REPORT

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BC MOE TECHNICAL GUIDANCE VAPOUR INTRUSION COMPUTER MODEL

USER’S GUIDE AND SUPPORTING INFORMATION

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1.0 INTRODUCTION

Golder Associates Ltd. (Golder) was retained by the British Columbia Science Advisory Board for Contaminated Sites (SABCS) to develop a soil vapour intrusion computer model that would support the development of soil vapour guidance in British Columbia. The primary purpose of the soil vapour model is to enable the backcalculation of chemical-specific soil, groundwater and soil vapour criteria starting from the BC Contaminated Site Regulation (CSR) Schedule 11 Vapour Standards[1] and using the assumptions for soil vapour transport embodied in BC Environment Technical Guidance (TG) 4 – Soil Vapour Investigation and Remediation (July 2009). The TG4 assumptions for vapour intrusion and attenuation factors are identical to those incorporated by Health Canada in their Preliminary Quantitative Risk Assessment (PQRA) spreadsheet model (coarse-grained soil).

The scope of work, developed based on input from SABCS and BC Environment, consisted of programming of the Johnson and Ettinger (1991) model equations for vapour intrusion into buildings and backcalculation of criteria using an EXCEL^{TM} spreadsheet developed for this purpose. A comprehensive chemical database was also compiled, consisting of the Schedule 11 Vapour Standards, physical-chemical parameters, odour thresholds, explosivity limits and analytical detection limits. The EXCEL^{TM} spreadsheet is currently intended as an internal working tool to assist SABCS and BC Environment in the vapour intrusion guidance development process, although with modifications the spreadsheet tool could be developed for broader use.

The computer model backcalculates criteria incorporating the TG4 attenuation factor approach, which assumes a single soil type (coarse-grained soil), varying distance between the building and vapour contamination source, and two different building types (residential and commercial/industrial). The transport assumptions for coarse-grained soil consistent with the TG4 guidance are programmed in the model. Currently, the model does not allow site-specific soil property data to be entered in the model. Modification of the model to enable full site specific calculation of the J&E attenuation factor could be considered as part of future refinements to the model.

The computer model utilizes the TG4 attenuation factors, based on the Health Canada approach, for distances between the building and sampling point that are greater than or equal to 1 m. For smaller distances, empirical attenuation factors are incorporated in the model for subslab soil vapour samples. There is on-going scientific evaluation that continues respecting attenuation factors including, for example, the representativeness of subslab soil vapour and attenuation factors for site screening. An evaluation of the basis for attenuation factors and empirical comparisons goes beyond the scope of this report.

The TG4 attenuation factors and this report also do not include an approach for screening of sites or adjustment of vapour attenuation factors to account for biodegradation of petroleum hydrocarbon vapours. There is recent research by the State of Utah (Robin Davis), which supports a pathway exclusion approach for vapour intrusion for petroleum hydrocarbon sites with certain characteristics. The USEPA is also currently developing vapour intrusion guidance for petroleum hydrocarbon sites that is assessing empirical data and models for biodegradation, which may incorporate exclusion or adjustment factors. In 2008, Golder Associates completed a research project for Health Canada and Canadian Petroleum Products Institute (CPPI) recommending a matrix of adjustment factors for biodegradation, and recommending further evaluation of an exclusion factor approach. Further research and guidance development of approaches that account for biodegradation is recommended, and it is recommended that the TG4 guidance be updated, as warranted, to reflect these new advances.

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[1] The Vapour Standards apply to the receptor zone and thus indoor and outdoor air

The report is structured as follows:

- Section 2 describes the Johnson and Ettinger model;
- Section 3 describes the partitioning model;
- Section 4 describes the rationale for the default input parameters chosen for the Johnson and Ettinger model to generate the TG4 vapour attenuation curves;
- Section 5 describes the computer spreadsheet model structure; and,
- Appendix I describes the compilation and sources of the physico-chemical data.

2.0 SOIL VAPOUR INTRUSION MODEL

The Johnson and Ettinger (J&E) model was chosen to calculate the attenuation factors since it is commonly used, is a relatively simple and easy to understand model, and incorporates the key processes for vapour intrusion into buildings (excluding biodegradation which can be important for petroleum hydrocarbon compounds). When used on a site-specific basis, the J&E model is considered to be reasonably accurate and generally compares with properly analyzed field data within one order-of-magnitude, for chemicals not subject to significant biodegradation or transformation processes (Johnson et. al., 2002, Hers et al., 2003). Given the inherent variability associated with empirical measurements and modeling of vapour intrusion, it is not feasible to expect a model to provide a better match with empirical data.

2.1 Overview of the Johnson and Ettinger Model

The Johnson and Ettinger (J&E) (1991) model is a one-dimensional analytical solution that accounts for diffusive and advective transport of vapours. The J&E model estimates the “vapour attenuation factor”, which is the ratio of the vapour concentration in the indoor space to the vapour concentration at the contamination source.

Soil vapour from the contamination source is assumed to diffuse directly upward (one-dimensional transport) through homogeneous soil layers with isotropic properties to the base of a building foundation, where soil gas advection and diffusion carry the vapour through cracks in the foundation into the building. Both diffusive and advective transport processes are assumed to be at steady state; therefore, absorption and dissolution processes no longer contribute to the retardation of vapour migration. Biodegradation is not considered in the base version of the J&E model, although Johnson et al. (1998) present algorithms for vapour intrusion that account for first-order biodegradation. Within the indoor space, vapours are assumed to be instantaneous and uniformly mixed (*i.e.,* box model).

Contaminants are assumed to be homogeneously distributed at their source. The base version of the J&E model assumes an infinite contamination source, which results in source concentrations that remain constant over time. Variations of the J&E model are available that include adjustments for a depleting soil contamination source.

2.2 J&E Model Variability

Model variability for the purposes of this discussion is defined as the aggregate range in model predictions that result from model sensitivity and uncertainty in input parameters. Model sensitivity is the relative variation in output caused by varying an input parameter. Of greatest significance are parameters that are uncertain (*i.e.,* vary over a large range) and to which the model is sensitive to. When site specific data are used properly and constrained to reasonable ranges, the overall variation in attenuation factors predicted by the J&E model is about one order-of-magnitude (for non-degrading chemicals), which is considered reasonable for a screening level model (Hers et al., 2003).

A qualitative ranking of the model variability (uncertainty combined with sensitivity) for J&E model inputs is provided in Table 1. Model parameters with moderate to high variability include:

- Water-filled porosity and capillary transition height for contaminated groundwater vapour sources;
- Soil gas advection rate (Q_{soil}) and soil-air permeability for shallow contamination and a depressurized building;
- Building crack ratio and crack moisture content for a shallow contamination scenario for a building that is not depressurized; and,
- Building air change rate and building mixing height for all scenarios.

Building-related parameters with low uncertainty and sensitivity include the foundation area, depth to the base of the foundation, and the foundation slab thickness.

As described in Johnson (2005), the potential pitfalls in selecting unrealistic parameter ranges as part of a sensitivity analysis can be avoided through the use of parameters such as the moisture saturation (S_m), which is the water-filled porosity divided by the total porosity ($S_m = \theta_w/\theta_T$), or the ratio of Q_{soil} to the building ventilation rate (Q_{soil}/Q_{build}). Both these parameters typically vary over a defined range depending on soil properties and building conditions (see Johnson (2005) for ranges).

2.3 Precluding Conditions for TG4 Application of J&E Model

There are several precluding conditions where the TG4 attenuation factor approach and use of the J&E model would not be considered applicable, as described below.

Distance between Building and Vapour Contamination Source: The TG4 attenuation factor curves apply when the distance between the vapour contamination source (as well as the media measurement point) and the building is equal to or greater than 1 metre. When there is an existing building with a concrete slab, a subslab vapour to indoor air attenuation factor of 0.02 applies when the distance to contamination is greater than 1 m. When the distance to contamination is less than 1 m, a subslab vapour to indoor air attenuation factor of 0.1 applies. In both cases, the above attenuation factors apply to soil vapour samples obtained below the foundation slab. A higher attenuation factor (*i.e.,* less dilution) is assumed for shallow contamination scenarios given the variability in near-building conditions (*e.g.,* fill layers and utilities), variability in contaminant concentrations and the potential for contact between the contamination and building due to seasonal water table fluctuations and the varying thickness of the tension-saturated zone (capillary fringe).

Earthen or Wooden Foundation Basements: Buildings with earthen or wooden foundation basements should not be assessed using the TG4 attenuation factors unless the distance between the building and the contamination source is sufficiently deep such that transport processes within the soil zone control the soil vapour flux into the building, as opposed to the building foundation characteristics. The depth where the foundation properties are of lesser importance will depend on site-specific conditions. A reasonable value for this depth considering a range of building sizes is 5 m, when other precluding conditions are taken into consideration.

Very High Gas Permeability Media: Buildings constructed on vertically or near-vertically fractured bedrock, karst, cobbles or other media with unusually high gas permeability should not be assessed using the TG4 attenuation factors regardless of the depth to contamination. Soil gas advection within the unsaturated zone (*i.e.*, beyond the soil zone near to the building), caused by barometric pumping or other environmental factors, can be important in these scenarios and is not part of the conceptual site model described by the J&E model.

***Gas Under Pressure*:** Sites where soil gas is under pressure should not be assessed using the TG4 attenuation factors because the J&E model does not account for the movement of gas under pressure, which is often the case at landfills or fill sites with woodwaste or organics where methane is produced and where trace VOCs may move with the landfill gas.

Subsurface Utility Conduit Connecting Contamination Source and Building: Utility conduits that directly connect the contamination source to the enclosed space of the building represent a precluding condition. Common anthropogenic features such as floor drains, sewer lines and utility conduits that are present at most sites are not normally considered a precluding condition.

The TG4 guidance indicates an unlined crawlspace is a precluding condition for application of the attenuation factors (what constitutes an unlined crawlspace is not defined). A crawlspace floor may range from concrete slab, concrete skim coat, plastic water vapour barrier (which may have little effect in limiting intrusion of VOCs) or dirt. Soil vapour intrusion into buildings will depend on pressure coupling between the building, crawlspace and soil, the crawlspace ventilation, and nature and condition of the crawlspace floor. While a crawlspace is inconsistent with the J&E conceptual model, there may be sufficient similarities between vapour intrusion for basement and crawlspace buildings to enable application of TG4 to all crawlspace buildings; however, further research and modeling is required to evaluate vapour intrusion for buildings with crawlspaces.

The presence or suspected presence of non-aqueous phase liquid (NAPL) is not considered to be a precluding factor for TG4 attenuation factors provided that soil vapour samples are obtained from above the NAPL zone. The presence of NAPL could be a precluding factor when only groundwater data are available and/or when there is significant uncertainty in the NAPL source and distribution. Section 3.1 provides guidance on how to theoretically calculate effective solubility or soil saturation (C_{sat}, see definition below). For LNAPL, there are practical indicators that may be also used to assess whether LNAPL is present including visual/olfactory indicators, headspace vapour tests, dye tests, diagnostic ratios of aliphatic to aromatic ratios in soil gas above contamination sources and profiles obtained using membrane interface probe (MIP) or laser-induced fluorescence (LIF) technologies.

The TG4 precludes the use of soil chemistry data for chemicals with a specific gravity greater than one (only soil vapour and/or groundwater may be used). The rationale for this precluding condition is that the distribution of DNAPL is highly variable within the unsaturated soil zone and soil sampling will often miss soil contamination zones. Soil physical property is useful for developing the conceptual model.

3.0 PARTITIONING MODEL

The partitioning relationships for estimation of soil vapour concentrations from groundwater or soil data are provided in Exhibits 1 and 2. The partitioning equations for estimation of soil vapour concentrations are based on a *three-phase* partitioning model, when NAPL is not present, and a *two-phase* model for partitioning between NAPL and vapour, when NAPL is present.

A *three-phase* model describes partitioning between the sorbed, soil-water and soil-air phases. The equilibrium partitioning of a chemical in the soil-air phase is related to the aqueous phase by Henry's Law, which states that the water-air partitioning is described by a linear relationship. Henry's Law is applicable for most organic contaminants that are sparingly soluble (the mole fraction of that contaminant in water is less than 0.001). For partitioning between the sorbed and aqueous phases, a linear absorption model based on the soil organic matter content is typically used to predict the sorbed concentration under equilibrium conditions. The *three-phase* model should be used when NAPL is not present.

For a pure chemical, NAPL will not be present at concentrations below the soil saturation limit (USEPA, 1996; ASTM E1739, ASTM PS103-98). When NAPL is present, the vapour concentration is proportional to the vapour pressure of the compound. When multi-component mixtures are present, partitioning based on Raoult's Law is typically used to quantify the effective solubility of an individual chemical in the mixture under equilibrium conditions, and is also used to predict the vapour concentration when NAPL is present. When the contamination consists of a mixture of chemicals and there is site specific data, the mole fraction of the chemical within the mixture may be entered into the model.

The three-phase model predicts that the vapour concentration directly above the source of soil contamination cannot be greater than that associated with the soil saturation concentration; for groundwater contamination, the vapour concentration cannot be greater than that associated with the effective solubility. When a soil concentration is greater than the soil saturation concentration, C_{sat} (see Exhibit 1 for definition), and groundwater concentration is greater than the effective solubility, the NAPL to vapour partitioning relationship is used, and vapour concentrations are constant regardless of concentration. If the vapour concentration predicted based on the NAPL to vapour relationship does not exceed the health-based limit in indoor air, the vapour intrusion pathway will not be of concern for that particular chemical. There may, however, be other potential exposure pathways of concern when NAPL is present at a site.

EXHIBIT 1
PARTITIONING EQUATIONS

1. Groundwater Contamination Source

If $C_{w,i} < X_i * S_i$ then $C_{v,i} = UCF_2 * C_{w,i} * H'$

If $C_{w,i} >= X_i * S_i$ then $C_{v,i} = \max [UCF_2 * X_i * S_i * H', \; UCF_1 * X_i * MW_i * P_i / RT]$

2. Soil Contamination Source

If $C_{soil,i} < C_{sat,soil,i}$ then $C_{v,i} = UCF_2 * C_{soil,i} * H' * \rho_b / (\theta_w + K_{oc} * f_{oc} * \rho_b + H' * \theta_a)$

If $C_{soil,i} >= C_{sat,soil,i}$ then $C_{v,i} = \max [UCF_2 * C_{soil,i} * H' * \rho_b / (\theta_w + K_{oc} * f_{oc} * \rho_b + H' * \theta_a), \; UCF_1 * MW_i * X_i * P_i / RT]$

$C_{sat,soil,i} = UCF_2 * C_{soil,i} * H' * \rho_b / (\theta_w + K_{oc} * f_{oc} * \rho_b + H' * \theta_a)$

Parameter	Default
$C_{w,i}$ = Soil-water concentration (mg/L)	Measured site specific
X_i = Mole fraction (unitless)	Estimated from chemical data
S_i = Pure-chemical solubility (mg/L)	Chemical specific
$C_{v,i}$ = Soil vapour concentration (mg/m^3)	Calculated
H' = Dimensionless Henry's Law Constant	Chemical specific
UCF_1 = Unit conversion factor	1,000 mg/g
UCF_2 = Unit conversion factor	1,000 L/m^3
MW_i = Molecular weight (g/mole)	Chemical specific
P = Pure chemical vapour pressure (atm)	Chemical specific
R = Gas constant (m^3-atm/K-mole)	8.21E-05
T = Absolute temperature (K, 273^{o}C + T(^{o}C))	Estimated, site specific
$C_{soil,i}$ = Total soil concentration (mg/kg)	Measured site specific
$C_{sat,soil,i}$ = Soil saturation concentration (mg/kg)	Calculated
ρ_b = Dry bulk density (kg/L)	1.6
θ = Total porosity (dimensionless)	0.375 (coarse-grained soil) 0.399 (fine-grained soil)
θ_w = Water-filled porosity (dimensionless)	0.054 (coarse-grained soil) 0.148 (fine-grained soil)
K_{oc} = Organic carbon-water partitioning coefficient (mg/kg-OC per mg/L-water)	Chemical specific
f_{oc} = Fraction organic carbon (dimensionless)	0.006 (recommend measure)
θ_a = Air-filled porosity (dimensionless)	$\theta - \theta_w$

Note: For chemicals that are solids at room temperature the subcooled liquid solubility should be used in place of the solid solubility. Calculations for temperature corrected vapour pressure and Henry's constant are shown in Exhibit 2. Soil partitioning equations should not be used for chemicals with specific gravity greater than one (*i.e.,* DNAPLs).

EXHIBIT 2.

TEMPERATURE CORRECTED VAPOUR PRESSURE AND HENRY’S CONSTANT

1. Temperature Corrected Vapour Pressure

$$P' = P \exp(\Delta H_1/R_1 * (1/T_r - 1/T_s))$$

2. Temperature Corrected Henry’s Law

$$H'' = \exp(-\Delta Hts/R_2 * (1/T_s - 1/T_r)) * H/(T_s * R_3)$$

$$\Delta H_{ts} = \Delta H_2 \, [(1 - T_s/T_c)/\,(1 - T_b/T_c)]^{\eta}$$

if $T_b/T_c < 0.57$ then $\eta = 0.3$

if $T_b/T_c = 0.57$ to 0.71 then $\eta = 0.74\,(T_b/T_c) - 0.116$

if $T_b/T_c > 0.71$ then $\eta = 0.41$

Parameter	Default
P = Pure chemical vapour pressure (atm)	Chemical specific
P’= Temperature corrected pure chemical vapour pressure (atm)	Chemical specific
ΔH_1 = Enthalpy of vapourization at normal boiling point (j/mol)	Chemical specific
ΔH_2 = enthalpy of vapourization at normal boiling point (cal/mol)	Chemical specific
ΔHt_1s = Enthalpy of vapourization at average soil temp (cal/mol)	Chemical specific
H = Henry’s Law Constant (atm-m^3/mol)	Chemical specific
H” = Temperature corrected dimensionless Henry’s Law Constant	Chemical specific
R_1 = Gas constant (j/mol-°K)	8.3145
R_2 = Gas constant (cal/°k-mol)	1.9872
R_3 = gas constant (m^3-atm/k-mol)	8.21×10^{-5}
T_r = Reference temperature (°K)	Specific to the temperature used for the derivation of the Henry’s Constant
T_s = Average soil temperature (°K)	Site specific
T_c = critical temperature (°K)	Chemical specific
T_b = normal boiling point (°K)	Chemical specific

4.0 MODEL INPUT PARAMETERS

4.1 General Considerations

The vapour attenuation factors calculated by the model are for a single soil type (coarse-grained), two different building types (residential and commercial) and variable distances between the building and the contamination source. The model calculates attenuation factors for two contamination scenarios:

i) A groundwater contamination source with chemical transport through both the capillary transition zone and unsaturated zone, and,

ii) A soil or soil vapour contamination source with transport through the unsaturated zone.

For the residential scenario, the attenuation factors assume a single family residence with a basement. A slab-on-grade scenario was also considered as part of the development process, and was found to yield lower attenuation factors compared to a basement[2], when only the depth to the base of the foundation was changed. Since there are many houses with basements, a basement scenario was assumed for generic standard development purposes (for site-specific modeling, it may be appropriate to assume slab-on-grade construction). For the commercial scenario, a slab-on-grade scenario was assumed.

The attenuation factors were calculated using the J&E model and input values provided in Table 2. These input parameters were developed considering soil-physics science, available studies of building characteristics, and expert opinion. Relatively conservative values were chosen for many J&E model inputs since the intent was to develop attenuation factors that would, in the large majority of cases, be protective of human health for a wide range of site conditions, excluding those precluding conditions described in Section 2.0. However, to avoid the compounding effect of choosing conservative values for all input parameters, “typical” or mean values were chosen for some input parameters.

The minimum site characterization information needed for use of the TG4 vapour attenuation factors includes: site conceptual model, nature and extent of contamination distribution, soil lithologic descriptions, groundwater concentrations and/or near source soil vapour concentrations. Grain size distribution tests, when available, can assist in determining the appropriate soil type. Basic information on building characteristics, although not directly needed, is useful for context and to determine whether precluding factors apply. The number of samples and measurements needed to establish the above information varies by site.

When there is a NAPL source at the water table, typically a soil vapour contamination scenario should be assumed because NAPL may be present above the capillary fringe.

Justification for the default input parameters and scenarios used to derive the attenuation factors are described below.

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[2] For a distance between the building and media measurement point of 1 m, the slab-on-grade scenario yields an attenuation factor that is 23% lower for the soil vapour-to-indoor air pathway and 36% lower for the groundwater-to-indoor air pathway.

4.2 Justification for Input Parameters

4.2.1 Water-filled Porosity and Total Porosity

The water-filled porosity was estimated using the van Genuchten (VG) water retention model (van Genuchten, 1980) and averages of fitted model parameters for laboratory soil tests for different soil texture classes (*e.g.,* Sand, Loam, etc.) based on a large sample agricultural study that adopted the US Soil Conservation Service (SCS) system of soil classification (*i.e.,* 12 different soil textures). For TG4, only a single coarse soil is considered under the attenuation factor approach, therefore, test data for the coarsest soil texture (Sand) was adopted. The total porosity is the published average laboratory test value for the soil texture classification.

Soil above the water table is divided into two zones for the purposes of estimating water-filled porosity: (i) the unsaturated zone, and (ii) capillary transition zone. For the unsaturated zone, the default value for water-filled porosity was a value equal to half-way between the residual saturation value and field capacity, using the VG model-predicted values derived from model curve-fit parameters computed by Schaap and Leij (1998) for US SCS soil types. For the capillary transition zone ($\theta_{w,cz}$), the water-filled porosity input into the model is the water-filled porosity at the inflection point in the water retention curve where $d\theta_w/dh$ is maximal, where θ_w and h equal the water-filled porosity and matric suction, respectively. Vapour-phase diffusion becomes negligible once the water-filled porosity exceeds the $\theta_{w,cz}$. The height of the capillary zone is estimated using an equation for capillary rise in a tube (Fetter 1994), and mean particle size for the SCS soil textural classifications (Nielson and Rogers, 1990). The bi-linear model for estimation of water-filled porosity is graphically shown in Figure 1.

Soil types coarser than SCS sand were also considered (*e.g.,* sand and gravel), but were found to have little effect on the calculated attenuation factor. This is because the water-filled porosity assumed for SCS sand is already quite low. For the unsaturated zone, the default water-filled porosity for sand used to derive the coarse-grained attenuation factor was 0.054. This corresponds to a relative saturation (water-filled porosity/total porosity) value of 0.14, which reflects the good drainage characteristics of sand. For the capillary zone, the water-filled porosity calculated using the above methodology was 0.253. The total porosity for sand was 0.375. In summary, the default porosity values used in the TG4 model were:

- Water-filled porosity unsaturated zone = 0.054;
- Water-filled porosity capillary zone = 0.253; and,
- Total porosity = 0.375.

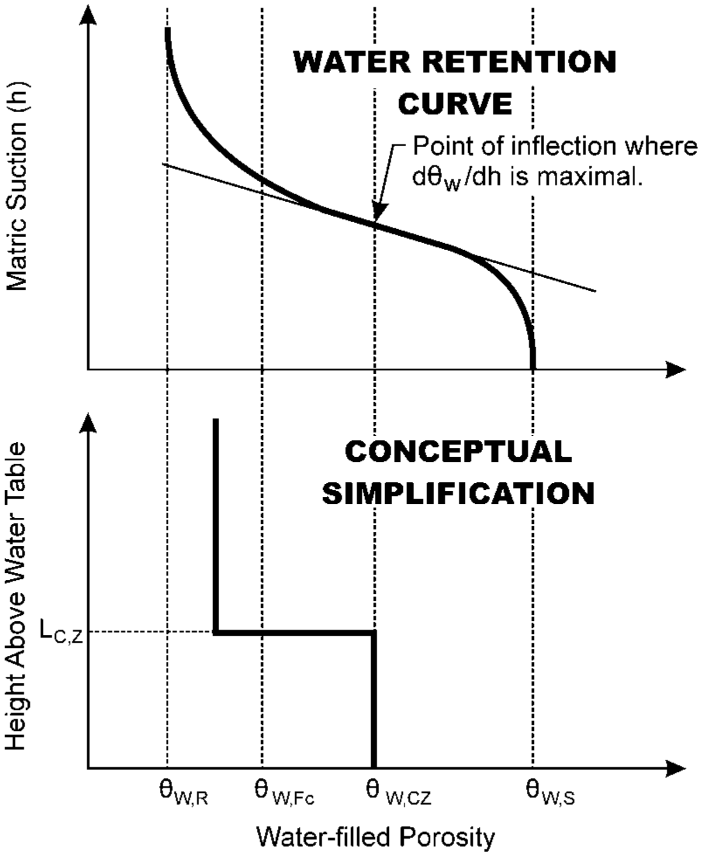

Figure 1: Model used to Estimate Water-Filled Porosity in Soil

The Health Canada approach for Detailed Quantitative Risk Assessment (DQRA) involves calculation of attenuation factors for four different SCS soil textures using the model described above. While not currently part of the BC TG4 model, the spreadsheet includes defaults for these other soil textures, in case future revisions include additional soil types (consideration of finer-grained soil types is recommended). The soil textures classes, which are Sand, Loamy Sand, Sandy Loam and Loam, are based on the proportion of sand, silt and clay in the sample. These four soil texture classes were considered representative of most common soil types. Clay was not chosen since unfractured homogeneous clay deposits are uncommon.

Although currently TG4 only has one soil type, if future modifications are made for multiple soil types, the preferred method for determining the soil texture class are lithological descriptions combined with grain size distribution tests. The soil textural triangle provided in Figure 2 may be used to determine the soil texture. If the soil plots on a soil texture class not addressed in the guidance, the next coarsest soil type should be chosen. If no grain size distribution tests are available, the following may be used to guide selection of the soil type:

If the coarsest soil type is:	The following soil texture is recommended:
"Sand" or "Sand and Gravel" or "Sandy Gravel", with less than about 15 % fines, where "fines" are smaller than 0.075 mm in size.	Sand
"Sand with some silt" or "Silty Sand" with about 15 % to 30 % fines	Loamy Sand
"Silty Sand" or "Silt and Sand", with about 25 % to 50 % fines	Sandy Loam
"Silt and Sand" or "Sandy, Clayey Silt" or "Sandy Silt" or "Clayey, Sandy Silt", with over 50 % fines	Loam

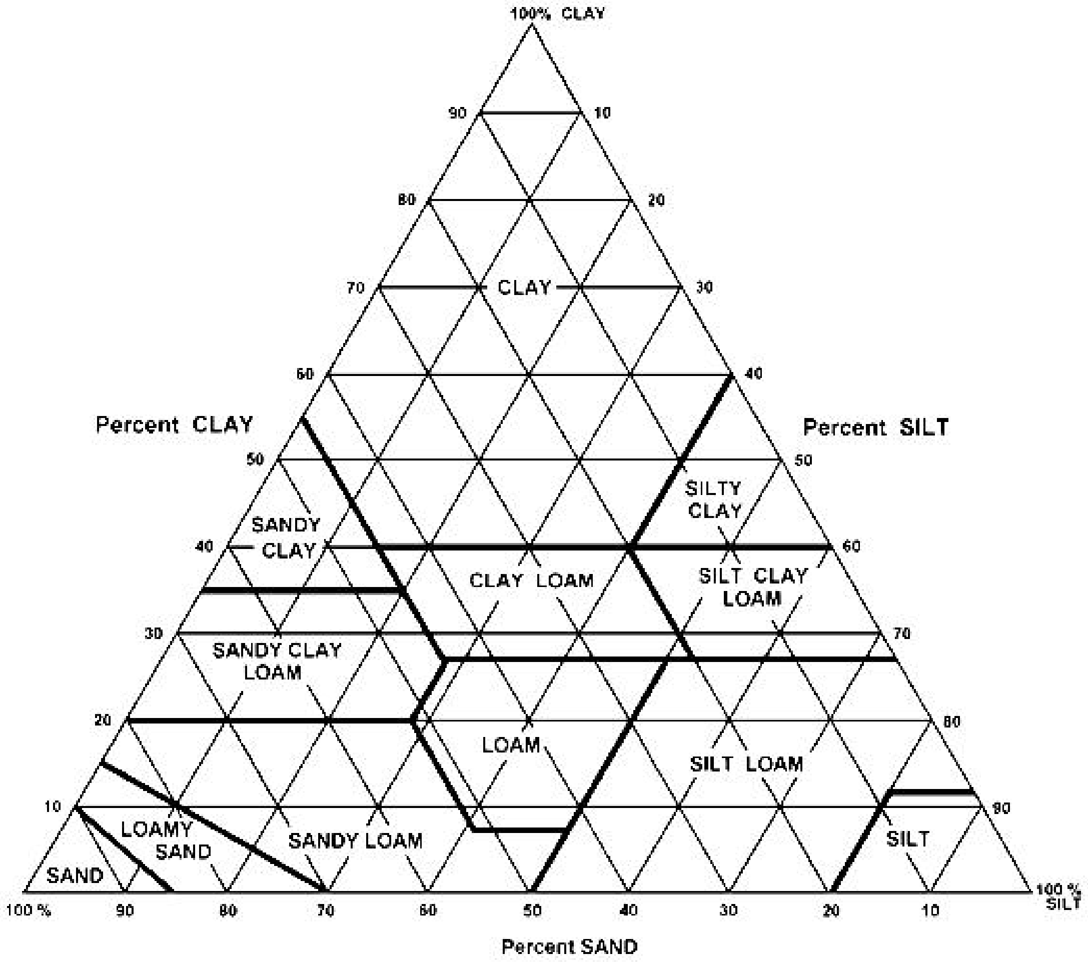

Figure 2: Soil Textural Triangle

The coarsest grain size present below the building should dictate the selection of soil texture; however, if the coarsest layer represents less than five to ten percent of the distance between the foundation and vapour contamination source, then the next coarsest layer can be selected.

4.2.2 Fraction Organic Carbon, Soil Bulk Density and Soil Temperature

The fraction organic carbon, soil bulk density and soil temperature are inputs for the partitioning calculations, while for the J&E model, only the soil temperature influences vapour transport indirectly through an adjustment to the Henry's Law Constant for temperature. The partitioning model is sensitive to the fraction organic carbon, but not soil bulk density and soil temperature. The vapour transport calculations are also not sensitive to the soil temperature. The input parameters were selected based on best judgment and were:

- Fraction organic carbon: 0.006 (dimensionless);
- Soil bulk density: 1.65 g/cm^3; and,
- Soil temperature: 15^{o}C.

The CCME Canada Wide Standards for Petroleum Hydrocarbons in Soil (CCME, 2008) defaults for fraction organic carbon, soil bulk density and soil temperature are 0.005, 1.7 g/cm^3 and 19^{o}C, respectively. The difference between the Health Canada and TG4 defaults, and CCME defaults for these parameters is small and does not have a significant influence on the results.

4.2.3 Residential Q_{soil} (Default Value = 10 L/min)

The soil gas advection rate (Q_{soil}) into a building is a function of the soil air permeability, building depressurization, building foundation properties and building size. Building pressures are affected by temperature, wind and operation of the heating, ventilation and air conditioning (HVAC) system inside a building. When indoor air is warmer than outdoor air, warm air tends to rise within a building causing the lower regions of the building to be under negative pressure, causing soil gas and outdoor air to infiltrate into the building. The differential pressure caused by wind loading can also result in a negatively pressurized building. Depressurization of a building through HVAC operation is typically caused by an imbalance between the intake airflow (coming into the building) and relief air flow (exiting the building), which can result from leaking supply air ducts, restricted or insufficient return air, or unbalanced exhaust systems. While mechanisms for a depressurized building are described above, it is important to recognize that buildings may also be positively pressurized and can "breath both ways" depending on building and weather conditions. Measurement data on building depressurization are compiled in Table 3.

The method often used with the J&E model for estimating Q_{soil} through the building envelope is an analytical solution for two-dimensional soil gas flow to a small horizontal drain (Nazaroff 1992) ("*Perimeter Crack Model*"). The use of this model can be problematic in that Q_{soil} values are sensitive to soil-air permeability and consequently a wide range in flows can be predicted.

An alternate empirical approach is to select a Q_{soil} value on the basis of published literature values from tracer tests. When soil gas advection is the primary mechanism for tracer intrusion into a building, Q_{soil} can be estimated according to a mass balance approach by measuring the concentrations of a chemical tracer in indoor air, outdoor air and in soil vapour below a building, and measuring the building ventilation rate (Hers et al. 2002; Fischer et al. 1996; Garbesi et al. 1993; Rezvan et al. 1991; Garbesi and Sextro, 1989). The Q_{soil} values measured using tracer techniques were compared to predicted rates using the Perimeter Crack Model, and were found to compare reasonably well for sites with coarse-grained soils (i.e., within one order of magnitude) (Hers et al., 2003). Although the Q_{soil} predicted by models and measured using field tracer tests are uncertain, the results suggest that a “typical” range for houses on coarse-grained soils is on the order of 1 to 10 L/min. A disadvantage with the tracer test approach is that there are only limited data, and there do not appear to be any tracer studies for field sites with fine-grained soils.

It is also important to recognize that the advective zone of influence for soil gas flow induced by building depressurization is limited to soil immediately adjacent to the building foundation. There are some data on pressure coupling that provides insight on the extent of the advective flow zone. For example, Garbesi et al. (1993) report a pressure coupling between soil and an experimental basement (*i.e.,* relative to that between the basement and atmosphere) equal to 96 % directly below the slab, between 29 % and 44 % at 1 m below the basement floor slab, and between 0.7 % and 27 % at a horizontal distance of 2 m from the basement wall. At the Chatterton site in Canada, the pressure coupling immediately below the building floor slab ranged from 90 % to 95 %, and at a depth of 0.5 m was on the order of 50 % (Hers et al., 2002). These results indicate that the advective zone of influence will likely be limited to a zone within 1 m to 2 m of the building foundation for smaller buildings. A larger zone of influence for soil gas flow would be expected for larger buildings.

Since the advective flow zone is relatively limited in extent, the soil type adjacent to the building foundation is of importance. In many cases, coarse-grained imported fill is placed below foundations and around drains, and either coarse-grained fill or disturbed, loose fill is placed adjacent to the foundation walls. Therefore, a conservative approach for the purposes of the guidance is to assume that soil gas flow will be controlled by coarse-grained soil, and not to rely on the possible reduction in flow that would be caused by fine-grained soils near the house foundation.

A rationale for a Q_{soil} value of 10 L/min was to obtain a Q_{soil} to building ventilation rate (Q_{build}) ratio that was representative of the available tracer test data (Table 4) and empirical subslab soil vapour attenuation factors.[3] When advection is the main process for vapour intrusion, the subslab vapour attenuation factor is approximately equal to Q_{soil} /$Q_{build.}$ The Q_{soil} /Q_{build} ratio chosen (4.7×10^{-3}) is only slightly higher than the median empirical subslab ratio (2.8×10^{-3}). The Q_{soil}/Q_{build} ratios are also consistent with those recommended by Johnson (2005). Since the building ventilation rate is approximately proportional to the building size, the use of Q_{soil}/Q_{build} indirectly takes into account the building size. A Q_{soil} value of 10 L/min is also consistent with the value predicted by the Perimeter Crack model using the guidance defaults for foundation size and crack wide, soil-air permeability representative of sand ($k = 10^{-7}$ cm^2), and building depressurization of about 8 Pa.

There is some recent research at volatile organic compound (VOC) and radon sites where there is additional subslab attenuation factor data. Consideration should be given to reviewing this data to evaluate whether possible refinement to Q_{soil}/Q_{build} is warranted.

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[3] As indicated in Appendix II, an in-progress USEPA study indicates that the subslab vapour attenuation factors for filtered data (417 data points) range from 6.2E-04 (10th percentile) to 1.4E-2 (90th percentile) with a median value of 2.8E-03 (personal communication, Dr. Helen Dawson, USEPA).

4.2.4 Commercial Q_{soil} (Default Value = 7 L/min)

For commercial buildings, there are large variations in size, design, and construction. As a result, prediction of soil gas advection is highly uncertain. There are also few, if any, empirical data on soil gas advection rates into commercial buildings.

HVAC systems are typically designed to control the pressure inside commercial buildings. Neither excessive depressurization nor pressurization of buildings is desirable based on energy consumption, moisture problems, and practical considerations relating to opening or closing of doors. According to Stanke (2002), the net pressure inside the building relative to outside should range from slightly negative to neutral during cold weather (minimizing exfiltration) to slightly positive during warm weather (minimizing infiltration). For multi-storey buildings in colder climates, it is difficult to avoid some depressurization of the ground floor space as a result of the stack effect. There are several case studies indicating negative pressures can occur in commercial buildings as a result of leaking ducts and/or unbalanced exhaust. Withers and Cummings (2000) report measured negative pressures of –14 Pa, -2.7 Pa and –19 Pa in three small commercial buildings located in Florida. The Canadian Building Digest (NRC-IRC CBD-107) indicates that significant negative pressures (several hundred pascals) can theoretically develop in multi-storey buildings unless controlled through building ventilation and measures to limit vertical air leakage between floors in buildings. The pressure inside a building may also vary temporally. For example, during the day when the HVAC system is on, the building may be positively pressurized; however, during evening hours, the pressure inside the building may become negative if the HVAC system is turned off due to the influence of environmental factors such as temperature and wind. While there is significant uncertainty for building pressurization and Q_{soil}, it is clear that there is the potential for negatively pressurized commercial buildings, and that predictive modeling of vapour intrusion into commercial buildings should include a soil gas advection component.

There are limited empirical data for commercial sites that would enable estimation of Q_{soil}. In general, a lower Q_{soil}/Q_{build} ratio would be expected for commercial buildings compared to residential houses based on building construction (typically slab-on-grade or subsurface parking garage) and typically better foundation construction quality than residential houses. The building depressurization for commercial buildings is also expected to be lower than for many residential buildings, although this can be variable as discussed above. For commercial buildings, a Q_{soil}/Q_{build} that was one order-of-magnitude less (4.7×10^{-4}) than the residential value was chosen based on best professional judgement. The corresponding Q_{soil} based on the default building size and ventilation rate is 7 L/min.

Although modeling of soil gas advection into commercial buildings is highly uncertain, the Perimeter Crack model was used to calculate Q_{soil} and Q_{soil}/Q_{build} for what is considered a reasonable range of building depressurization (2 to 4 Pa) and sandy soils. The other defaults used for the modeling are provided in Table 2. Using a building depressurization of 2 to 4 Pa, a Q_{soil} of 4.3 L/min to 8.6 L/min and Q_{soil}/Q_{build} of 2.9×10^{-4} to 5.8×10^{-4} is calculated. The Q_{soil}/Q_{build} chosen is within the range calculated using the model suggesting it is reasonable.

4.2.5 Residential Building Air Change Rate (Default Value = 0.35 hr^{-1})

Ventilation has three components (Nazaroff, 1992):

i) infiltration, or uncontrolled leakage of air into a building through openings in the building envelope;

ii) natural ventilation through open windows and doors; and,

iii) mechanical ventilation provided by fans.

Ventilation rates reported in the literature vary significantly with results from 27 studies summarized in Table 5. Two broad trends suggested by the data are a general reduction in ventilation rates over the past two decades and lower ventilation rates for houses in cold climates. In regions with relatively cold climates, the recent trend has been to construct "air-tight" houses with reduced ventilation rates to minimize energy consumption and costs (*e.g.,* "R-2000" or "Energy Star" houses in Canada; Gusdorf and Hamlin, 1995). For houses with high energy efficient systems and that typically have mechanical ventilation supplied through a heat recovery ventilator, ventilation rates may be as little as 0.1 air changes per hour (ACH) (Fellin and Otson, 1996).

Standards in Canada and the U.S. both specify minimum ventilation rates for residential dwellings. In Canada, the minimum required ventilation rate under the CSA F326 standard for "*Residential Mechanical Ventilation Systems*" depends on the number and types of rooms in the house but usually works out to about 0.3 ACH. In the US, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) 62-2001 standard recommends an outside air ventilation rate of not less than 7.5 L/s per person, and also not less than 0.35 ACH (ASHRAE, 2001). As of 2007, the ASHRAE standards (62.2-2007) for whole building ventilation were changed to an addition of 3 CFM/100 sq. ft. (15 l/s/100 sq. m.) to the 7.5 CFM/person (3.5 L/s/person) standard for outdoor air exchange (ASHRAE, 2007a). It appears that mechanical ventilation systems are quite frequently operated at less than the design or installed capacity (Figley, 1997; Hamlin and Gusdorf, 1995).

The results from 22 studies for which building air change data are available are summarized in Hers et al. (2001). There is a wide variation in ventilation rates ranging from about 0.1 air changes per hour (ACH) for energy efficient "air-tight" houses (built in cold climates) (Fellin and Otson, 1996) to over 2 ACH (ASHRAE (1985); upper range). In general, ventilation rates will be higher in summer months when natural ventilation rates are highest. Several Canadian studies indicate average air change rates in houses between 0.34 and 0.45 ACH. In an Ontario study, air exchange rates from 70 houses ranged from 0.06 ACH to 0.77 ACH, with the lowest air exchange occurring in summer in R-2000 houses with closed windows (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). In a study of houses in Saskatoon of medium air-tightness, the air change rates measured in 18 houses varied from a low of 0.08 ACH to high of 0.43 ACH, with an average change rate of 0.2 ACH for this study (CMHC, 1995). It was determined that improved mechanical ventilation systems were required to address low ventilation rates and indoor air quality issues.

One of the most comprehensive studies of U.S. residential air change rates (sample size of 2,844 houses) was conducted by Murray and Burmaster (1995). The data set was analyzed on a seasonal basis, and according to climatic region. When all the data were analyzed, the 10th, 50th and 90th percentile values were 0.21, 0.51 and 1.48 ACH. Air change rates varied depending on season and climatic region. For example, for the winter season and coldest climatic area (Region 1, Great Lakes area and extreme northeast US), the 10th, 50th and 90th percentile values were 0.11, 0.27 and 0.71 ACH. In contrast, for the winter season and warmest climatic area (Region 4, southern CA, TX, Florida, Georgia), the 10th, 50th and 90th percentile values were 0.24, 0.48 and 1.13 ACH. While building air change rates would be higher during the summer months, vapour intrusion during winter months (when house depressurization is expected to be most significant) would be of greatest concern. An air change rate of 0.35 hr^{-1} was selected to represent the lower end of these distributions.

4.2.6 Commercial Building Air Change Rate (Default Value = 1 hr^{-1})

The data set for commercial buildings is relatively limited (Table 5). The actual ventilation rate often varies depending on operational conditions inside the building. Fang and Persily (1995) and Dols and Persily (1995) report air changes that ranged between about 0.3 ACH, measured when the HVAC system was providing the minimum intake of fresh air, to about 2.6 ACH, measured when the HVAC system was providing the maximum intake of fresh air.

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[4]. For example, ASHRAE (2007b) recommends for office use a minimum outdoor air ventilation rate based on occupancy (5 cfm per person) and floor area (0.06 cfm per square foot). Combined with the minimum assumed occupancy of 5 people per 1000 square feet, a minimum outdoor air change rate of 0.57 ACH is calculated (however, often a minimum occupancy of 7 people per 1000 square feet is assumed resulting in a design air change rate of about 0.72 ACH). 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 25th, 50th and 75th percentile air change rates were 0.47 hr^{-1}, 0.98 hr^{-1} and 2.62 hr^{1}, respectively (NIST, 2004).

The default ventilation rate selected for a commercial building was 1 ACH.

4.2.7 Residential Building Vapour Mixing Height (3.66 m for Basement Scenario)

The J&E model assumes that subsurface vapours are completely mixed within the building air space, which is determined by the building area and mixing height. The building vapour mixing height will depend on a number of factors including the building height, the HVAC system operation, environmental factors such as indoor-outdoor pressure differentials and wind loading, and seasonal factors. For a single-storey house, the variation in mixing height can be approximated by the room height. For a multi-storey house or apartment building, the mixing height will be greatest for houses with HVAC systems that result in significant air circulation (*e.g.,* forced-air heating systems). Mixing heights would likely be less for houses with electric baseboard heaters. It is likely that the mixing height, to some degree, is correlated to the building air change rate.

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[4] Examples are CSA F326 and ANSI / ASHRAE Standard 62.1 – 2004 Ventilation for Acceptable Indoor Air Quality.

There are few data available that provide for direct inference of mixing height. There are few sites, with a small number of houses where indoor air concentrations were above background, and where both measurements at ground level and the second floor were made (CDOT, Redfield, Eau Claire, Juniper[5]). Persons familiar with the data sets for these sites indicate that in most cases a fairly significant reduction in concentrations (factor of two or greater) was observed between the first and second floor level. For the CDOT site apartments, there was an approximate five-fold reduction between the concentrations measured for the first floor and second floor units (Mr. Jeff Kurtz, EMSI, personal communication, June 2002). A fairly significant reduction (factor of two or greater) was observed at the Redfields site in homes where multiple indoor air quality tests were made. At one site (Eau Claire, “S” residence), the indoor trichloroethene (TCE) concentrations were similar in both the basement and second floor of the house. At the Juniper site, the ratio between basement and second floor concentrations in five homes ranged between 0.6 and 3.7 (average of 1.9). There may be less mixing for an apartment depending on leakage between floors. Although there are stairwells and elevator shafts in an apartment, there may be less conduits for mixing compared to a house. The value chosen for a basement house scenario (3.66 m) would be representative of a two-fold reduction or attenuation in vapour concentrations between floors.

4.2.8 Commercial Building Vapour Mixing Height (Default Value = 3 m)

The default commercial building vapour mixing height (3 m) is considered a representative value for a single-storey building. The mixing height for a multi-storey commercial building would be greater as a result of mixing within the building caused by ventilation and leakage across floors. For some buildings such as large (“big-box”) warehouses, the default height of 3 m would be overly conservative. Under the current regulatory framework in British Columbia, adjustment of the attenuation factor for larger vapour mixing height would require a site specific risk assessment. Under the Health Canada detailed quantitative risk assessment (DQRA) approach, the mixing height may be readily adjusted in the model up to a height of 6 m, if supported based on site conditions.

4.2.9 Residential Crack Width (Default Value = 1 mm) and Crack Ratio (Default Value = 0.00022 for Basement House)

The crack width and crack ratio are related. Assuming a square house and that the only crack is a continuous edge crack between the foundation slab and wall (“perimeter crack”), the crack ratio and crack width are related as follows:

$$\text{Crack Ratio} = \frac{4\left(\text{Crack Width}\right)\sqrt{\text{Subsurface Foundation Area}}}{\text{Subsurface Foundation Area}}$$

There is a slight difference in crack ratio for the basement and slab-at-grade scenarios based on the slight difference in subsurface foundation area. However, this difference has no effect on the calculated attenuation factors.

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[5] These sites are described in Health Canada Vapour Intrusion Guidance (under development)

There is little information available on typical values for crack width or crack ratio. One approach used by radon researchers is to back-calculate crack ratios using a model for soil gas flow through cracks and the results of measured soil gas flow rates into a building. For example, the back-calculated values for a slab/wall edge crack based on soil gas-entry rates reported in Nazaroff (1992), Revzan et al. (1991) and Nazaroff et al. (1985) range from about 0.0001 to 0.001. Another possible approach is to measure crack openings although this, in practice, is difficult to do. Figley and Snodgrass (1992) present data from ten houses where edge crack measurements were made. At the eight houses where cracks were observed, the cracks widths ranged from hairline cracks up to 5 mm wide, while the total crack length per house ranged from 2.5 m to 17.3 m. Most crack widths were less than 1 mm. The suggested defaults for crack ratio in regulatory guidance, literature and models also vary. In ASTM E1739-95, a default crack ratio of 0.01 is used. The crack ratios suggested in the VOLASOIL model (developed by the Dutch Ministry of Environment) range from 0.0001 to 0.000001. The VOLASOIL model values correspond to values for a "good" and "bad" foundation, respectively. The crack ratio used by Johnson and Ettinger (1991) for illustrative purposes ranged from 0.001 to 0.01. The selected default values (Table 2) fall within the ranges observed.

4.2.10 Commercial Crack Width (Default Value = 1 mm) and Crack Ratio (Default Value = 0.00021 for Slab-on-Grade Building)

The default crack width for a commercial building is 1 mm. For slab-on-grade scenario, this corresponds to a crack ratio of 0.0002 using the default building area of 180 m^2.

4.2.11 Residential Building Area (Default 10 m by 10 m) and Subsurface Foundation Area for Basement (Default Value = 180 m^2)

The residential building area, area corresponds to a building with a 1076 ft^2 (100 m^2) footprint, is a subjectively chosen default value. However, the building area chosen is considered appropriate based on the Q_{soil} input selected, which is linked to building area through the Q_{soil}/Q_{build} relationship.

The default building area chosen is similar to the (i) default values used in the Superfund User's Guide for the J&E Model (9.61 m by 9.61 m or 92.4 m^2), and (ii) default values used by the State of Michigan, as documented in Part 201, Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria: Technical Support Document (10.5 m by 10.5 m or 111.5 m^2). The Michigan guidance document indicates that the 111.5 m^2 area approximately corresponds to the 10th percentile floor space area for residential single family dwellings, based on statistics compiled by the U.S. Department of Commerce (DOC) and US Department of Housing and Urban Development. The assumed foundation thickness is 0.1 m. The assumed depth to the base of the foundation slab is 2 m for the basement scenario and 0.3 m for the slab-on-grade scenario. For the basement scenario, the foundation area is obtained by adding the base area (100 m^2) plus the perimeter (40 m) multiplied by the depth (2 m). For the slab-on-grade scenario, a slightly greater distance is assumed than the thickness of the floor slab since typically foundation wall footings extend slightly below the base of the floor slab.

4.2.12 Commercial Building Area (Default 20 m by 15 m) and Subsurface Foundation Area (Default Value = 335 m^2)

Commercial buildings vary in size and there is little basis for selection of a representative building area. The default area chosen is the same as that used for the CCME CWS-PHC (June, 2008). The assumed foundation thickness is 0.15 m. The depth to the base of the foundation slab is 0.5 m. For the slab-on-grade scenario, a greater distance is assumed for the depth to the base of the foundation slab (*i.e.,* 0.5 m) than the thickness of the floor slab since typically foundation wall footings extend slightly below the base of the floor slab.

4.3 Considerations Relating to Foundation Type

Vapour attenuation factors were calculated for both a residential basement and slab-on-grade scenario for the input parameters in Table 2. Both scenarios assumed a Q_{soil} of 10 L/min since cracks, drains and other foundation openings may exist for both foundation types. There was little difference in attenuation factors between the basement and slab-on-grade scenarios (less than 10 percent). The reason that there was little difference in attenuation factors relates to the building foundation area and volume. The mass flux into the building is approximately proportional to the foundation area (180 m^2 for basement and 106 m^2 for slab-on-grade). The indoor air concentrations are proportional to the flux divided by the building mixing volume (366 m^3 for basement and 244 m^3 for slab-on-grade). Although the flux is higher for the basement scenario, there is also greater dilution, which results in attenuation factors similar to the slab-on-grade scenario. Provided that the Q_{soil} for each scenario is the same, the balancing effect of flux area and dilution volume can also be expressed through the foundation area (A) to enclosed space volume (V) ratio, which is 0.49 for the basement scenario and 0.43 for the slab-on-grade scenario. Since there was little difference between the basement and slab-on-grade scenarios, only attenuation factors for the basement scenario are provided.

5.0 SPREADSHEET MODEL STRUCTURE

The worksheets that comprise the model are described below.

Instructions Worksheet: The model equations and instructions on how to use the model are provided in this worksheet.

Input Worksheet: Information summarizing pertinent aspects of the problem formulation, the chemical concentrations, soil type for vapour attenuation factor, the vertical distance between the vapour contamination source and building, 10X bioattenuation reduction factor (optional), and soil properties at the vapour contamination source are provided in this worksheet. The indoor air and background air concentration are not used at this time in the model, but could be incorporated in future versions of the model. The **Input Worksheet** inputs attenuation factors are calculated in and read from the **JE Worksheet**.

JE Worksheet: The J&E model equations for vapour transport are provided in this worksheet. The J&E model input parameters, excluding those related to soil type and distance between the building and vapour contamination source, are also entered in this sheet.

Results: The results sheet summarizes the target indoor air concentrations, media concentrations, and back-calculated soil, groundwater and soil vapour criteria. Checks are included to determine if (i) the odour threshold is below the risk-based indoor soil concentrations (CSR Schedule 11), (ii) the back-calculated soil vapour concentration is greater than maximum theoretical vapour concentration, and (iii) the back-calculated soil vapour concentration is greater than the explosivity limit divided by a safety factor (these checks are further described in Section 6).

Models: The partitioning equations are provided in this worksheet.

Chemical Database: The physico-chemical properties are provided in this worksheet (see Appendix **I**) for additional details.

6.0 CHECKS OF CRITERIA BASED ON MANAGEMENT CONSIDERATIONS

6.1 Ceiling Limits Based on Maximum Theoretical Vapour Concentration

The calculated soil vapour criteria are compared in the spreadsheet model (Results sheet) to ceiling limits based on the maximum theoretical vapour concentrations (Exhibit I) because concentrations in excess of these maximum concentrations are theoretically not possible.

An example calculation is presented for commercial land use for toluene, a compound with a relatively high CSR Schedule 11 Vapour Standard (15 mg/m^3). A soil vapour attenuation factor of 3.7x10^{-4} is obtained assuming the TG4 attenuation factors for commercial land use, coarse-grained soil (default), and a distance between the building and measurement point of 1 m. A soil vapour criterion is calculated as follows:

C_v = 15/3.7x10^{-4} = 40,540 mg/m^3

The maximum theoretical soil vapour concentration is calculated as follows:

NAPL Present: C_v^{NAPL} = UCF_1 * MW*P/(R*T) = 1000 mg/g * 92 g/mole * 3.75x10^{-2} atm / (8.21x10^{-5} m^3 atm/K-mole * 298 K) = 141,000 mg/m^3

No NAPL Present: $C_v^{NO\ NAPL}$ = UCF_2 * S * H' = 1000 L/m^3 * 515 mg/L * 0.27 = 141,000 mg/m^3

C_v^{max} = Max (C_v^{NAPL}, $C_v^{NO\ NAPL}$) = 141,000 mg/m^3

In this case, the soil vapour criterion does not exceed the maximum theoretical soil vapour concentration. It is noted that a mole fraction of one was used for the calculations. This would be conservative for most scenarios since toluene would typically be present as one of many compounds in a mixture. However, to account for possible pure chemical releases, a mole fraction of one is considered appropriate for soil vapour criteria development purposes.

6.2 Ceiling Limits Based on Explosivity

The calculated soil vapour criteria is compared to ceiling limits based on potential explosivity in the spreadsheet model (Results sheet) because the potential accumulation of soil vapours above explosive limits represents a safety hazard.

An example calculation is presented for commercial land use for toluene, a compound with a relatively high tolerable concentration. The toluene concentration in the previous section is converted to ppm below and then compared to a toluene concentration that is 20% of the lower explosive limit (LEL) of toluene. The LEL of toluene, which is 1.1%, is provided in the Chemicals sheet in the model. A safety factor of five (20% of the LEL) was chosen since some regulatory jurisdictions[6] define this as a level of concern when addressing near-building soil vapour or within building concentrations. This safety factor can be adjusted as warranted.

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[6] In British Columbia there are no specific regulations or criteria that would address explosive safety hazards associated with volatile contaminants in soil gas. The BC Landfill Criteria does address potential explosive hazards associated with methane. The WorkSafe BC

C_v = 40,540 mg/m^3 = 10,502 ppm (at 20^{o}C) = 1.06%

20% of LEL = 0.2 x 1.1% (see Chemicals sheet in model) = 0.22%

In this case, the backcalculated soil vapour criterion exceeds 20% of the LEL and therefore consideration should be given to limiting the soil vapour criteria to 20% of the LEL (or applicable % of the LEL chosen).

It is important to recognize that the greater explosivity concern is associated with methane at sites with extensive petroleum contamination and landfills and fill sites with organics.

6.3 Comparisons of Soil and Groundwater Criteria to Analytical Detection Limits

The backcalculated soil and groundwater criteria are compared to analytical detection limits in the Results sheet of the model. The analytical detection limits consisting of low and high range values were provided by BC Environment. Initial comparisons for a residential scenario and 1 m distance between building and receptor indicate the soil criteria are less than the detection limit for several common substances (*e.g.,* benzene, trichloroethylene, vinyl chloride). For groundwater, there are only a very few chemicals where the criteria is less than the detection limit (*e.g.,* vinyl chloride).

6.4 Comparison of Schedule 11 Vapour Standards to Odour Thresholds

The odour thresholds selected (see Appendix I) are compared to the Schedule 11 Soil Vapour Residential Standards in the Results sheet and in the Chemicals sheet (column 19) of the model. There are 19 chemicals for which the odour threshold is less than the Schedule 11 Vapour Standard (Table 6). It is important to recognize that there is considerably subjectivity and variability in establishing odour thresholds.

OH&S regulation addresses explosive/safety hazards associated with explosivity, although not directly related to soil gas. The OH&S threshold for explosive hazard for certain occupational settings is 20% of the LEL.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Golder developed a soil vapour intrusion computer model with the specific purpose of back-calculating chemical-specific soil, groundwater and soil vapour criteria starting from the CSR Schedule 11 Vapour Standards and using the assumptions for soil vapour transport embodied in BC Environment Technical Guidance TG 4 (July 2009). The spreadsheet enables efficient calculation of soil and groundwater criteria for multiple chemicals for residential and commercial land use and single soil type (coarse-grained soil or sand).

As part of possible future work, it is recommended that the regulatory framework and models be expanded to incorporate biodegradation of petroleum hydrocarbon compounds and different soil types. For backcalculation of soil criteria for vapour pathway, it is recommended that the possible influence of contaminant source depletion be considered.

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Table 1: Qualitative Uncertainty and Sensitivity Analysis for Inputs Used for Johnson Ettinger Model

Input Parameter	Parameter Sensitivity and Uncertainty Shallower Contamination Building Underpressurized	Deeper Contamination Building Underpressurized	Shallower Contamination Building Not Underpressurized	Deeper Contamination Building Not Underpressurized
Soil Properties				
Unsaturated Zone Water-filled Porosity	Low to Moderate	Moderate to High	Moderate to High	Moderate to High
Total Porosity	Low	Low	Low	Low
Capillary Transition Zone Water-filled Porosity	Low to Moderate	Moderate to High	Moderate to High	Moderate to High
Capillary Transition Zone Height	Low to Moderate	Moderate to High	Moderate to High	Moderate to High
Qsoil	Moderate to High	Low to Moderate	N/A	N/A
Soil air permeability	Moderate to High	Low to Moderate	N/A	N/A
Soil Bulk Density	Low	Low	Low	Low
Henry's Law Constant (for single chemical)	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Free-Air Diffusion Coefficient (single chemical)	Low	Low	Low	Low
Building Properties				
Building Depressurization	Moderate	Low to Moderate	N/A	N/A
Building Air Change Rate	Moderate	Moderate	Moderate	Moderate
Building Mixing Height	Moderate	Moderate	Moderate	Moderate
Subsurface Foundation Area	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Building Crack Ratio	Low	Low	Moderate to High	Low to Moderate
Crack Moisture Content	Low	Low	Moderate to High	Low to Moderate
Building Foundation Slab Thickness	Low	Low	Low	Low
Depth to Base of Foundation	Low	Low	Low	Low

Note: Attenuation factor inversely proportional to building mixing height and build air change rate

Table 2: Johnson and Ettinger Model Input Values for Derivation of Attenuation Factor Charts

Input Parameter	Units	Residential	Commercial
Soil and Chemical Properties			
Coarse-Grained (SCS Sand)			
Unsaturated Zone Water-filled Porosity	cm^3/cm^3	0.054	0.054
Total Porosity	cm^3/cm^3	0.375	0.375
Capillary Transition Zone Water-filled Porosity	cm^3/cm^3	0.253	0.253
Capillary Transition Zone Height	cm	17	17
Fine-Grained (SCS Loam)			
Unsaturated Zone Water-filled Porosity	cm^3/cm^3	0.148	0.148
Total Porosity	cm^3/cm^3	0.399	0.399
Capillary Transition Zone Water-filled Porosity	cm^3/cm^3	0.332	0.332
Capillary Transition Zone Height	cm^3/cm^3	37.5	37.5
Effective soil gas permeability	cm^2	Not Used	$1x10^{-7}$
Qsoil	L/min	5 (empirical)	4.3 (calculated)
Soil Temperature	^oC	15	15
Soil Bulk Density		chemical specific	chemical specific
Henry's Law Constant		chemical specific[1]	chemical specific[1]
Free-Air Diffusion Coefficient		chemical specific	chemical specific
Building Depressurization	Pa	Not Used	2
Building Air Change Rate	hr^{-1}	0.3	1
Building Mixing Height - Basement scenario	m	3.66	N/A
Building Mixing Height - Slab-on-grade scenario	m	2.44	3
Building Footprint Area - Basement Scenario	m^2	100	N/A
Building Footprint Area - Slab-on-Grade Scenario	m^2	100	300
Subsurface Foundation Area - Basement Scenario	m^2	180	N/A
Subsurface Foundation Area - Slab-on-Grade Scenario	m^2	106	370
Depth to Base of Foundation - Basement Scenario	m	2	N/A
Depth to Base of Foundation - Slab-on-Grade Scenario	m	0.15	0.5
Perimeter Crack Width	mm	1	1
Building Crack Ratio - Slab-on-Grade Scenario	dimensionless	0.00038 (calculated)	0.0002 (calculated)
Building Crack Ratio - Basement Scenario	dimensionless	0.0002 (calculated)	N/A
Crack Dust Water-Filled Porosity	cm^3/cm^3	Dry	Dry
Building Foundation Slab Thickness	m	0.1	0.15

Notes:

1. Henry's Law constant adjusted for temperature based on method provided in Superfund User's Guide for the J&E Model.

Table 3: Survey of Building Depressurization Relative to Atmospheric Pressure

Reference	Data Type	Location	Building Type & Number	Measure-ment Date	Measurement Statistic	Depressuri-zation (Pa)	Comments
19 [1]	Measured	Netherlands	Houses with Crawlspace	N/A		~ 2 ~ 2	Between indoor space and crawlspace Between crawlspace and soil
14	Measured	Canada	Houses: Halifax (12), Ottawa/Hull (16), Winnipeg(12) ,Vancouver (12)	Winter 93	range average for house	-5 to 15 0.5 to 8.5	Mix older & newer houses, most houses had forced air heating system & basement, depressurization correlated to house construction (full, partial basement, slab on grade) & climate
9	Measured	Spokane River Valley, WASH, USA	House (14)	Winter	average	2 to 6	
7	Measured	Chicago, Ill., USA	House (1)	Feb 17 to June 1, 1982	range	0.6 to 4.3	Basement ΔP decreased between Feb. & June 1
20	Predicted	Alameda, California, USA	Small commercial building (1)	N/A	range	1 to 4	Predicted based on wind loading
8	Predicted	Portland, Or	2-storey house with basement	N/A		~ 2 ~ 2	Predicted based on wind Predicted based on stack effect
47	General reference	N/A	Houses	N/A		up to 10	upper range associated with extreme weather conditions
18	Guidance	Canada	slab-on-grade house slab-on-grade house 1 to 2 storey house 1 to 2 storey house 3 storey house 3 storey house	N/A	range range range range range range	1 to 3 3 to 5 4 to 6 8 to 10 7 to 9 13 to 15	range mild to severe winter, without chimney range mild to severe winter, with chimney range mild to severe winter, without chimney range mild to severe winter, with chimney range mild to severe winter, without chimney range mild to severe winter, with chimney

Notes:

[1] references Put and Meijer, 1989 (report in Dutch)

[2] if the house has a fresh air intake duct or combustion air supply, reduce differential pressures by 2 Pa. If the house has a fireplace, central exhaust system or other large or frequently used exhaust equipment, increase the differential pressures by 2 Pa.

Table 4: Measured Soil Gas Advection Rate into Buildings from Tracer Studies

Study	Building	Soil Type	Tracer	ΔP	Q_{soil}/Q_{build}	Q_{soil} (L/min)	Q_{soil}/Area (L/m^2)	Q_{soil}/Area-ΔP (L/m^2-Pa)
Hers (on-going study, 2003)	House w\ basement&crawl space	Sand	MTBE, cyclo-hexane, 224-trimethyl-pentane	0.6	0.0039 to 0.0084	N/A	N/A	N/A
Hers (on-going study, 2003)	Houses w\ basement	Sand & gravel	TCE	4 (avg)	0.001 to 0.0064	N/A	N/A	N/A
Olson & Corsi (2001)	House w\basement Paulsboro	Sand, some silt	SF_6	3.6 to 6.2	0.003 to 0.01	5.8 to 6.7	0.18 (6.2 Pa)	0.03
Mose & Mush-rush (1999)	Houses Virginia	N/A	Radon	N/A	0.003 to 0.02	N/A	N/A	N/A
Hers (Chatterton) (1998)	Experimental Greenhouse	M. Sand	BTX	10 to 30	0.00009 to 0.0005	0.52 to 2.8	N/A	0.001 to 0.005
Fischer et al. (1996)	Small Commercial Building	F. Sand	SF_6	10	0.0002 to 0.0004	4.5	0.018	0.006
Garbesi et al. (1993)	Small Experimental Basement	F. Sand	N/A	20	N/A	20		0.04
Little et al. (1992)	Houses USA	N/A	Radon	N/A	0.0016 (Avg)	N/A	N/A	N/A
Garbesi & Sextro (1989)	House w\basement	Sandy Loam to Loamy Sand	SF_6	30	~0.001	67 (Best)	N/A	0.01(Best)
Rezvan et al. (1989)	Houses	Gravel	Rn	N/A	0.0079 to 0.045	17 to 96[2]	N/A	N/A

1 Estimated by Fischer et al (1996) from wind-loading (Qbuilding not available)

2 Estimated using assuming values for house volume (366 m3) and AEH (0.35/hr) (Qbuilding not available)

3 Cyclohexane, MTBE, Pentane, 2,2,4-Trimethylpentane

Table 5: Survey of Building Ventilation Rates

Reference	Data Type	Location	Building Type & Number	Measure-ment Date	Measurement Statistic	Air Ex-change (ach)	Comments
Residential Houses							
NREL, 2002	Measured SF$_6$	San Antonio	2 houses	Aug-00	Range	0.2 to 0.3	When AC on (measurements taken in summer)
					Range	0.05 to 0.15	When AC off (measurements taken in summer)
LBNL, 2001	Measured SF$_6$	Florida	11 houses	Fall 1997 to Spring 1998	Range	0.14 to 0.78	Lower ACH were obtained in homes with HRV
Otson and Zhu, 1997	Measured PFT	Greater Toronto, ONT, Canada	Houses (44)	Feb. 12 to Apr. 9, 1996	average	0.45	
					median	0.4	
Murray and Burmaster, 1995	Measured PFT	U.S. Region 1	Houses (467)	All seasons	mean	0.4	5th and 95th percentile = 0.1, 0.95
		U.S. Region 2	Houses (1496)	All seasons	mean	0.55	5th and 95th percentile = 0.14, 1.38
		U.S. Region 3	Houses (332)	All seasons	mean	0.55	5th and 95th percentile = 0.15, 1.25
		U.S. Region 4	Houses (1549)	All seasons	mean	0.98	5th and 95th percentile = 0.21, 2.82
		U.S. Region 1	Houses (161)	Winter	mean	0.36	5th and 95th percentile = 0.08, 0.90
		U.S. Region 1	Houses (254)	Spring	mean	0.44	5th and 95th percentile = 0.14, 1.06
		U.S. Region 1	Houses (5)	Summer	mean	0.82	5th and 95th percentile = 0.27, 2.01
		U.S. Region 1	Houses (47)	Fall	mean	0.25	5th and 95th percentile = 0.1, 0.58
SRC, 1995	Measured PFT	Saskatoon, SASK, Canada	Houses (20)	1993 - 1994 (9 months)	minimum	0.08	all houses had natural gas forced air heating systems and chimneys connected to the natural gas furnaces
					average	0.2	
					maximum	0.43	
Fellin and Otson, 1993	Measured PFT	Canada	Houses (24)	1992 to 1993	average	0.34	most measurements in fall and winter months
SRC, 1992	Measured PFT	Saskatoon, Regina SASK, Tillsonburg, ONT, Canada	Houses (44)	Jan. 14 to Feb. 11, 1991	average	0.34	
					median	0.31	
Rothweiler et al., 1992	Measured N$_2$O	Switzerland	Houses (10)	N/A	10th percentile	0.06	new houses or renovated houses
					50th percentile	0.16	
					90th percentile	2.06	
Panadian et al., 1993	Measured PFT	USA	Houses (4000)	Mostly 80's early 90's	average	2	all regions (std. dev. = 3.3)
					average	3.3	southwest
					average	0.6	northeast
					average	0.4	northwest
					average	0.5	winter, all regions
					average	1.9	spring, all regions
					average	5.4	summer, all regions
					average	0.4	fall, all regions
Lewis and Zweidinger, 1992	Measured SF$_6$	Boise, Idaho, USA	Houses (10)	Nov. 15, 1986 to Feb. 4, 1987	average	0.45	
					median	0.45	
Mailahn et al., 1989.	Measured PFT&HFB	Berlin, Germany	Houses (10)	Sept. 1986 to Apr. 1987	average	1.01	older houses had statistically significant higher ach (1.2) then newer houses (0.88)
					median	1.02	
Mueller et al., 1988.	Measured	USA	Houses	N/A	typical range	0.5 - 1.5	typical houses
						0.5 - 0.8	new or energy efficient houses, some as low as 0.2
Walkinshaw, 1987	Measured	ONT, Canada	Houses (70)		range	0.06 - 0.77	lowest ach occurred in summer with windows closed in R-2000 houses
			R-2000 Houses (?)		range	0.34 - 0.37	
Boman and Lyberg, 1986.	Measured	Sweden	Detached & row houses	1974-1982	average	0.17	no mechanical ventilation, 1975 and later
			3-storey apparments	1974-1982	average	0.78	no mechanical ventilation, with fireplace, 1940-1960
Gerry et al., 1986	Measured		Houses (typical)		typical range	0.7 - 1.1	
			Recently built houses		typical range	0.5 - 0.8	
Parker, 1986	Measured	Bangor, Washington	2-storey, four unit building (4)		range	0.24 - 0.91	electric heating
Lamb, 1985	Measured PFT	Eastern Washington, USA	Houses (10)		range	0.3 - 1.0	during typical meterological conditions extended use of doors caused ach to exceed 3
ASHRAE, 1985	Measured	USA	Houses	N/A	typical range	0.2 to 2	
					median	0.5, 0.9	median values for 2 studies
Grimsrud et al., 1982	Mostly Predicted	North America	Houses (312)	N/A	average	0.63	mostly predicted using LBL model (stack & wind effect)
					median	0.5	
Gusdorf and Hamlin, 1995	Predicted AIM-2 HOT-2000	Canada	Houses (47)	Annual Average	average	0.36	R-2000 houses, high energy efficiency houses use heat recovery ventilators
					median	0.34	
					minimum	0.14	
					maximum	0.68	
CMHC, 1997	Guidance	Canada	Wood frame pre 1945	N/A	typical range	0.5-1	Estimated heating season natural ventilation
					typical range	None	Estimated mechanical ventilation
			Wood frame 1946-1960	N/A	typical range	0.2-0.4	Estimated heating season natural ventilation
					typical range	None	Estimated mechanical ventilation
			Wood frame 1961-1980	N/A	typical range	0.15-0.3	maybe 0.2 intermittent
			Airtight new house	N/A	typical range	0.05-0.1	0.3 installed capacity
Otson et al., 1996	Guidance	Canada	Houses	N/A	low	0.1	low
					typical	0.3	typical
Commercial Buildings							
Ekberg (1994)	Measured SF$_6$	Malmo, Goteburg, Sweden	Office buildings (4)	Jan. 90 to Dec. 91	range	3.2 to 4	measured during periods of mechanical ventilation
Sheldon et al., 1988	Measured SF$_6$	Washington D.C., USA	Old-age home	Winter 83		1.72 +/-0.41	high ach attributed to excessive heating and cold outdoor temperatures
			School	1983		0.85 +/- 0.31	
			Office	July 1983		0.61+0.32	
			Office	Sept. 1983		0.52+0.25	
Dols and Persily (1995)	Measured SF$_6$	Portland, Oregon	Office Building (7 stories, floor area of 34,600 m2)	Aug 6., 1991 Jan. 13, 1992	Measured @ min intake fresh air	0.45	Designed to ASHRAE 62-1981, which is approximately 0.18 ACH for an office building
					~ 10th to 90th building air change	0.6 to 1.9	the percent outdoor air generally ranged between 70 and 100 % of total building air exchange rate
Fang and Persily (1995)	Measured SF$_6$	Overland, Missouri	Office Building (7 stories, floor area of 32,500 m2)		Measured @ min intake fresh air	0.3	
					Measured @ max intake fresh air	2.6	
NRC - CNRC	-	Canada	Office Building		0.5		

TABLE 6

Table 6: Chemicals with Selected Odour Thresholds Less than CSR Schedule 11

Chemical	Lowest CSR Schedule 11 Standard	Odour Threshold Selected	Odour Threshold Source
	(µg/m^3)	(µg/m^3)	
Acetaldehyde	4.5	2.7	1
Carbon disulfide	700	654	1
Chloroethane (ethyl chloride)	10000	9763	2
Cumene (isopropylbenzene)	400	59	2
Dichlorobenzene, 1,4-	800	721	3/4
Dimethylamine	200	87	5
Ethyl acetate	2000	577	2
Ethyl acrylate	7	1.2	2
Ethylbenzene	1000	738	1
Methanethiol (methyl mercaptan)	2	0.14	1
Methyl acrylate	60	16.8	2
Methyl ethyl ketone (2- butanone)	5000	1298	1
Methyl isobutyl ketone (4-methyl-2-pentanone)	3000	696	1
Methyl methacrylate	700	201	3
Methyl styrene (alpha) (1-methyl-1-phenylethylene)	200	14.5	5
Methyl t-butyl ether (MTBE)	3000	191	5
Nitrophenol, 2-	NA	1.2	2
Styrene	1000	149	1
Toluene	5000	1244	1

1) Nagata, Y. 2003. Measurement of Odour Threshold by Triangular Odour Bag Method. Odour Threshold Review. Japan Ministry of the Environment. pgs 118-127.
2) Verscheuren, K. 1983. Handbook of Environmental Data on Organic Chemicals. Van Nostrand Reinhold Company. New York, USA
3) American Industrial Hygiene Association (AIHA). 1989. Odour Thresholds for Chemicals with Established Occupational Health Standards. Akron, Ohio.
4) United States Environmental Protection Agency (USEPA). 1992. Reference Guide to Odor Thresholds for Hazardous Air Pollutants Listed in the Clean Air Act Amendments of 1990. U.S. Environmental Protection Agency, Washington, D.C., EPA/600/R-92/047
5) 3M. 2009 Respirator Selection Guide. Odour Thresholds. Available on-line at: http://multimedia.3m.com/mws/mediawebserver

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APPENDIX I

Physico-Chemical Properties

Golder was retained by the Science Advisory Board for Contaminated Sites (SABCS) to develop a chemical-specific vapour intrusion model. As part of this exercise, physico-chemical properties were collected for all of the substances that are included in British Columbia Contaminated Sites Regulation (CSR) Schedule 11 (BC MoE 2009a). This appendix summarizes the rationale for selection of the physico-chemical properties, odour thresholds and explosivity limits utilized in this model.

1.0 SELECTION OF PHYSICO-CHEMICAL PROPERTIES

A number of physico-chemical properties were obtained for the BC CSR Schedule 11 substances for modeling purposes as listed in Table 1. The primary source of physico-chemical properties was the preliminary quantitative risk assessment (PQRA) spreadsheet developed by Health Canada (March 16, 2009). The source of the physico-chemical parameters in these spreadsheets was a comprehensive evaluation conducted by Ms. Heather Jones-Otazao and Mr. John Fisher of Health Canada (unpublished memorandum). Their evaluation was conducted as follow-up to a hierarchy for physico-chemical parameter selection proposed by Golder Associates in their vapour intrusion spreadsheet developed for Health Canada (Golder, 2005). The rationale for selection of physico-chemical parameter selection is further described below.

As part of this project, the British Columbia Ministry of the Environment (BC MoE; Personal Communication with Glyn Fox, July 2, 2009) provided Golder with a spreadsheet containing physico-chemical properties that had been collected as part of the development of the Schedule 11 Vapour Standards. The information provided was the boiling point, vapour pressure, molecular weight and Henry's Law constant. It is understood that BC MoE obtained most of the data from ORNL (2009) and USEPA (2009). These data were incorporated in the chemical worksheet as separate data to the physico-chemical data obtained by Health Canada. For model calculation purposes, the BC MOE data were not used (except for molecular weight) because other sources were these sources were deemed to be more reliable (see footnotes in spreadsheet).

Table 1: Physico-Chemical Properties Collected for BC CSR Schedule 11 Substances

Parameter	Units
Water solubility	mg/L
Molecular weight	g/mol
Mass density	g/cm^3
Log K_{oc}	L/kg
K_{oc}	L/kg
Log K_{ow}	L/kg
Henry's Law Constant	$Pa\text{-}m^3/mol$ $atm\text{-}m^3/mol$ dimensionless mol/kg-barr
Diffusivity in air	cm^2/s
Diffusivity in water	cm^2/s
Vapour pressure	Ps atm mm Hg torr

Parameter	Units
Melting point	°C K
Normal boiling point	°C K
Critical temperature	K
Enthalpy of vapourization at normal boiling point	cal/mol kJ/mol
Half life in the unsaturated zone	Days
Half life in the saturated zone	Days
Permeability coefficient from water	cm/h
Adjustment factor for vapour intrusion	Unitless
Maximum theoretical soil vapour concentration (calculated)	mg/m^3
Estimated diffusion coefficient in air	m^2/s

The following sources of data were searched (in order of general preference) to find the physico-chemical properties listed in Table 1.

- MacKay et al. 2006. Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals;
- Environmental Quality Management. 2004. User's Guide for Evaluating Subsurface Vapour Intrusion into Buildings. Appendix B: Chemical Properties Lookup Table and References. Available on-line at: http://www.epa.gov/oswer/riskassessment/airmodel/pdf/guide.pdf;
- Oak Ridge National Laboratories (ORNL). 2009. Risk Assessment Information System (RAIS). Chemical Specific Factors. Available on-line at http://rais.ornl.gov/cgi-bin/tools/TOX_search?select=chem;
- Montgomery. 2000. Groundwater Chemicals Desk Reference. CRC Press. 2000;
- Syracuse Research Corporation (SRC). 2009. Interactive Phys-Chem Data Base. Available online at: http://www.srcinc.com/what-we-do/databaseforms.aspx?id=386;
- United States Environmental Protection Agency (USEPA). 2009. Region Screening Levels. Chemical Specific Parameters. Available on-line at: 9 Preliminary Remediation Goals (PRGs). Available on-line;
- http://www.epa.gov/region09/superfund/prg/pdf/params_sl_table_run_APRIL2009.pdf;
- ChemSynthesis Chemical Database. 2009. Available on-line at: http://www.chemsynthesis.com/; and,
- Chemical Book. 2009. Available on-line at: http://www.chemicalbook.com/

2.0 SELECTION OF ODOUR THRESHOLDS

Odour thresholds were compiled from the following sources:

- 3M. 2009 Respirator Selection Guide. Odour Thresholds. Available on-line at: http://multimedia.3m.com/mws/mediawebserver?66666UuZjcFSLXTtNXfVMxftEVuQEcuZgVs6EVs6E666666--;
- American Industrial Hygiene Association (AIHA). 1989. Odour Thresholds for Chemicals with Established Occupational Health Standards. Akron, Ohio;
- American Society for Testing and Materials (ASTM). 1978. Compilation of Odour and Taste Threshold Values Data;
- Nagata, Y. 2003. Measurement of Odour Threshold by Triangular Odour Bag Method. Odour Threshold Review. Japan Ministry of the Environment. pgs 118-127;
- National Oceanic and Atmospheric Agency (NOAA). 2009. Cameo Chemicals. Database of Hazardous Materials. Available on-line at: http://cameochemicals.noaa.gov/;
- United States Environmental Protection Agency (USEPA). 1992. Reference Guide to Odor Thresholds for Hazardous Air Pollutants Listed in the Clean Air Act Amendments of 1990. U.S. Environmental Protection Agency, Washington, D.C., EPA/600/R-92/047; and,
- Verscheuren, K. 1983. Handbook of Environmental Data on Organic Chemicals. Van Nostrand Reinhold Company. New York, USA.

For each substance, the odour thresholds were compared to determine whether they were approximately the same order of magnitude. In cases where the odour thresholds varied significantly, the types of thresholds were examined (when the information was available). Generally the following hierarchy was followed in selection of values:

- Nagata (2003);
- AIHA (1989);
- Verscheuren (1983); and,
- ASTM (1978).

Nagata (2003) was usually the most conservative source of information but also the most current. When data were not available from Nagata (2003), the most conservative value from the sources listed above was selected (as long as the odour thresholds were derived on the same basis).

3.0 SELECTION OF EXPLOSIVITY LIMITS

Explosivity limits (lower and upper explosivity limits) were compiled from the following sources:

- National Oceanic and Atmospheric Agency (NOAA). 2009. Cameo Chemicals. Database of Hazardous Materials. Available on-line at: http://cameochemicals.noaa.gov/;
- National Institute for Occupational Safety and Health (NIOSH). 2009. NIOSH Pocket Guide to Chemical Hazards. Available on-line at: http://www.cdc.gov/niosh/npg/npgname-a.html; and,
- Wang et al. 2004. Air Pollution Control Engineering. Humana Press.

The NIOSH explosivity limits were by far the most prevalent source of data and were selected in most cases. Where NIOSH limits were not available, the NOAA or Wang et al. (2004) values were selected.

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