meet minimum requirements based on building occupancy, although actual ventilation system efficiency may be variable depending on operation of the HVAC system. Standards in Canada and the U.S. both specify minimum ventilation rates for residential and commercial buildings.<sup>7</sup> For

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<sup>7</sup> Examples are CSA F326 and ANSI / ASHRAE Standard 62.1 – 2004 Ventilation for Acceptable Indoor Air Quality.

example, ASHRAE (2004) indicates that for office use, 20 standard cubic feet of outdoor air is blown into the building per person to maintain sufficient fresh air supply, which corresponds to an air exchange of about 0.72 ach for typical occupancy. Ventilation rates for institutional buildings are higher. The USEPA BASE study of one hundred randomly selected commercial buildings, which represented a wide range in construction, found that the 25<sup>th</sup>, 50<sup>th</sup> and 75<sup>th</sup> percentile air change rates were 0.47 hr<sup>-1</sup>, 0.98 hr<sup>-1</sup> and 2.62 hr<sup>-1</sup>, respectively (NIST, 2004). When conducting a site specific assessment, it may be instructive to obtain information on building ventilation from building HVAC engineers since often design and test information providing data on air flow rates for return and supply air will be available.

#### 4.2.4 Building Depressurization and Weather Conditions

The indoor and outdoor temperature, number of storeys, degree of air leakage between floors, and presence of chimney, flues, exhaust fans and vents, may contribute to the pressure differentials that affect the rate of intrusion of soil gas. Of particular importance is the “stack effect” that may occur during the heating season as a result of hot air rising in a building and leaving near the top of the building (e.g. through a chimney, leaky attic, exhaust vent). This creates a negative pressure within the building, thus drawing outdoor air and soil gas into the building through openings with the lower regions of the building (i.e. doors, windows, cracks and/or the building foundation). Pressure differences during the heating season for houses with basements typically range from 2 to 10 Pa, but may be as high as 15 Pa (Figley, 1997; Hers et al., 2001).

The operation of the HVAC system may also result in building depressurization through intake and exhaust systems that are not balanced or through insufficient combustion air. The operation of fans and fireplaces also can result in a depressurized building. For commercial buildings, the HVAC system may be designed to provide for positive pressure under most conditions, but for tall buildings, the stack effect may be sufficient to maintain a negative pressure at ground level during cold weather. Commercial building pressures may also depend on operation of the HVAC system and exhaust fans (e.g., fume hoods, oven vents).

Wind force may create pressure differentials between upwind and downwind sides of the building, which is another mechanism that causes the building interior to be underpressurized. Changes in barometric pressure as a result of meteorological conditions can also cause pressure differences between the building interior and exterior. These pressure differences may occur at varying temporal scales (hourly to seasonally), but in general, the most significant pressure differences occur under severe winter conditions.

Thus, weather conditions and HVAC operation may have a marked effect on air exchange rates and pressure differences between indoor and outdoors, which can both affect the rates of soil vapour intrusion into buildings and the degree of mixing and dilution within the building structure.

#### **4.2.5 Mixing of Vapours Inside Building**

Within the building, contaminants will diffuse as a result of chemical gradients and disperse through air movement. Mixing between building floors will depend on the HVAC system and air leakage between floors. Elevator shafts often include a sump and are not ventilated; they may represent points where migration and accumulation of soil vapours could occur. Elevator shafts can also represent conduits for inter-floor migration of vapours.

#### **4.2.6 Vapour Depletion Mechanisms**

Chemical or physical mechanisms may result in the removal of vapours from indoor air, in addition to dilution through building ventilation. Since soil vapour intrusion typically occurs over timescales of months to years, the removal of volatiles in air through adsorption onto building materials is unlikely to have a significant long-term effect on indoor vapour concentrations since adsorption sites on building materials will likely be filled over time. Adsorption onto building materials can be reversible (i.e. desorption can occur) and thus should also be considered as a source of volatiles, depending on building conditions. For example, even after soil vapour intrusion is mitigated through a subslab venting system, there may be a period of time over which the chemical of concern is detected in indoor air as a result of desorption from building materials. Chemical transformations due to processes such as photo-oxidation are generally relatively slow processes (i.e., half-lives of days) and biodegradation is unlikely to be a relevant process in an indoor environment.

### **4.3 Development of Indoor Air Quality Study Approach and Design**

#### **4.3.1 Define Study Objectives**

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

There may be other specific objectives of the IAQ study that would result in a different sampling strategy. For example, if the goal is to evaluate potential entry points for soil gas into a building, samples may be collected from close to cracks or within utility openings. Samples collected to meet this objective are typically referred to as “pathway” samples. If the objective of the IAQ study is to evaluate the potential influence of background sources of indoor air quality relative to subsurface sources, several indoor air

samples from different locations within a building may be required. In addition, the building environment may be artificially controlled at the same time IAQ sampling is conducted to assist in evaluation of background sources, as described in Section 4.3.7.

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

#### **4.3.2 Identify Target Compounds**

The target compounds for the sampling plan are dependant upon the contaminant source under evaluation. Target compounds would generally include the primary constituents of the contamination source and may also include potential breakdown products of these constituents. For an IAQ study designed to evaluate soil vapour intrusion from contaminated soil or groundwater, a screening process based on volatility and toxicity can be used to identify target compounds (SAB, 2004). Target compounds may also be identified based on the results of previous indoor air sampling at the site or based on the history of the site and/or neighbouring properties.

For petroleum hydrocarbons, target compounds also may include petroleum fractions as well as specific chemicals of potential concern. Specific chemicals are often the more potent chemicals associated with the petroleum fraction and include carcinogenic compounds such as benzene.

#### **4.3.3 Develop Communications Program**

An important part of the IAQ program is communication with the building occupants and owners and other stakeholders, to keep them informed and involved in the process. This can be done throughout the sampling process, but is especially important in the preparatory stage. Issues to address with building occupants include: why the study is being conducted and what the study objectives are; scheduling the pre-sampling building survey; discussing the types of activities to avoid prior to the sampling events (see Section 4.3.7); scheduling and discussing the sampling that will be conducted; background sources and issues, and communication of the results of the sampling program. Consideration should be given to development of an access agreement between parties prior to sampling.

#### **4.3.4 Conduct Pre-Sampling Building Survey**

Buildings should be inspected prior to and during IAQ testing to assess whether there are potential background sources of chemicals and also to describe building conditions that may influence indoor air concentrations. Building occupants may also be interviewed to derive additional information on factors that may affect IAQ and to determine the building occupancy characteristics. Examples of a pre-sampling building survey, that could be used to direct a building inspection and occupant interviews, are included in Appendix IV. The pre-sampling building survey may be used as a tool to refine the sampling plan and identify any building preparation activities that should be considered prior to sampling. Such activities might include the removal of consumer products and/or other sources of VOCs from the buildings, if possible. Relevant portions of the survey should be reviewed again at the time indoor air sampling is performed. A survey should be completed for each building being investigated.

#### **4.3.5 Conduct Preliminary Screening**

In conjunction with the pre-sampling building survey, a preliminary screening of the study building using a portable air monitoring instrument such as a photoionization detector (PID) can provide useful information on background VOC sources in indoor air. When sensitive PIDs are used (low ppbV range), they may also be capable of identifying entry points where soil gas intrusion is occurring. It is important to note that most direct-measuring instruments measure relative levels of organic compounds as a group and are not capable of identifying specific compounds. Furthermore, for most conventional PIDs/FIDs, the sensitivity of these instruments is often insufficient to detect compounds at levels that may be of concern for human health. Therefore, while they may be a useful tool for identifying indoor VOC sources or targeting sampling locations at some sites, they may not be used to rule out the presence of background contaminants in indoor air.

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

#### **4.3.6 Identify Immediate Health or Safety Concerns**

If the building survey or preliminary screening identify immediate health or safety concerns associated with chemical odours or where occupants exhibit signs of illness due to inhalation of volatiles in indoor air, further actions should be taken to identify the chemical source and mitigate the hazard, as warranted. There may also be instances where there are safety concerns associated with the accumulation of potentially explosive levels of methane inside or near to buildings.

#### 4.3.7 Define Number and Locations of Indoor Air Samples

The number and locations of indoor air samples will be dictated by several factors. If a preliminary investigation of IAQ is being undertaken, a limited number of samples may be sufficient. If the study objectives require a statistical approach or analysis of results, multiple samples would be required. The building characteristics including size, construction and ventilation patterns will also influence the required number of samples. For example, if the building is a small house with reasonably good ventilation, the indoor air concentrations within the house may be relatively uniform. For this scenario, one sample may be sufficient, although a minimum of two samples is initially recommended, unless previous testing at the site has been conducted to characterize concentration variability.

For a larger house, commercial building, or school, where indoor air concentrations may vary in different parts of the building, multiple samples are required to characterize indoor air quality. For a residence with multiple floors, consideration should be given to collecting at least one sample per floor (per sampling event) to characterize inter-floor variability. Where minimal sampling is conducted for a preliminary assessment, it is generally preferable to target the first level of the building (e.g., basement) since vapour concentrations are expected to be highest in lower regions of the building in instances of soil vapour intrusion. Exposure samples should be collected within the typical breathing zone at a height of approximately 1 to 1.5 m above the floor, preferably near the centre of the room, which is generally representative of overall room conditions.

#### 4.3.8 Define Sampling Duration

The duration for sample collection may depend on the study objectives. The selected sample duration should yield an average concentration of chemicals of potential concern over the expected daily exposure duration. For a residential scenario, it is possible that residents may be present in the home 24 hours per day. Therefore, a 24-hour sample duration is recommended for a residential scenario.<sup>8</sup> For a commercial scenario, a sample duration equivalent to the standard 8-hour commercial exposure duration is recommended. However, a longer or shorter sample duration could be selected, if warranted, based on site-specific conditions and site use. When determining the sampling duration, potential limitations in the sampling device should be considered. For example, for sorbent tubes, chemical breakthrough may be an issue depending primarily on the sampling duration and flow rate.

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<sup>8</sup> To provide perspective on sampling duration it is noted that it is generally recommended that radon samples be collected over a period of one week or longer to account for temporal variability ([www.epa.gov/radon](http://www.epa.gov/radon)). The feasibility and need for longer duration active air sampling for evaluation of vapour intrusion is an area of current research.

#### **4.3.9 Define Sampling Frequency**

The sampling frequency will depend on study objectives, the nature of the contamination source and variability expected due to factors such as building characteristics, weather conditions and occupancy characteristics during sampling. Since it is not possible to accurately predict concentration variability due to the site specific and complex nature of the processes that contribute to soil vapour intrusion, repeat sampling is generally required to establish concentration variability at a given site. In general, a minimum of two sampling events that capture possible seasonal variability (e.g., winter/summer) are required; however, additional sampling events may be warranted at some sites. In general, higher indoor vapour concentrations would be expected when sampling is performed under winter conditions. Repeat sampling may also be warranted, for example, if the subsurface source concentrations are changing over time (e.g., mobile groundwater plume).

#### **4.3.10 Preparing the Building for Sampling and Conditions During Sampling**

Indoor sources, such as consumer products, combustion sources and new building materials may contribute significantly to the background levels of the target compounds, complicating the interpretation of test results. It is generally desirable to minimize background sources prior and during indoor air sampling when conducting IAQ programs to evaluate soil vapour intrusion.

Often indoor sampling programs may be tailored to minimize these background sources. For example, consumer products (e.g., solvents, gasoline containers) may be removed and combustion sources (i.e., candles, wood stoves) temporarily extinguished prior to sampling. Furthermore, sampling can be delayed to allow elevated VOCs associated with new construction materials, paint or furnishings, or sealing work, to dissipate. A list of measures that should be considered when performing IAQ sampling programs is provided in Exhibit 4.1. It is important that specific instructions be provided to building occupants in advance of the sampling event.

**EXHIBIT 4.1. PREPARATION OF BUILDING FOR IAQ SAMPLING**

Summary of measures implemented prior to IAQ sampling:

- Removal of products that are known significant sources of VOCs, such as gasoline or solvents, as practical;
- Ensuring that containers of VOC-containing products are tightly sealed, as practical;
- Combustion sources (i.e., candles, wood stoves) should be extinguished prior to sampling (preferably 24 hours prior to sampling).
- Consideration should be given to delaying sampling to allow elevated VOCs associated with new construction materials, paint or furnishings, sealing work, to dissipate;
- After removal or control of known VOC sources, ventilation may be required to help eliminate residual contaminants. This may be done through operation of the building HVAC system or opening of doors, windows, or operation of exhaust fans. It should be completed at least 24 hours prior to sampling; and,
- HVAC systems (heating and cooling) should generally be operating under normal occupied conditions for at least 24 hours prior to and during the scheduled sampling time (unless the objective is to artificially control building conditions).

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

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

Although not usually part of most vapour intrusion assessments, in some cases, it may be desirable to adjust building HVAC conditions to control conditions for soil gas intrusion. For example, monitoring of IAQ under conditions of positive and negative building pressure may confirm whether volatiles measured in indoor air are from subsurface or background sources. One way to control building conditions is to either extract or blow in air using a blower or fan. One way to implement this test is to replace a door of a building with custom door of the same size fitted with a blower (i.e., referred to as “blower door test”).

#### **4.4 Indoor Air Analytical Methods**

The selection of the indoor air analytical method depends on a number of factors, including data quality objectives, risk assessment objectives, detection limits and the contaminants of potential concern. While sampling methods for indoor air can include screening techniques using direct-reading instruments, typically indoor air samples are obtained using either sorbent materials or canisters (e.g., Summa canisters) and sent to a laboratory for analysis.

Since analytical protocols were addressed in detail for soil vapour, this section is limited to describing differences in analytical considerations for indoor air. Since there are accepted methods for collection of indoor air samples using passive methods (unlike soil vapour), indoor air testing using passive diffusive samplers is also described.

The main differences between soil vapour and indoor air sampling are that lower detection limits, larger sample volumes and longer sampling durations are generally required for indoor air testing. The required analytical reporting limit will depend on the compound, but typically is less than 1 ug/m<sup>3</sup>. For some analytes, the target risk-based indoor air concentration may be below a practically achievable detection limit and/or below typical background levels in indoor or ambient air. The low detection limits require that a high level of care be taken to avoid cross-contamination both by the laboratory (e.g., cleaning of sampling device) and by persons performing the sampling (e.g., handling and storage of sampling device).

For indoor air testing, Summa canisters (six litre) are frequently used (USEPA TO-15). To provide the sensitivity required, GC/MS analysis may need to be performed in selective ion model (SIM). For active sorbent tube analysis, modified industrial hygiene methods involving solvent extraction (e.g., modified OSHA 7 or NIOSH 5515) may not provide sufficiently low detection limits. Instead, thermal desorption methods may be required.

##### **4.4.1 Issues for Air Analysis Using USEPA Method TO-15**

While a complete discussion goes beyond the scope of this guidance, there are subtle issues for analytical protocols, which may be important, and are relevant since TO-15 methods are not completely prescriptive. The use of selective ion mode (SIM) may be desirable when sub ppbV detection limits are desired. However, since the use of SIM mode only allows specific masses to be characterized, other potential compounds are not monitored. The lack of complete mass ion data may result in inaccurate compound identification and quantification, which may result in false positives or negatives. The use of SIM mode is not recommended during the initial site characterisation phase. The specifications for tuning and data acquisition of the GC/MS are important when analyzing in SIM mode. While there is not agreement between laboratories on tuning protocols, in many cases, the protocol developed by the State of Colorado has been

adopted (Colorado, 2000). There are also differences in methods used to calibrate detectors; the use of gas, as opposed to liquid, standards is recommended for this purpose to avoid potential negative bias.

#### **4.4.2 Issues for Air Analysis using Passive Diffusive Badge Samplers**

The use of passive diffusive badge samplers is a common method for evaluation of workplace exposures to VOCs. Typically, these badge-type samplers are used to evaluate exposures in the high part per billion (ppbV) to part per million (ppmV) range over an 8-hour period, although they can be deployed for longer periods of time (up to one week) to evaluate lower concentrations. The absorbent medium is typically charcoal, which is extracted using solvent (carbon disulphide) and analyzed using GC/MS methods (reference). Passive samplers are easy to use and do not require a sampling pump.

The sampling (i.e., diffusive uptake) rate is a function of the diffusive coefficient, which is compound and sorbent specific, and the geometry of the sampler. Other factors that affect performance include temperature, pressure, humidity, air velocity and transient changes in contaminant concentrations. More recently, passive diffusive badges have been used for indoor air quality studies involving longer sampling periods and lower detection limits. The use of sorbents that are thermally desorbed (Chromosorb 106, Carbotrap Z) has also recently been investigated (OSHA, 2003).

There are several potential limitations associated with passive diffusive sampling methods that should be recognized:

- The sampling rate is compound specific; there are varying (up to four) levels of validation studies, which range from laboratory testing programs, designed to evaluate the stability of the sampling rate under varying conditions, to calculated values
- The sampling rate is typically relatively stable over a certain time interval, but will decrease once saturation of the media is approached;
- In stagnant air, the sampling rate will decrease; one study indicated a significant decline for sampling face air velocities less than 0.5 m/s (OHSA, 1998);
- Back-diffusion of compounds out of the sampler may occur for some compounds;
- Humidity above 50 percent will reduce recovery of certain compounds such as vinyl chloride, acetone and methyl ethyl ketone (3M Bulletin 1028, 2001);
- Extraction recovery varies depending on compound; project specific recovery tests are recommended by some badge manufacturers (3M Bulletin 1028, 2001) to address varying recovery for contaminant mixtures;
- There is an absence of established methods for low-level VOC analysis and studies involving longer sampling durations; and

- Detection limits for passive diffusion samplers typically exceed 0.5 to 1.5  $\mu\text{g}/\text{m}^3$  for common VOCs (Phil Fellin, personal communication, February 5, 2006).

Due to the above limitations, the use of passive badge samplers are not recommended for low or sub-ppbV indoor air quality testing, unless efforts are taken to validate the method based on the anticipated chemicals of concern.

## **5.0 DATA INTERPRETATION AND ANALYSIS**

### **5.1 Soil Vapour Characterisation**

#### **5.1.1 Data Organization and Reporting**

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

- Tabulate all data including sample location identifier, sample date, sample depth, sampling methods (including sampling duration and flow rate), chemical analysis methods, laboratory detection limits and results of chemical analysis;
- Tabulate field screening and laboratory analysis data to enable side by side comparisons;
- Prepare plan drawings showing soil vapour concentration data that includes pertinent structures (buildings, utilities, paved areas, vegetated areas);
- Compare soil vapour with nearby groundwater concentration data; consider geologic conditions when evaluating variability;
- Prepare vertical profiles of soil vapour concentration data that includes oxygen, carbon dioxide and methane and boring log data where available;
- Identify soil vapour target concentrations and background indoor and outdoor air concentrations, where available.

#### **5.1.2 Data Quality Analysis**

Following receipt of the soil vapour results, the data should be evaluated to determine whether they meet data quality objectives outlined in the sampling plan (Section 3.5.5). The data quality checks should include the following:

- Review reported detection limits relative to data quality objectives. In some cases, sample dilution is required which results in raised detection limits.
- For Summa canister analyses, review canister pressure upon completion of sampling and receipt by the laboratory. There should be a small vacuum left in the canister, if not, the sample integrity could be compromised. Obtain pre-delivery canister testing and certification results from the laboratory. When there are significant differences in the elevation at which the sample was obtained and the laboratory, it may be possible to correct for the effect of ambient pressure on the sample concentration (i.e., using Boyle's Law for an ideal gas), providing that the barometric pressure at the time of sampling and analysis are recorded.

- For sorbent tube analyses, review results of analyses of front and back sections of the tube (or two tubes in series) to evaluate possible chemical breakthrough. Breakthrough can be caused when the adsorptive capacity is exceeded, the air flow through the tube is too high, and chromatographic effects caused by other compounds. If the laboratory considers the first tube saturated, then results are potentially biased and re-sampling should occur. The criterion for evaluating breakthrough is method and chemical dependent but typically is a concentration in the second tube that is greater than 10 to 25 percent of the concentration in the first tube. If the sample media is not saturated, the front and back concentrations should be added together for numerical evaluation.
- Compare precision for laboratory and field duplicate or co-located samples, as quantified by relative percent difference (RPD). The acceptable precision is method and chemical dependent, but for laboratory duplicates is generally 20 percent. For field duplicates, the acceptable RPD is higher since there is sampling variability in addition to laboratory variability.
- Review analytical results for blank samples (e.g., field blanks, laboratory blanks and trip blanks) to identify possible issues with the laboratory or field procedures that may have affected the results.
- Recognize that reported concentrations within five times of the quantification limit are typically more uncertain than higher concentration values.

### 5.1.3 Data Consistency Analysis

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

- The soil vapour concentrations should be spatially consistent with the soil and groundwater concentrations, for example, the highest soil vapour concentration should be measured in source contamination areas where soil and groundwater concentrations are also highest.
- The soil vapour concentrations should decrease with increasing distance from a source, and, in general, oxygen concentrations should decrease and carbon dioxide concentrations should increase close to petroleum hydrocarbon sources. If this pattern is not observed, there may be additional contamination sources present or there may be data quality issues (e.g., short circuiting).
- The vertical gradients of petroleum hydrocarbon vapours, oxygen, carbon dioxide and methane should be internally consistent. A decrease in hydrocarbon vapour concentrations should be associated with a decrease in oxygen and increase in carbon dioxide concentrations. As described in API (2005), stoichiometric relationships for aerobic biodegradation can be used to quantify the fluxes and concentration profiles expected.

- Typically, oxygen concentrations are depleted to some extent in soil gas. Significant depletion in oxygen concentrations are observed close to petroleum hydrocarbon source zones and below confining layers. Oxygen concentrations close to atmospheric levels (20.9 percent) can be a strong indicator that the soil gas sample was compromised through short-circuiting or leakage.
- Soil vapour concentrations should be consistent with expected temporal trends. A priori it may be difficult to predict the effect of temporal factors on soil vapour data; therefore, a database that already includes some temporal data may be required to make this evaluation.

#### **5.1.4 Further Evaluation**

An in-depth discussion of further evaluation and action that may be warranted when evaluating soil vapour intrusion at sites is beyond the scope of this guidance. As a minimum, the data quality and consistency should be evaluated to determine whether additional soil vapour characterization is warranted. The soil vapour concentrations are typically initially compared to risk-based generic (if available) or site-specific soil vapour criteria. If soil vapour concentrations exceed these criteria, options can include additional soil vapour characterization (i.e., closer to the building) or indoor air testing.

## **5.2 Indoor Air Quality Testing**

### **5.2.1 Data Organization and Reporting**

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

- Tabulate all data including sample location identifier, sample date, sample height, sampling methods, chemical analysis methods, laboratory detection limits and results of chemical analysis.
- Calculate constituent ratios (Section 5.2.3) and evaluate trends with respect to (i) indoor air to soil vapour or subslab vapour samples, (ii) first building level to higher level air samples, and (iii) indoor air to outdoor air samples.
- Note building conditions during indoor air sampling and qualitatively describe opening of windows and doors, operation of fireplace, furnace and fans.
- Note potential significant indoor sources of VOCs present during sampling.
- Identify target risk-based indoor air concentrations and background indoor and outdoor air concentration, where available.

### 5.2.2 Data Quality Evaluation

Following receipt of the indoor air testing results, the data should be evaluated to determine whether they meet data quality objectives outlined in the sampling plan (Section 3.5.4). The data quality analysis for indoor air is similar to soil vapour (Section 5.1.2).

### 5.2.3 Methods for Discerning Contributions of Background from Indoor Sources

There are a large number of background sources of VOCs including indoor sources such as building materials and consumer products, and outdoor ambient air sources. Since the intent of this guidance is to evaluate impacts to indoor air resulting from soil vapour intrusion, careful consideration must be given to determining which constituents are derived from background sources and which are likely related to the contaminant release or spill. To the extent possible, multiple lines-of-evidence should be considered when evaluating IAQ data. By relying on several lines-of-evidence rather than a single line-of-evidence, the overall level of uncertainty of the study can be reduced.

The relative importance of various lines-of-evidence should be based on professional judgment and should consider site conditions, data quality, as well as an understanding of background sources of contamination, factors affecting IAQ as well as contaminant fate and transport mechanisms. Data collected from all lines-of-evidence should be evaluated in the context of all of the information gathered and the evaluator's knowledge of the site.

#### Constituent Ratios

An evaluation of the ratios between contaminant concentrations in groundwater, soil vapour and indoor air for concurrent data and chemicals with similar fate and transport properties can assist in discerning background sources of contaminants. Chemical ratios in indoor air and soil vapour should be similar if vapour intrusion is the cause for the elevated indoor air concentrations. If the ratios are significantly different (greater than one order-of-magnitude), there are likely background contributions of VOCs for some or all the chemicals under consideration. If groundwater data are used, adjustments should be made to take into account different relative volatilities between contaminants (i.e., corrected for varying Henry's Law constants).

Since there are differences in fate and transport properties (e.g., partitioning and biodegradation rate) even for similar chemical groupings (e.g., BTEX for petroleum hydrocarbon compounds, tetrachloroethene and trichloroethene for chlorinated solvent compounds), the constituent ratio technique is a relatively crude order-of-magnitude method.

### Marker Chemicals

Marker chemicals are compounds which are associated with the subsurface contamination, but not background air sources. An example of a marker chemical is 1,1-dichloroethylene (DCE), which is a degradation product of 1,1,1-trichloroethane, and which is not known to be present as background chemical in indoor air. Therefore, detectable levels of 1,1-DCE in indoor air would suggest soil vapour intrusion is occurring (unless from an ambient air source). Marker chemicals, if present, are also useful compounds when evaluating constituent ratios using the method described above.

### Spatial Trends

An evaluation of spatial trends may provide insight on differentiating background sources from the contaminants of interest. For instance, VOC concentrations in a basement may be higher than in upper floors. This provides support for a subsurface vapour source, but care must be taken to ensure that the results were not biased by products stored in the basement. Also, testing of “pathway” samples collected near foundation cracks, unsealed utility entry points or other possible preferential transport zones could be compared to samples collected at other parts of the building. Concentrations in pathway samples that are elevated relative to concentrations in samples from other parts of the building may indicate soil vapour intrusion is occurring. However, spatial differences may be minimal in buildings with efficient ventilation systems.

For larger spatial trends, it may be possible to examine the results of indoor air testing for multiple buildings and compare this to known subsurface conditions (i.e., extent of plume, contaminant gradients, location of hot spots, depth of groundwater). Buildings located outside the plume may also be used as “reference” sites to establish typical background IAQ (refer to the following section).

### Comparison of Indoor Air Data to Literature Background Concentrations

Indoor air quality data may be compared to published data on indoor air quality. Typical background sources and concentrations of VOCs in indoor air were discussed in Section 4.2.1. The data should be compared to data for buildings of similar type (e.g., single family residence, apartment, commercial).

### Comparison of Indoor Air Data to Control Building Survey

The IAQ data from buildings above the contaminated area may be compared to IAQ data from nearby “reference” buildings outside the contaminated area. This method requires a sufficient number of buildings to be tested such that statistical comparisons between data sets can be made. There are a number of confounding factors that could contribute to differences in air quality unrelated to soil vapour intrusion. To the extent possible, building construction and occupant usage of the reference buildings should be similar to the buildings of interest.

Modification of Building Pressurization

Indoor air quality testing under positive and negative building pressurization can be used to determine whether soil vapour intrusion is occurring and to evaluate the possible influence of background sources on indoor air quality. Indoor air concentrations that are significantly different under positive and negative pressures suggest vapour intrusion is occurring, since typically, soil gas advection caused by building depressurization is the main cause for soil vapour intrusion. Building pressures can be modified through control of the building HVAC system and use of temporary fans or blowers.

While modification of building pressurization goes beyond the typical scope of testing for IAQ studies, it could be considered when it is important to distinguish background from possible subsurface vapour sources.

Evaluation of Source Vapour Strength and Minimum Vapour Attenuation Ratios

An evaluation of the source vapour strength, which is the concentration near to the contamination source, combined with the expected minimum vapour attenuation based on empirical data and/or modeling appropriate to the location of groundwater or soil vapour measurement point, can be used to evaluate whether measured indoor air concentrations are practically feasible in terms of a soil vapour intrusion source. Care must be taken when following this approach since there may be uncertainty in source vapour concentrations and minimum vapour attenuation ratios, therefore it can only be as an approximate guide. An in-depth discussion on this approach goes beyond the scope of this guidance, but is provided in USEPA (2006).

**Groundwater Source**

$C_{\text{air}}^{\text{v}} = 1000 * C_{\text{g}} * H' * \alpha_{\text{g}}$  ;  $\alpha_{\text{g}} = 1 \times 10^{-3}$  ; If  $C_{\text{air}}^{\text{m}} > C_{\text{air}}^{\text{v}}$  then likely background source

**Soil Vapour Source (External, Minimum 1 m below foundation)**

$C_{\text{air}}^{\text{v}} = C_{\text{v}} * \alpha_{\text{v}}$  ;  $\alpha_{\text{v}} = 1 \times 10^{-2}$  ; If  $C_{\text{air}}^{\text{m}} > C_{\text{air}}^{\text{v}}$  then likely background source

**Subslab Soil Vapour Source**

$C_{\text{air}}^{\text{v}} = C_{\text{ss}} * \alpha_{\text{ss}}$  ;  $\alpha_{\text{ss}} = 1 \times 10^{-1}$  ; If  $C_{\text{air}}^{\text{m}} > C_{\text{air}}^{\text{v}}$  then likely background source

Where  $C_{\text{air}}^{\text{v}}$  is the maximum expected indoor vapour concentration ( $\text{ug}/\text{m}^3$ ),  $C_{\text{g}}$  is the maximum groundwater concentration,  $\alpha_{\text{g}}$  is the maximum expected groundwater-to-indoor attenuation factor,  $C_{\text{v}}$  is the maximum soil vapour concentration,  $\alpha_{\text{v}}$  is the maximum expected soil vapour -to-indoor attenuation factor,  $C_{\text{ss}}$  is the maximum subslab vapour concentration,  $\alpha_{\text{ss}}$  is the maximum expected subslab vapour -to-indoor attenuation factor.

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**7.0 GLOSSARY**

ACH	air change per hour
AEC	area of environmental concern
ATSDR	US Agency for Toxic Substances and Disease Registry
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene and xylenes
CCME	Canadian Council of Ministers of the Environment
COPC	contaminant of potential concern
CSM	conceptual site model
CWS-PHC	Canadian Wide Standards - Petroleum Hydrocarbon Compounds (CCME guidance)
DNAPL	dense non-aqueous phase liquid
DRA	detailed risk assessment
FID	flame ionization detector
GC/MS	gas chromatography/mass spectrometry
HDPE	high density polyethylene
HI	hazard index (sum of HQs)
HQ	hazard quotient
HVAC	heating, ventilation and air conditioning
I.D.	inside diameter
IAQ	indoor air quality
IRIS	Integrated Risk Information System
J&E	Johnson and Ettinger
LNAPL	light non-aqueous phase liquid
NAPL	non-aqueous phase liquid
PCE	perchloroethylene
Phase I ESA	phase one environmental site assessment
Phase II ESA	phase two environmental site assessment
PID	photo ionization detector
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
$Q_{soil}$	advective soil gas flow rate into building
RA	risk assessment
RPD	relative percent difference
SF	slope factor
SFR	single family residence
SLRA	screening-level risk assessment
SSD	subslab depressurization (vapour intrusion mitigation system)
TC	tolerable concentration
TCE	trichloroethene (trichloroethylene)
TRV	toxicity reference value
UR	unit risk
USEPA	US Environmental Protection Agency
USSCS	US Soil Conservation Service (for soil texture classification)
VOC	volatile organic compound
WHO	World Health Organization

## **APPENDIX I**

### **CHECKLISTS FOR SOIL VAPOUR CONCEPTUAL SITE MODEL AND SOIL GAS SAMPLING AND ANALYSIS PROGRAMS**

**APPENDIX I****CHECKLIST FOR VAPOUR INTRUSION CONCEPTUAL SITE MODEL**

This checklist is intended to address conceptual model development for soil vapour intrusion studies, but does not include considerations relating to characterization of indoor air quality. It is recognized that some of the information on buildings may not be available in the absence of indoor air sampling.

**Information Sources and Status**

- Summarize the information sources that have been used to develop the conceptual site model
- Summarize the status of investigations completed at the site
- Summarize the status of remediation completed at the site including contamination source zone, groundwater or vapour remediation

**Contamination Source Characteristics**

- Describe the type, source and history of the contamination release
- Describe the presence, distribution and composition of LNAPL and/or DNAPL, if present at the site, describe whether LNAPL and/or DNAPL is potential mobile
- Describe the distribution and extent of dissolved organic chemicals in groundwater
- Describe whether there could be transformations to daughter products of potential concern (e.g., chlorinated solvents)
- Describe the migration characteristics of the dissolved plume, and whether the plume is expanding, stable or shrinking,
- Describe possible evidence for natural attenuation and bioattenuation in both saturated and unsaturated zones

**Geology/Hydrogeology**

- Describe the physical properties of soil in the unsaturated zone and shallow saturated zone (grain size, moisture content, porosity, density, permeability)
- Describe the natural organic carbon (or organic matter) content in soil
- Describe the soil lithology (i.e., type of soil) with particular attention to soil layering
- Describe the bedrock with particular attention to fracture occurrence and orientation, if bedrock is present
- Describe the depth to groundwater and fluctuations in the water table (e.g., seasonal, tidal, long-term due to pumping)

- Describe the hydrostratigraphic units and shallow groundwater flow system, and perched water table, if present
- Describe hydrogeological parameters ( e.g., hydraulic conductivity, hydraulic gradient)
- Describe foundation subsoils

### **Utilities**

- Identify the location of subsurface utilities; indicate the type of utility, the plan location, depth, and backfill properties, as available
- Identify the location of any utilities that intersect the vapour contamination zone and directly connect to buildings

### **Site Characteristics and Anthropogenic Features**

- Describe the surface cover in the area of the vapour contamination source(s) and nearby buildings
- Estimate the vertical and lateral distances from the vapour contamination source(s) to nearby buildings. Estimate distances for soil, groundwater (dissolved) and NAPL contamination sources.
- Describe potential future changes to land use and implications for surface cover

### **Buildings**

- Identify location of existing buildings
- Identify potential future buildings
- Describe the occupancy and use of the buildings (residential, institutional, recreational, commercial, industrial)
- Approximate age of building
- Describe characteristics of the building
  - Size of building
  - Number of storeys
  - Height of storeys
  - Foundation type (e.g., basement, crawlspace, slab-at-grade); if combination of foundations, indicate percentage for each type
  - Depth below grade to base of foundation
  - Foundation construction for both floor and subsurface walls (e.g., poured concrete, concrete block, brick, wood)
  - General condition of foundation (cracks, openings)
  - Building construction (e.g., wood frame, concrete, brick)
  - Elevator shafts
  - Moisture vapour barrier below building

- Sumps
  - Attached garage (i.e., single family residential)
  - Below building parking (i.e., apartment, commercial building)
  - Chemical use and storage.
- Describe the HVAC system in the building including:
- Type of heating system (natural gas, oil, radiant, steam, electrical)
  - Type of air conditioning system
  - Location of heating and air conditioning units
  - For commercial buildings, air intake and exhaust units
  - For residential buildings with forced air furnace systems, return air ducting, does furnace have source of combustion air
  - Describe sub-slab ventilation systems or moisture barriers present on existing buildings, or identify building- and fire-code requirements for sub-slab ventilation systems (e.g., for methane) or moisture barriers below foundations.

## **CHECK LIST FOR SOIL GAS SAMPLING AND ANALYSIS PROGRAMS**

### **CONCEPTUAL SITE MODEL**

1. Identification of contaminants of concern (COC), physical-chemical properties, and potential for biodegradation.
2. Information on concentration, phase, distribution and extent of COCs.
3. Hydrogeological information.
4. Depth to contamination source zones.
5. Distance (vertical, lateral) from building to contamination source zones.
6. Vadose zone properties.
7. Size, location and type of buildings.
8. Location of subsurface utilities.
9. Potential for meteorological or seasonal factors to influence soil vapour concentrations.

### **SOIL GAS SAMPLING DESIGN (WHY, WHERE AND WHEN)**

1. Identify objectives of the soil gas sampling.
2. Integrate CSM into soil gas sampling design.
3. Identify buildings of potential concern.
4. Identify number of probes needed and where to install soil gas probe locations. Typically, soil gas investigations should start with characterization of soil vapour concentration near to the contamination source zone (i.e., deep samples). Beyond source soil vapour characterization; should consider whether:
  - a. Are lateral transects needed?
  - b. Are vertical profiles needed? Is biodegradation assessment needed?
  - c. Are subslab soil gas probes needed?

The number of probes will depend on several factors including the size and distribution of the contamination source zone, geologic heterogeneity, size and number of buildings and objectives of the sampling program.

5. When determining when to sample, consider possible temporal variations. Is repeat soil gas testing warranted? If so, what should monitoring frequency be? In general, a minimum of two monitoring events should be conducted to evaluate possible seasonal trends.

6. Do not conduct sampling during and after heavy rain. Wait at least one day after rain at sites with coarse-grained soils and longer at sites with fine soils.

## **SOIL GAS PROBE INSTALLATION (HOW)**

1. Review utility locations.
2. For subslab soil gas probes, evaluate safety issues and whether integrity of building envelope and structure will be affected. Use geophysical probes to locate utilities and rebar, as warranted.
3. Select probe type (probe installed in borehole, driven probe, direct push).
4. Select probe materials (typically stainless steel, PVC, polyethylene).
5. Select tubing materials (typically nylon, Teflon™ or polyethylene). Use new tubing.
6. Test field blanks (ambient or zero air drawn through probe assembly) to evaluate whether probe materials are clean, prior to installing probe, as warranted.
7. Install probe.
8. Complete soil gas probe with valve or stopcock at surface to prevent atmospheric air from entering probe.
9. Seal subslab probes through concrete with temporary seal (e.g., rubber stopper) after drilling hole.
10. Seal driven probes at ground surface using inert material (e.g., bentonite, modeling clay).

## **SOIL GAS SAMPLING PROCEDURES**

1. Allow soil gas probe to equilibrate. If drilling method to install probe used air, remove this volume of air from probe.
2. Select sampling container or device, in conjunction with analytical protocol.
3. Ensure sampling container or device, and sample tubing is clean. For sampling container or device supplied by laboratory, batch or individual certification of each container or device may be warranted.
4. Test sampling train excluding probe for leaks and short circuiting prior to sampling, as warranted.
5. Purging and sampling of probe;
  - a. Calculate dead volume of probe (probe and tubing diameter times length).
  - b. Purge three purge volumes. Avoid over-purging. Consider monitoring using PID, FID or fixed gas detector (O<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>) as part of purging process.

- c. Use relatively low flow rate (i.e., 20 to 200 ml/min). Pumps should be accurately calibrated prior to use.
  - d. Monitor the vacuum during purging. Reduce the flow rate if the vacuum exceeds 10 inches water.
  - e. When purging is complete, turn off pump and allow vacuum to dissipate.
  - f. Collect soil gas sample using relatively low flow rate (i.e., 20 to 200 ml/min).
  - g. Samples collected for laboratory analysis should never be collected through a pump, for Tedlar bag samples collected for field screening, avoid using pump and instead use vacuum-box to fill bag.
  - h. Analysis field samples using PID, FID and fixed gas detector; obtain sample for laboratory analysis, as required based on investigation objectives. Use consistent order for field and laboratory sampling.
  - i. Use consistent procedures between probes at a site and record procedures.
6. During sampling, test integrity of probe surface seal using tracer (e.g., helium) as warranted. The concentration of the tracer in the soil gas sample should be less than 1 percent of the concentration introduced at ground surface.
  7. Place sampling container or device in non-chilled container, except for sorbent tubes where a chilled container is acceptable.
  8. Record weather conditions prior to and during sampling.

## **SOIL GAS ANALYTICAL METHODS**

1. Determine data quality objectives. Establish required detection limits based on conservative vapour intrusion dilution factors and other factors.
2. Select analytical method and sampling container and device.
3. Determine sampling duration for sorbent tube sampling.
4. Establish program quality assurance and quality control protocols. Analyze field duplicate, laboratory duplicate, blank and spiked samples, as warranted.

## **DATA INTERPRETATION AND ANALYSIS**

1. Table all data including sample location identifier, sample date, sample depth, sampling methods, chemical analysis methods, laboratory detection limits and chemistry results.
2. Evaluate data quality.
3. Evaluate data quantity.
4. Evaluate whether results are reasonably representative of site conditions.

5. Evaluate data completeness (were samples proposed actually collected and analyzed).
6. Were holding times met?
7. Evaluate data consistency with respect to data comparisons (i.e., self-consistent) and expected results based on CSM.
8. Plot plan maps and cross sections of soil vapour (and other) data to improve data interpretation.
9. Conduct any additional analysis needed based on program objectives.

**APPENDIX II**  
**PROCEDURE FOR TESTING OF SOIL GAS**  
**EQUIPMENT FOR LEAKS**

## APPENDIX II

### PROCEDURE FOR TESTING OF SOIL GAS EQUIPMENT FOR LEAKS

API (2005) provides a method for testing sampling equipment for potential leaks using a tracer gas (e.g., diluted helium) of known concentration that is drawn through the sampling equipment at the approximate vacuum anticipated during sampling.

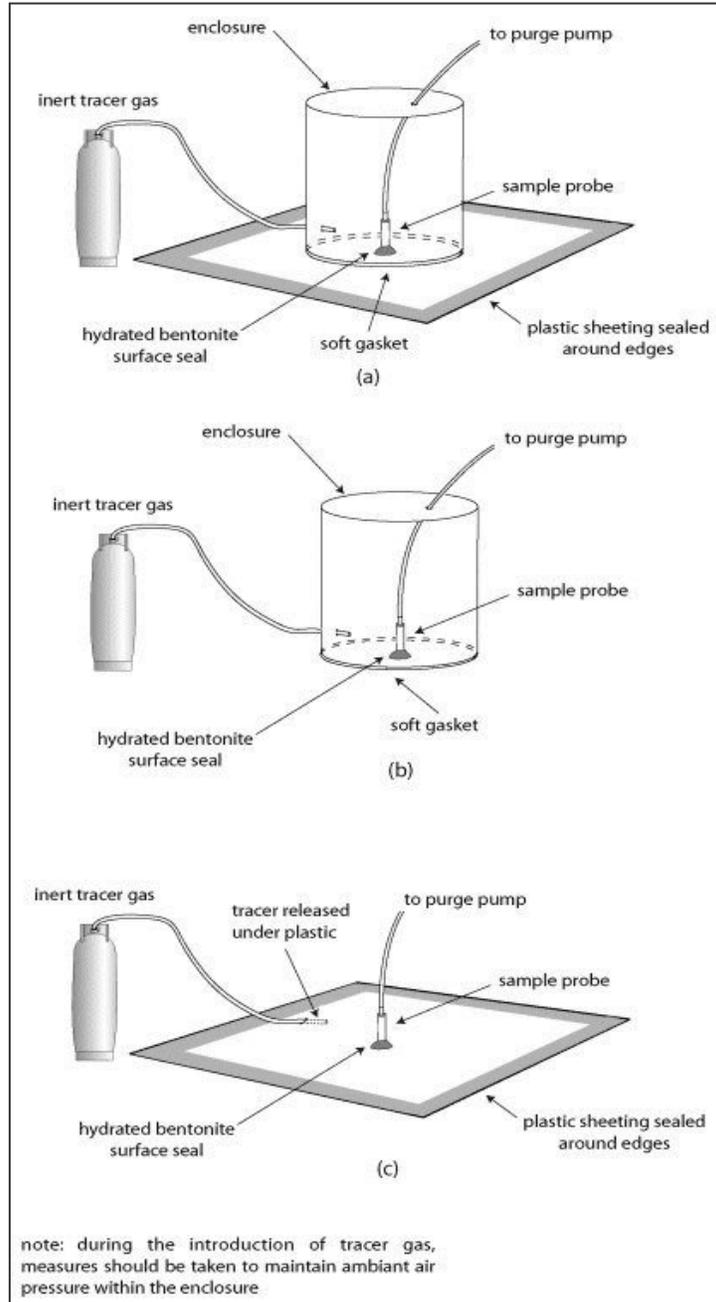
The gas removed under vacuum at the end of the sampling train is tested for the tracer gas. If the measured gas concentration is less than the input concentration, leakage has occurred. The test requires the following equipment:

- Large bag (i.e., 10 litre Tedlar<sup>TM</sup>) filled with known concentration of helium;
- Small bags (i.e., 1 litre Tedlar<sup>TM</sup>) to take samples;
- Helium cylinder, pressure and flow regulator;
- Vacuum gauge, and
- Tubing and fittings.

The probe surface seal integrity and possible short-circuiting of atmospheric air may be tested by introducing a tracer gas (e.g., butane, helium) around the probe at the contact with the ground surface and then analyzing the collected soil gas samples for the tracer gas (Hartman, 2002; CRWQCB, 2003). The leak test should be conducted using a tracer chemical not expected to be present in the soil gas being tested. If helium is used as a tracer, a temporary shroud should be constructed around the soil gas probe. The helium should be released below the shroud and measurements of the helium concentration should be made to measure the approximate concentration near the probe. It is recommended that high purity helium be used for this purpose. If the concentration of the tracer in the soil gas is less than about 0.1 to 1 % of the concentration at ground surface, then leakage is considered negligible.

Other tracers that can be used are butane, which is the primary component of lighter fluid, and some shaving cream products, which use butane as a propellant. Methods for applying a liquid tracer include wetting a paper towel with shaving cream or lighter fluid and wrapping the towel around the base of the probe. The laboratory analytical method selected for soil gas should include butane (or other tracer) as an analyte tested. Possible disadvantage of this test is that the gas-phase concentration of the tracer at the probe is unknown and therefore is not possible to make quantitative comparison of the tracer concentration at ground surface near the probe and in soil gas. In addition, shaving cream and lighter fluid may include trace levels of the compounds of concern, depending on contaminants present at the site.

If there are nested probes in a single borehole, the seal between the probes can be tested by measuring the pressure in the probe from which soil gas is being drawn and the adjacent probes. There should be little pressure influence on the adjacent probes if the seal is adequate.



**Figure III-1. Tracer Test Apparatus Guidance for Evaluating Vapour Intrusion in the State of New York**  
[http://www.health.state.ny.us/nysdoh/gas/svi\\_guidance/](http://www.health.state.ny.us/nysdoh/gas/svi_guidance/)  
 (permission to be obtained)

**APPENDIX III**  
**SELECTED LABORATORY ANALYTICAL METHODS**

## APPENDIX III –

## SELECTED LABORATORY ANALYTICAL METHODS

Method No.	Type of Compounds	Collection Device	Method	Stability	Detection Limit <sup>2</sup>	Reference
TO-13	VOC	Tenax® solid sorbent	GC/MS or GC/FID		0.02 - 200 ug/m <sup>3</sup> (0.01-100 ppbv)	USEPA 1999
TO-23	VOC	Molecular sieve sorbent	GC/MS		0.2 - 400 ug/m <sup>3</sup> (0.1-200 ppbv)	USEPA 1999
TO-3	VOC	Canister, Tedlar Bag (Cryotrap)	GC/FID		0.2 - 400 ug/m <sup>3</sup> (0.1-200 ppbv)	USEPA 1999
TO-9A, 10A	SVOC	Polyurethane foam (PUF)	GC/MS		1 - 20 ug/m <sup>5</sup> (0.4-2.5 ppbv)	USEPA 1999
TO-12	NMOC	Canister or on-line	FID		200 - 400,000 ug/m <sup>3</sup> (100-200,000 ppbvC)	USEPA 1999
TO-13A 3	PAH	Polyurethane foam (PUF)	GC/MS		0.5-500 ug/m <sup>3</sup> (0.6 - 600 ppbv)	USEPA 1999
TO-14A	VOC (nonpolar)	Specially-treated canister	GC/MS		0.4 - 20 ug/m <sup>3</sup> (0.2-2.5 ppbv)	USEPA 1999
TO-15	VOC (polar/nonpolar)	Specially-treated canister	GC/MS	30 days	0.4 - 20 ug/m <sup>3</sup> (0.2-2.5 ppbv)	USEPA 1999
TO-15A	VOC	Specially-treated canister	GC/MS/SIM	30 days	0.005 - 0.02 ug/m <sup>3</sup> (0.002-0.04 ppbv)	USEPA 2000b
TO-17 3	VOC	Single/multi-bed adsorbent	GC/MS, FID	30 days	0.4 - 20 ug/m <sup>3</sup> (0.2-2.5 ppbv)	USEPA 1999
Modified OSHA 7	VOC	sorbent, solvent extraction	GC/MS, FID	14 days	1 - 20 ug/m <sup>5</sup> (0.4-2.5 ppbv)	OSHA (2000)
Modified NIOSH 1550	Hydrocarbon fractions	sorbent, solvent extraction	GC/FID	30 days 4	100 - 400 ug/m <sup>5</sup>	NIOSH (1994)
Method 3C	N <sub>2</sub> , O <sub>2</sub> , CO <sub>2</sub> , and CH <sub>4</sub>	Canister	GC/TCD		20,000 - 150,000 ug/m <sup>3</sup> (10,000 ppbv)	USEPA 2002a
Method 16	H <sub>2</sub> S	Tedlar Bag, Canister, Glass vials	GC/FPD		100 - 700 ug/m <sup>3</sup> (50 ppbv)	USEPA 2002a

Method No.	Type of Compounds	Collection Device	Method	Stability	Detection Limit <sup>2</sup>	Reference
8015B/8051 D	TPH/VOC	Tedlar Bag, Canister, Glass vials	GC/FPD		300 - 3000 ug/m <sup>3</sup> (100 - 10,000 ppbv)	USEPA 1998
8021B	VOC	Tedlar Bag, Canister, Glass vials	GC/PID		4.0 - 60.0 ug/m <sup>3</sup> (0.3 ppbv to 30 ppbv)	USEPA 1998
8260B	VOC	Tedlar Bag, Canister, Glass vials	GC/MS		10.0 - 50.0 ug/m <sup>3</sup> (0.6 ppbv to 25 ppbv)	USEPA 1998
8270C	SVOC	Tedlar Bag, Canister, Glass vials	GC/MS		1,000 ug/m <sup>3</sup> (20,000 ppbv to 100,000 ppbv)	USEPA 1998
D1945-03	natural gases and mixtures	Tedlar Bag, Canister, Glass vials	GC/TCD		800 - 29,000 ug/m <sup>3</sup> (10,000 ppbv)	ASTM 2003
D1946-90(2000)	H <sub>2</sub> , O <sub>2</sub> , CO <sub>2</sub> , CO, CH <sub>4</sub> , C <sub>2</sub> H <sub>6</sub> , and C <sub>2</sub> H <sub>4</sub>	Tedlar Bag, Canister, Glass vials	GC/TCD		800 - 18,000 ug/m <sup>3</sup> (10,000 ppbv)	ASTM 1990

## Notes:

Adapted from API (2005).

<sup>1</sup>This is not an exhaustive list. Some methods may be more applicable in certain instances. Other proprietary or unpublished methods may also apply.

<sup>2</sup>Detection limits are compound specific and can depend upon the sample collection and the nature of the sample. Detection limits shown are for the range of compounds reported by the analytical methods.

<sup>3</sup>To achieve high sensitivity, the indicated methods utilize a trapping-type sampling method and relation of results to air-borne concentrations may not be possible.

<sup>4</sup>Taken from NIOSH 1500 "Hydrocarbons, BP 36°-216 °C" and NIOSH 1501 "Hydrocarbons, Aromatic".

<sup>5</sup>Based on a sample volume of 50L. Larger volumes can be collected to improve sensitivity.

GC/MS = Gas chromatography/mass spectrometry

GC/FID = Gas chromatography/flame ionization detector

GC/FPD = Gas chromatography/flame photometric detector

GC/TCD = Gas chromatography/thermal conductivity detector

VOC = Volatile organic compounds

PAH = Polycyclic aromatic hydrocarbons

NMOC = Non-methane organic compounds

SVOC = Semi-volatile organic compounds

Hydrocarbon Fractions include TVOC C6-10, TVOC C10-19, CCME CWS-PHC fractions for F1 and F2