

## TECHNICAL RATIONALE AND SAMPLING PROCEDURES FOR ASSESSING THE EFFECTS OF SUBSURFACE VOLATILE ORGANIC CONTAMINANTS ON INDOOR AIR QUALITY

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**ABSTRACT:** Human health risks associated with the inhalation of vapours from volatile organic chemicals (VOCs) in contaminated soils and groundwater are sometimes the most critical risks that must be addressed during the environmental risk management and remediation of contaminated sites. Potential indoor air quality impacts can be assessed by collecting air samples indoors and submitting them for chemical analyses. However, indoor air quality is often affected by VOC vapours released indoors by cigarette smoke, building materials, and common household solvents and cleaners, and thus may not be a reliable indicator of the impact due to subsurface contamination. Some Canadian and U.S. environmental regulatory bodies have accepted the following method of indirect assessment. The method is comprised of soil gas sampling near the basement or ground floor slab of a building and VOC vapour transport modelling to estimate soil gas flow rates and VOC flux into a building. The VOC flux concentration can then be used to evaluate the potential human exposure to soil or groundwater derived VOCs and estimate the associated human health risks.

O'Connor Associates has designed a shallow vapour sampler and sampling procedure specifically for collecting representative soil gas samples in the zone adjacent to a building basement or a ground floor slab. This paper presents the results of numerical modelling and the technical rationale for designing a soil gas sampling program for various soil types. The influence of such factors as soil type, depth to groundwater, and sampling well construction will be discussed as they relate to soil gas sampling programs and human health risk evaluations.

**RÉSUMÉ:** Les risques pour la santé humaine associés à l'inhalation de vapeurs de composés organiques volatils (COV) provenant des sols contaminés et des eaux souterraines sont parfois les risques les plus critiques qui doivent être adressés dans la gestion des risques et le traitement des sites contaminés. Les impacts potentiels sur la qualité de l'air intérieur peuvent être évalués en obtenant des échantillons d'air à l'intérieur et en les soumettant à des analyses chimiques. Cependant, la qualité de l'air intérieur est souvent affectée par des COV produits à l'intérieur par la fumée de cigarette ainsi que les solvants et autres produits de nettoyage ménagers, et n'offrirait pas ainsi une évaluation fiable. L'agence de protection de l'environnement américaine et quelques provinces canadiennes ont accepté la méthode d'évaluation indirecte suivante. L'échantillonnage de gaz de sol près du sous-sol ou de la dalle de sol d'un bâtiment, accompagné de modélisation de transport de vapeur de COV sont employés pour estimer les débits de gaz de sol et les taux d'infiltration de COV dans un bâtiment et peuvent être employés pour évaluer le potentiel d'exposition humaine aux COV dérivés des sols ou des eaux souterraines ainsi qu'aux risques à la santé humaine associés.

O'Connor Associates a conçu un échantillonneur peu profond de vapeur spécifiquement pour l'échantillonnage d'air de sol dans les zones près d'un sous-sol de bâtiment ou d'une dalle de sol. Cet article présente les résultats de la modélisation numérique et du raisonnement technique pour la conception d'un programme de prélèvement de gaz de sol pour différents types de sol et configurations de bâtiment. L'influence des facteurs tels que le type de sol, le contenu en carbone organique, la perméabilité relative et le profil d'humidité, la profondeur de la nappe phréatique, les propriétés du COV, les conditions météorologiques, la construction du puit d'échantillonnage, la conception des bâtiments ainsi que les services souterrains seront adressés puisqu'ils sont reliés aux programmes d'échantillonnage de gaz de sol et aux évaluations de risque pour la santé humaine.

### 1. INTRODUCTION

Human health risks associated with the indoor inhalation of vapours from volatile organic chemicals (VOCs) originating from contaminated soils and groundwater are one of the critical risks that must be addressed in the environmental risk management and remediation of sites contaminated by VOCs. Potential indoor air quality impacts can be assessed by collecting air samples indoors and submitting them for laboratory chemical analyses. Since indoor air quality is generally affected by VOCs generated indoors by cigarette smoke, building materials, and common household solvents and cleaners,

it is very difficult to distinguish these background VOCs from those VOCs that may have emitted from the subsoils. For example, some automotive products may emit benzene, ethylene, toluene and xylenes (BTEX); while some household cleaners can cause elevated levels of TEX, methylene chloride and methyl chloroform (Sweet et al, 1995).

As an alternative to direct indoor sampling, the US Environmental Protection Agency (USEPA 2002) and some Canadian authorities, e.g. Council of Canadian Ministers of the Environment (CCME, 2000) and Alberta Environment (AENV 2001a), have accepted the following

method of indirect assessment. VOC concentrations in soil gas samples taken near the basement or ground floor slab of a building together with vapour transport modelling are used to estimate soil gas flow rates and VOC flux into a building and can be used to evaluate the potential human exposure to soil or groundwater derived VOCs and associated human health risks through the inhalation pathway. Both soil gas sampling and transport modelling are required for a proper assessment. In this paper, the discussion is limited to the development of a shallow soil vapour sampler and the sampling procedure.

## 2. SOIL GAS SAMPLING – CURRENT PRACTICE

Soil gas samples are usually collected through monitoring wells or probes using either active or passive means. At present, Canadian authorities have not specified the configuration of the sampler, the location of the sampler, or the sampling methods. The US Environmental Protection Agency (EPA) has published a standard operating procedure (SOP) for soil gas sampling outlining the methods of installation and measurements (US EPA, 1996).

Typical soil gas sampling devices (or samplers) range from 50 mm (2 in) diameter PVC slotted pipes to 6 mm (1/4 in) or 13 mm (1/2 in) diameter hollow steel probes. The samplers are installed either in auger-drilled boreholes, or pushed or driven to the appropriate depth below the ground surface (bgs). When installed in auger-drilled boreholes, the sampler (well screen) is normally surrounded by a sand pack and sealed from the ground surface by hydrated bentonite or modelling clay. The sampler probe or well screen is connected to the surface using plastic or steel tubing and each soil gas sampler is completed as a monitoring well. The location and depth of installation are determined by the investigator.

Active sampling involves extracting soil gas through a sampler using a small vacuum pump or vacuum canisters at a pre-determined flow rate. When a vacuum pump is used, the sample is normally collected using sorbent tubes, charcoal tubes, or Tedlar bags. When a vacuum canister is used, soil gas is collected directly into the canister. Vacuum canisters are stainless steel cylinders with SUMMA™ polished or fused silica lined inner walls to minimize the adsorption of VOCs and are initially evacuated to a high vacuum. They are typically available in volumes of 0.45L, 1.6L or 6.0L. The sample collected can be analyzed either onsite or offsite using some form of gas chromatography (GC) analyses. For gasoline sites, the GC/MS (mass selective) detectors are the preferred instruments for risk assessments due to the high potential for the alkanes to interfere with benzene and other oxygenates (Hartman, 2002).

Passive sampling devices use a non-polar sorbent contained in a supporting material which is in turn put into a sampler tube and left for a period of time (typically 14 days or longer). Although passive samplers can be very sensitive, they are incapable of providing mass concentration values necessary for risk assessment.

## 3. FACTORS AFFECTING THE PERFORMANCE OF A SOIL VAPOUR SAMPLER

The quality of a soil gas sample collected can be affected by the following factors:

- the location of the sampler, both its location relative to the building and hydrocarbon source as well as the depth below ground surface,
- the size of the sampler,
- the rate of sampling, i.e. how fast is a sample extracted,
- soil type and moisture content,
- soil temperature, and,
- barometric pressure.

Each of these factors either controls or is affected by the advection or diffusion processes. Advection is the movement of soil gas under a pressure differential while diffusion is the transport of VOC vapours in the soil gas under a concentration gradient.

The location of the sampler below grade will control the likelihood of short-circuiting, i.e. the possibility of drawing in fresh air from the atmosphere. Similarly, short-circuiting will occur if the sampler is installed inside the gravel backfill that usually surrounds the foundation of a house. Subsequent to sampler installation or sampling, the equilibrating time, which is the time required for the vapour contained in the sampler to return to the same concentration as that in the surrounding soil gas, will depend on the size of the sampler. The volume of soil gas available to be sampled during a sampling event will also depend on the size of the sampler. Soil type, moisture content, and degree of saturation will also influence the amount of pore space for soil gas movement.

In order to understand better the effect of the factors outlined above, a parametric study was carried out and is described in the following section.

## 4. PARAMETRIC STUDY

A parametric study, as described below, was carried out to investigate the effects of various factors on the advection and diffusion processes during soil gas sampling.

### 4.1 Soil Parameters and Contaminant Characteristics

For the parametric study, following AENV (AENV 2001b), two distinct soil types are used: coarse-grained and fine-grained. Their respective properties are presented in Table 1.

Table 1. Typical Soil Parameters

Soil Properties	Coarse - Grained	Fine- Grained
Intrinsic permeability, $k$ [ $\text{cm}^2$ ]	1.00E-08	1.00E-09
Hydraulic conductivity $K_{\text{sat}}$ [ $\text{cm/s}$ ]	1.00E-03	1.00E-06

Total porosity, $\theta_T$ [-]	0.4	0.3
Air-filled porosity, $\theta_a$ [-]	0.281	0.132

For diffusion simulations, the diffusion coefficient in air,  $D_a$ , for petroleum hydrocarbon (PHC) fraction F1 or F2 is used and is equal to  $0.05 \text{ cm}^2/\text{s}$ .

#### 4.2 Equilibrating Time

The equilibrating time is the time required for the vapour concentration inside a sampler to return to that in the surrounding soil gas by diffusion after the sampler volume has been evacuated as a result of sampler installation or sampling. Crank (1975) provided two analytical solutions that can be used to approximate the equilibrating time, both assume the medium is isotropic and homogeneous and a symmetrical cylindrical geometry.

The first solution is a non-steady state solution for the concentration inside a cylinder with the concentration,  $C_o$ , at the cylinder wall kept constant. If the concentration inside the cylinder is initially zero, the concentration,  $C$ , at time  $t$  is given by:

$$\frac{C}{C_o} = 1 - \frac{2}{a} \sum_{n=1}^{\infty} \frac{\exp(-D_a \alpha_n^2 t) J_0(r \alpha_n)}{\alpha_n J_1(a \alpha_n)}, \quad [1]$$

where  $a$  is the radius of the cylinder,  $r$  is the radial distance from the centre,  $J_0$  and  $J_1$  are Bessel functions of orders 0 and 1, respectively, and  $\alpha_n$  is the roots of the following equation:

$$J_0(a \alpha_n) = 0. \quad [2]$$

Figure 1 shows the variation of concentration with time inside a cylinder 0.0762 m (6") in radius that is located in a fine-grained soil. A uniform vapour concentration within the cylinder is attained after about 1 day.

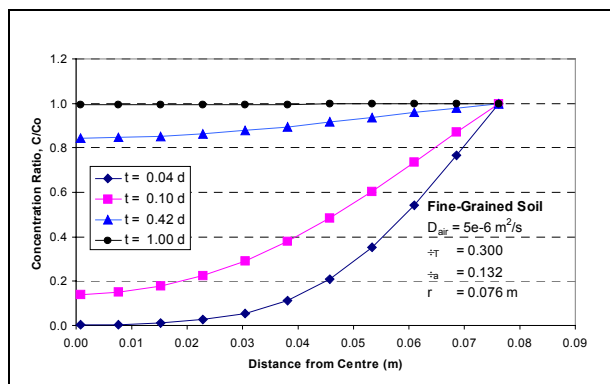


Figure 1. Variation of Concentration inside a Cylinder – Constant Concentration on Cylinder Wall

The equilibrating times in days for the two soil types for various radii are summarized in Table 2. When solving Equation 1, it is assumed that the sampler cylinder is also

filled with soils. Consequently, the results will be conservative since the air diffusion coefficient is reduced by the tortuosity factor.

Table 2. Equilibrating Times ( in days) – Constant Concentration at Cylinder Wall.

Radius (m)	0.0127	0.0508	0.0762
Coarse-grained	0.004	0.070	0.250
Fine-grained	0.021	0.417	1.000

The second solution is for diffusion into a cylinder from a well-mixed medium of limited volume. This solution allows for a possible reduction of source concentration at the cylinder wall as soil gas is diffusing into the cylinder. If the cylinder occupies the space  $r < a$  and if the cross-section of the medium the cylinder is located in is  $A$ , the final fractional uptake,  $\alpha$ , of VOC vapours by the cylinder is given by:

$$\frac{M_{\infty}}{AC_o} = \frac{1}{1+\alpha}, \quad [3]$$

where  $M_{\infty}$  is the final amount of vapours diffused into the cylinder at time  $t = \infty$ , and  $C_o$  is the initial vapour concentration in the surrounding medium. The concentration inside the cylinder at time  $t$ ,  $C_t$ , can be calculated using

$$\frac{C}{C_{\infty}} = 1 + \sum_{n=1}^{\infty} \frac{4(1+\alpha) \exp(-Dq_n^2 t/a^2) J_0(q_n r/a)}{(4+4\alpha+\alpha^2 q_n^2) J_0(q_n)}, \quad [4]$$

where all symbols are as previously defined in Equations [1] and [3] except for  $q_n$ 's, which are the positive, non-zero roots of

$$\alpha q_n J_0(q_n) + 2J_1(q_n) = 0. \quad [5]$$

Solutions of Equation [4] for various sampler radii are presented in Table 3 for  $\alpha = 0.9$ . Comparing Tables 2 and 3, it can be seen that similar equilibrating times are obtained using the two different approximations especially for the fine-grained soil.

Table 3. Equilibrating Times ( in days) – Diffusion from a Well-Mixed Source of Limited Volume.

Radius (m)	0.0127	0.0508	0.0762
Coarse-grained	0.004	0.050	0.200
Fine-grained	0.021	0.417	1.000

#### 4.3 Advective Process during Sampling

During active sampling, a volume of soil gas is extracted from inside the sampler at a pre-determined flow rate either using a vacuum pump or by an induced vacuum in a steel canister. Analytical solutions for air flow in the subsurface are used to simulate this advective process.

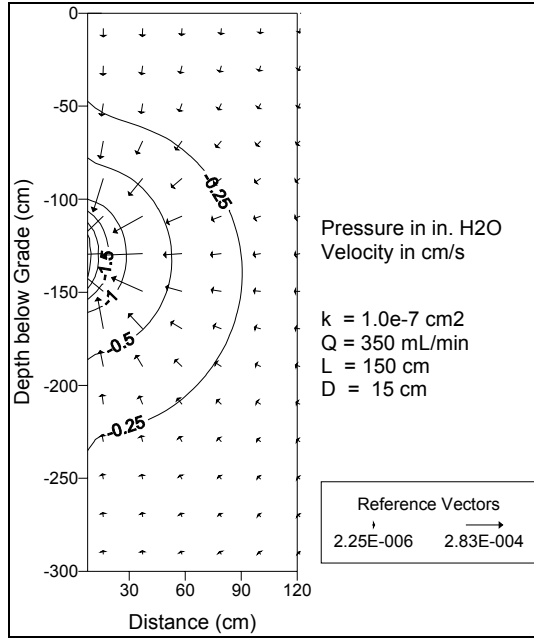


Figure 2. Typical Air Pressure Contours and Air Flow Velocity Vectors around a Soil Gas Sampler

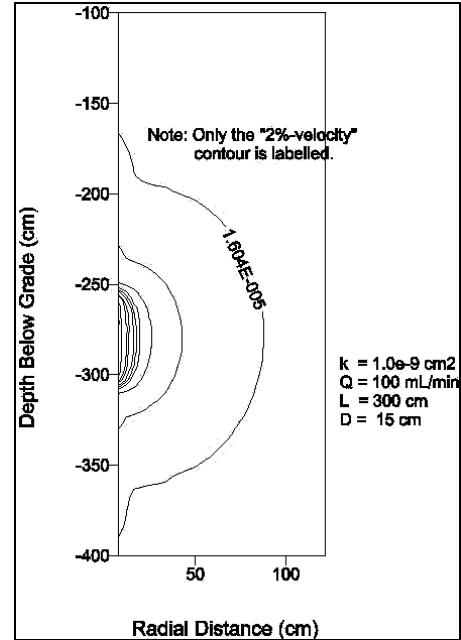


Figure 3. Velocity Contours Illustrating the Zone of Influence

Baehr and Hult (1991) provide analytical solutions for the steady state air pressure distribution resulting from axisymmetric air flow to a single well that is partially screened in an unsaturated soil layer extending an infinite lateral distance with or without a confining layer at the ground surface. These solutions were programmed into the in-house computer code, AIRSUMP, together with velocity calculations (Cho and DiGuilio, 1992). AIRSUMP is then used to perform a parametric study on the following four parameters:  $k$ , the intrinsic permeability of the soil;  $Q$ , the extraction flow rate;  $L$ , depth to the top of the screened sampling chamber; and,  $D$ , the diameter of the sampling chamber. Values of these parameters are shown in Table 4.

Table 4. Values of Parameters Used in the Parametric Study

Intrinsic Permeability, $k$ [ $\text{cm}^2$ ]			
1.0E-07	1.0E-09	1.0E-10	1.0E-11
Sample Extraction Rate, $Q$ [mL/min]			
360	100	50	20
Depth to Sampling Chamber, $L$ [m]			
1.0	1.5	3.0	4.5
Diameter of Sampling Chamber, $D$ [m]			
0.025	0.010	0.015	0.020

For the parametric study, the soil temperature is constant at 10 °C, the height of the sampling chamber (or the screened interval) is 0.40 m, and the ground surface is open to the atmosphere. For simplicity, boundary effects due to proximity to foundation walls and heated building temperatures are not included in this study.

#### 4.3.1 Results of Parametric Study

In total 256 trial runs were carried out for all the possible combinations of each of the four variables presented in Table 4. Figure 2 shows a typical vacuum pressure distribution and air flow velocity vectors in the subsurface surrounding a soil gas sampler in a coarse-grained soil.

In general, lower permeability and higher extraction rate will induce higher vacuum in the subsurface. The highest and lowest vacuum calculated are 217" H<sub>2</sub>O (in. of water) and 0.001" H<sub>2</sub>O, respectively. However, for the combination of the lowest permeability (1e-11 cm<sup>2</sup>/s) and the highest flow rate (360 mL/min), no valid solution can be obtained. This indicates that low permeability clays or water-saturated soils will not yield significant volume of soil gas when sampled at flow rates higher than 360 mL/min.

The maximum vertical air flow velocity at grade directly above the sampler is controlled by the depth to the well screen and the extraction rate; and is not affected by the permeability or the size of the sampling chamber. The maximum in-flow velocity from the atmosphere ranges between 1.5e-5 and 7.0e-7 cm/s.

In order to establish a common basis to compare the zone of vacuum and air flow influence around a sampling chamber for the various cases, the concept of radius of influence (ROI) is introduced. As shown in Figure 3, the locus of a velocity contour is approximately circular. The zone of influence can be defined as the sphere bounded by the contour of 2% of the maximum air flow velocity at

the sampler (hitherto referred to as the “2%-velocity”). Consequently, from a 2%-velocity plot, as shown in Figure 3, one can estimate the ROI using the radius of the semi-circle bounded by the 2%-velocity. If the enclosed area is more elliptical than circular, the ROI is calculated as the geometric mean of the vertical and horizontal radii. Kinks in the contours around the centre line can be attributed to the coarse grid spacing used to calculate velocities in this region.

As shown in Figure 4, the zone of influence may intersect the ground surface. This indicates that atmospheric air may be drawn into the well screen potentially causing dilution of soil gas collected in the sampling chamber. In fact, the possibility of short-circuiting exists when the sampler diameter is larger than 0.025 m and the depth to screened length is less than 1.5 m. For these cases, the ROI's cannot be estimated.

Results of the parametric study indicate that the ROI increases with sampler diameter and is relatively unaffected by permeability or extraction rate.

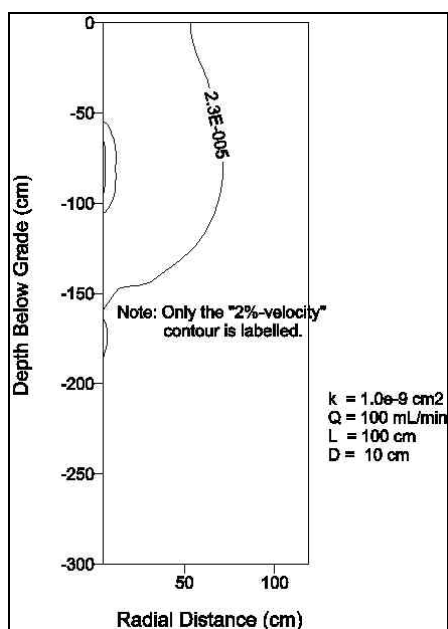


Figure 4. 2%-Velocity Contour Illustrating Possibility of Short-Circuiting from the Ground Surface

## 5. SOIL GAS SAMPLING METHODS

Although Tedlar bags (US EPA 1996) and charcoal tubes can be used to collect soil gas samples, the quality of samples collected and the associated analysis methods cannot provide the parts per billion by volume (ppbv) level of precision typically required for human health risk assessment. Instead, sorbent tubes or specially coated stainless steel canisters are preferred.

Soil gas samples can be collected using sorbent tubes, e.g. CarboTrap™ tubes, and a sampling pump calibrated

to a known flow rate. The sample collected is then analyzed in the laboratory using thermal desorption and GC/MS analysis. A detailed description of this method is provided in Compendium Method TO-17 (USEPA, 1999a). Ideally, sorbent tubes are capable of providing method detection limits (MDL's) at the ppbv level. However, tests on 18 CarboTrap tubes using an Escort Elf pump calibrated to 100 mL/min recorded flow rates ranging from 71.9 to 122.6 mL/min and the mean flow rate was  $94.5 \pm 10.1$  mL/min. The flow rates were measured in-line using a DryCal® DC-Lite flow meter. With this range of variability in flow rates, it is recommended that continuous in-line flow measurement is a must at sensitive sites where high precision results are required.

Sampling and laboratory chemical analysis procedures using vacuum canisters are described in USEPA Compendium Method TO-14A (1999b). In brief, the stainless steel canister is prepared and evacuated to a high vacuum in the laboratory. To collect a soil gas sample, the canister is connected to a sampling port provided on the sampling well through a flow controller. Sampling is started by opening a valve on the canister and continues until the vacuum inside the canister is depleted. The canister is sealed by closing the in-line valve and then returned to the laboratory for GC/MS analysis. The field procedure is straightforward and allows the same volume of soil gas to be collected each time. However, high moisture content or carbon dioxide concentration in the soil gas will increase the method detection limit (MDL).

It is the authors' opinion that stainless steel canisters are the preferred method of sample collection due to the simplicity of the procedure and the fact that the sample volume can be maintained constant.

## 6. DESIGN OF A NEW SOIL GAS SAMPLER AND SAMPLING PROTOCOL

Based on previous discussions, a well-designed soil gas sampler should enable a representative sample of the soil gas to be collected at the sampling location while minimizing the possibility of short-circuiting from the atmosphere.

One recommended shallow soil gas sampler design is made up of the following three components:

1. a sampling chamber made from a 75 mm (3") or 100 mm (4") diameter slotted Schedule 40 pipe. The total length of the chamber is 400 mm (16") with a 300 mm (12") centrally located slotted section (No. 10 slots).
2. a connector section made from a 20 mm (¾") diameter unslotted Schedule 80 pipe, and,
3. a 50 mm (2") cleanout fitted with a threaded top cap equipped with a valved sampling nipple.

The soil gas sampler may be constructed using commonly available PVC plastic or stainless steel,

depending upon the application. The connector pipe is threaded to the sampling chamber, but the cleanout can be either threaded or friction-fitted to the connector pipe. The sampler should be installed inside a 150 mm (6") diameter auger-drilled borehole constituting a soil gas monitoring well (SGMW). The volume of the sampling chamber is 1.8L to 3.2 L. If the pore volume in the sand backfill is included, the total volume of air available for sampling is about 3.8 L to 5.0 L. The volume inside the

connector pipe is approximately 0.28 L/m. If 1.7L vacuum canisters are used for sample collection, there is ample volume available inside the sampler such that it is unlikely any soil gas will have to be drawn in from the surrounding soils. In this manner, the possibility of short-circuiting is reduced.

As discussed in Section 4.2, vapour concentration inside the sampling chamber will equilibrate with that in the surrounding soil gas in about 1 day. However, vapour concentration inside the connector pipe may take much longer, i.e. perhaps up to 4 months to attain the same concentration in the full 1.5m length of pipe via diffusion. This duration is estimated using the solution presented in Crank (1975) for diffusion from a semi-infinite sheet.

The placement of the SGMW relative to the building to be monitored is also important. It should be located in undisturbed native soil outside the mixing zone near the building foundation; i.e. it should typically be at least 1.5 m away from the building foundation wall and should be outside the backfill that surrounds a building foundation. The top of the sampling chamber should normally be at least 1.5 m below grade. A typical SGMW installation is shown in Figure 6.

### 6.1 Recommended Soil Gas Sampling Protocol

When sampling from a shallow SGMW, the recommended protocol is as follows.

Immediately after installing the SGMW, about 12 L to 16 L of air should be purged from the well. The top valve should then be closed. There should be at least 10 days (in silts or clays) or 5 days (in sands or gravels) before any air sampling is conducted. After the initial purging,

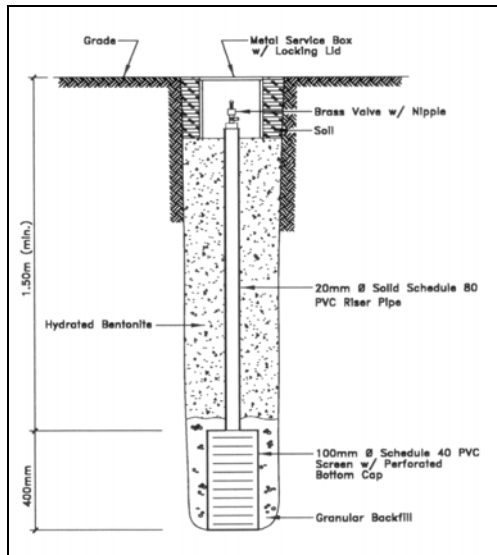


Figure 5. Typical Soil Gas Monitoring Well (SGMW) Construction

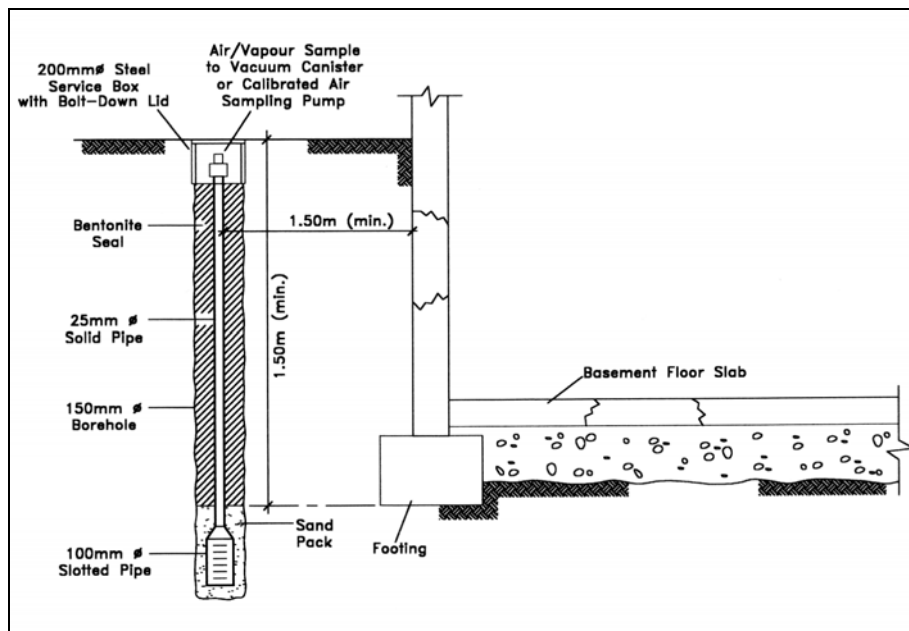


Figure 6. Typical Soil Gas Sampling Setup

the top valve of the sampler should only be opened when the well is being sampled or alternatively the purging procedure must be repeated.

A shallow SGMW is sampled using a 1.7 L (or smaller) specially prepared stainless steel (SUMMA™ polished or fused silica lined) canister. Together with the canister, a flow controller set at 300 mL/min. and a vacuum gauge should be requisitioned from the laboratory. When the canister arrives, the vacuum of the canister should be checked to ascertain that it is at an acceptable level indicating that no leakage has occurred during transit. When assessing the vacuum level, one should bear in mind the atmospheric pressure variation due to the difference in altitude between local and laboratory locations.

At the SGMW, before taking a soil gas sample using a canister, a volume of air approximately equal to that inside the connector pipe is removed using either a squeeze bulb or a sampling pump. For each metre length of connector pipe, approximately 0.25 L of soil gas should be removed. This reduces the possibility of dilution by the air residing in the dead space inside the connector tube as discussed at the beginning of this section. The canister is then connected to the well through the flow controller and sampling is started by opening the top valve at the well. After 8 to 10 minutes, both the top valve and the valve on the canister are closed and the vacuum in the canister is checked. Sampling should continue until the vacuum in the canister is totally depleted. After sampling, the top valve of the sampling well should remain closed until the next sampling event.

In addition, atmospheric pressure and, if possible, indoor pressure should be recorded during a sampling event.

## 6.2 Comparison of Chemical Analysis Results

Comparative analytical results for soil gas and indoor air samples collected from SGMW's, indoors, and directly beneath basement floor slabs are summarized in Table 5 for 7 locations in fine-grained soils at sites within southern

Alberta. All of the samples for which analytical results are presented in Table 5 were collected using 1.7L SUMMA™ vacuum canisters and were analyzed by GC/MS for BTEX and total hydrocarbons (hexane equivalent TPH).

The sub-slab soil gas samples were collected after a 100 mm (4") diameter hole was cored through the concrete basement floor slab to access the underlying gravel layer that was laid down prior to pouring the concrete floor slab. Immediately after removing the concrete core, a sampling valve was sealed in the core hole to facilitate the collection of soil gas samples. Prior to sample collection, 20 L of soil gas were purged to remove any basement air that might have entered beneath the floor slab during coring and valve installation.

As the data in Table 5 indicate BTEX and TPH in the soil gas samples collected from SGMW's are significantly higher than those collected from the sub-slab. It is noted that the BTEX and TPH concentrations for the sub-slab samples are in the same order of magnitude as the indoor samples. This similarity can be attributed to the fact that the sub-slab samples were collected from within the mixing zone and the concrete foundation walls and floors were cracked. Clearly, the soil gas samples collected from properly designed SGMW's provide more conservative results than sub-slab samples for human health risk assessment. Due to space limitations, the implications of these results on vapour intrusion modelling can only be discussed in a separate paper.

## 7. CONCLUSION

A new configuration of soil gas monitoring well has been developed. By providing sufficient volume of soil gas for sample extraction using canisters, the chance of short-circuiting to atmospheric air is minimized.

During the design process, the effects of soil permeability, depth to sampling screen interval, and sample extraction were considered when designing this sample well. However, the effect of soil moisture has only

Table 5. Comparative Hydrocarbon Vapour Analysis Results for Soil Gas Monitoring Wells, Indoor Air and Sub-Slab Vapours

Location	Total BTEX (ppbv)			TPH (ppbv)		
	SGMW	Indoor	Sub-Slab	SGMW	Indoor	Sub-Slab
A	980	4	54	440 000	10	790
B	3 089	5	96	19 000	142	988
C	2 400	4	12	2 900 000	176	754
D	970	4	22	1 300 000	19	368
E	970	4	11	1 300 000	89	82
F	38	7	11	780	192	296
G	38	8	9	780	158	162

been simulated indirectly - higher degree of water saturation will lower the soil permeability. In addition, the effect of barometric pressure variations and soil temperature variations should be investigated.

In order to provide valid soil gas concentration data for assessment of indoor vapour inhalation pathway and human health risk assessment, a soil gas monitoring well should be located at an elevation below that of the building foundation and away from the backfill material surrounding the building foundation. However, the proximity of a foundation wall to a SGMW will induce boundary effects which have yet to be studied in detail.

At present, the performance of this SGMW design is being continuously evaluated. Analytical results to date confirm that soil gas samples from SGMW's provide more conservative than sub-slab samples and are, therefore, more protective of human health. Well design and sampling protocol will be revised if additional data indicate the necessity.

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