

## **Note To Readers:**

The following errors were identified after publication.

Table 5.1 with target air concentrations and maximum predicted air concentrations should not be used, as some of the toxicological reference values (TRVs) are no longer up-to-date and this affects risk-based calculations. Please refer to Appendix A (Exhibit A1), on how to complete the screening process and calculate air screening concentrations for the protection of human health.



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## Part VII:

# Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites



**Federal  
Contaminated  
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in Canada**

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# FEDERAL CONTAMINATED SITE RISK ASSESSMENT IN CANADA

## PART VII: GUIDANCE FOR SOIL VAPOUR INTRUSION ASSESSMENT AT CONTAMINATED SITES

September 2010

Prepared by:  
Contaminated Sites Division  
Safe Environments Directorate



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## PREFACE

The Federal Contaminated Sites Action Plan (FCSAP) is a program of the Government of Canada designed to ensure improved and continuing federal environmental stewardship as it relates to contaminated sites located on federally owned or operated properties. Guidance documents on human health risk assessment (HHRA) prepared by the Contaminated Sites Division of Health Canada, in support of the FCSAP, are available on our website and may also be obtained by contacting the Contaminated Sites Division at [cs-sc@hc-sc.gc.ca](mailto:cs-sc@hc-sc.gc.ca).

This guidance document (*Federal Contaminated Site Risk Assessment in Canada, Part VII: Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites*) was prepared to provide guidance for custodial departments.

As is common with any national guidance, this document will not satisfy all of the requirements presented in every case by contaminated sites, custodial departments, or risk assessors. As the practice of HHRA advances, and as the FCSAP proceeds, new and updated information on various aspects of HHRA will be published. As a result, it is anticipated that revisions to this document will be necessary from time to time to reflect this new information. Health Canada should be consulted at the address below to confirm that the version of the document in your possession is the most recent edition and that the most recent assumptions, parameters, etc., are being used.

In addition, Health Canada requests that any questions, comments, criticisms, suggested additions, or revisions to this document be directed to: Contaminated Sites Division, Safe Environments Directorate, Health Canada, postal locator 4111A, 99 Metcalfe Street, 11th Floor, Ottawa, ON K1A 0K9. E-mail: [cs-sc@hc-sc.gc.ca](mailto:cs-sc@hc-sc.gc.ca)

See also: <http://www.hc-sc.gc.ca/ewh-semt/contamsite/index-eng.php>.

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## ABBREVIATIONS AND ACRONYMS

BTEX	benzene, toluene, ethylbenzene, and xylenes
CCME	Canadian Council of Ministers of the Environment
COPC	contaminant of potential concern
CSM	conceptual site model
DQRA	detailed quantitative risk assessment
HI	hazard index (sum of HQs)
HQ	hazard quotient
J&E	Johnson and Ettinger
NAPL	non-aqueous phase liquid
PQRA	preliminary quantitative risk assessment
TRV	toxicity reference value
VOC	volatile organic compound

## 1.0 INTRODUCTION

Vapour intrusion is the migration of volatile or semi-volatile chemicals from contaminated groundwater and soil into overlying buildings. This document provides risk assessment guidance specific to the vapour intrusion exposure pathway (“vapour intrusion”) and the evaluation of potential risk to human health from inhalation of subsurface vapours in indoor air. This vapour intrusion guidance is intended to supplement the Health Canada *Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA)* (HC, 2010a), which does not provide quantitative guidance for the soil vapour intrusion pathway. It should be noted that some of the options for vapour intrusion evaluation provided in this guidance document will not be appropriate to use with the type of data that are typically available for a preliminary quantitative risk assessment (PQRA) (See Table 1.1).

A flow chart summarizing the guidance framework for vapour intrusion is provided in Figure 1.1. The vapour intrusion guidance consists of two tiers. The first tier is a qualitative screening step to categorize sites according to their potential for vapour intrusion and to determine whether the assessment should proceed to the second tier. The second tier consists of a screening-level quantitative risk assessment where representative semi-site-specific vapour attenuation factors are used to estimate indoor air concentrations that, in turn, are used to predict human health risk. This guidance also provides methodology for calculation of groundwater and soil vapour screening levels for the vapour intrusion exposure pathway. The vapour attenuation factors, defined as the indoor air concentration divided by the soil vapour concentration at some depth, are based on the Johnson and Ettinger (J&E) model. An overview of the model and the assumptions used to develop the attenuation factors given in this guidance are provided in Appendix A.

Health Canada has developed two spreadsheets that have the capability to estimate vapour intrusion. Both spreadsheet tools include a toxicity and physical-chemical database for over 150 chemicals that can be accessed for risk-screening purposes. The first spreadsheet is the *PQRA Spreadsheet Tool for Human Health Preliminary Quantitative Risk Assessment* (HC, 2008). The PQRA spreadsheet is designed to conservatively calculate human health risks at most sites and in most cases from various exposure

pathways, including vapour intrusion, based on soil and/or groundwater data and the following assumptions:

- Soil temperature is set at 25°C because this is the temperature for which Henry’s constant is often measured.
- The user has a choice of fine or coarse soil.
- The user specifies the depth to contamination, which must be at least 1 m (see Section 3.0).

The second spreadsheet is the *Spreadsheet Tool for Detailed Quantitative Risk Assessment (DQRA)* (HC, 2009) that incorporates the semi-site-specific attenuation factors developed in this guidance. It allows a wider range of soil types and the modification of soil properties. The model has the following features:

- includes a source depletion check, groundwater flux adjustment, and biodegradation adjustment;
- estimates vapour intrusion and subsequent risk from soil vapour in addition to soil and groundwater (at the detailed quantitative risk assessment [DQRA] level – it is expected that samples from multiple media will be available); and
- incorporates both the Canadian Council of Ministers of the Environment (CCME) and Health Canada vapour intrusion model. The model selection should be justified.

Further guidance on site characterization and sampling for vapour intrusion assessment is available in the Health Canada *Guidance Manual for Environmental Site Characterization in Support of Human Health Risk Assessment* (HC, unpublished). Guidance on PQRA and DQRA can be found in the Health Canada *Federal Contaminated Site Risk Assessment in Canada, Part I: Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA), Version 2.0* (HC, 2010a) and *Federal Contaminated Site Risk Assessment in Canada, Part V: Guidance on Human Health Detailed Quantitative Risk Assessment for Chemicals (DQRA<sub>CHEM</sub>)* (2010c).

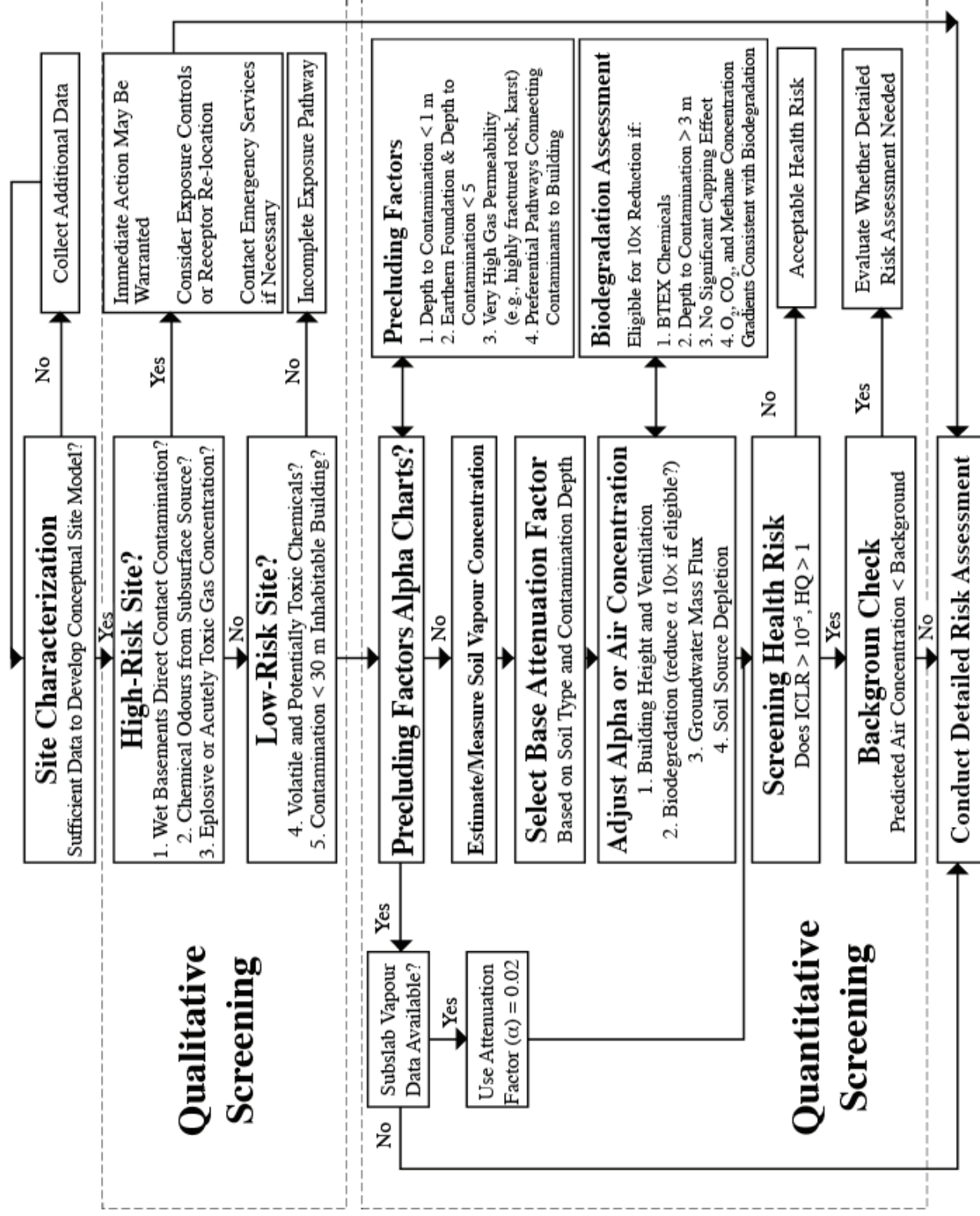
**Table 1.1 Comparison of Vapour Intrusion Assessment Parameters for Preliminary Quantitative Risk Assessment (PQRA) and Detailed Quantitative Risk Assessment (DQRA)**

Assessment Parameters	PQRA	DQRA
Site Data	Soil or Groundwater	Multiple lines of evidence including groundwater and soil vapour data
Soil Types	Coarse or Fine	Sand, loamy sand, sandy loam, and loam Soil parameters may be specified in the spreadsheet
Depth to Contamination	Adjustable	Adjustable
Bioattenuation Adjustment	Should not be used	May be used if sufficient data are available
Mass Flux Adjustment	Should not be used	May be used if sufficient data are available
Source Depletion Check	Should not be used	May be used if sufficient data are available

It is very important to note that significant limitations are associated with the use of soil data, particularly at sites contaminated with chlorinated hydrocarbons. Health Canada will investigate if vapour intrusion from chlorinated solvents is underpredicted in coarse soil. Although Health Canada will

accept a vapour intrusion assessment based on soil data at the PQRA level, we recommend that additional information, such as groundwater data and indoor air data, be compiled for the site.

Figure 1.1 Flow Chart for Vapour Intrusion Guidance





## 2.0 GUIDANCE APPLICATION AND SCOPE

This vapour intrusion guidance describes how to determine if there is the potential for subsurface vapours to migrate into a building, and if so, if vapour intrusion poses a potential unacceptable risk to human health. The guidance is written in a series of questions and steps the user is to follow to evaluate the potential risks. The information in the appendices is intended to provide technical rationale for the document.

This guidance is intended for application where residential or commercial buildings at an existing contaminated site are currently occupied, or where there is potential for the presence of occupied buildings in a future land use scenario. This guidance should be used only for future development or land use if it can be verified that conditions at the site will correspond with the assumptions made in this guidance. Predictions of future exposure scenarios are only as good as the predictions of future site conditions, and as such, risks may need to be reassessed in the future to ensure proper characterization. Separate vapour attenuation factors are provided for representative residential and commercial buildings.

The focus of this guidance is protection of human health, based on chronic health risks due to long-term exposure to vapours at low concentrations. In extreme cases, vapours can accumulate in occupied buildings or confined spaces at levels that may pose near-term safety hazards (e.g. explosion), acute health effects, or aesthetic problems (e.g. odours). Although this guidance will not discuss these, immediate and appropriate measures should always be taken to protect human health should such conditions exist.

The exposure of workers to chemicals used in industrial processes is evaluated; occupational exposure controls based on legislation or guidance developed for occupational settings are used, as opposed to the conservative human health toxicity reference values (TRVs) for air adopted for this guidance. However, where subsurface chemicals are different than those used in the workplace or are a significant portion of worker exposure, it is recommended that the potential implications of vapour intrusion on worker safety be considered.

The intended users of this guidance are risk and exposure assessment professionals with some experience in vapour intrusion risk assessment.

### 3.0 CONCEPTUAL SITE MODEL

The vapour intrusion risk assessment can be implemented in sequential steps, starting with characterization of the contamination source through soil and groundwater sampling together with the data collection (hydrogeological and soil properties) needed to understand contaminant migration within both the unsaturated and saturated zones. The assessment should proceed to soil vapour sampling near to the contamination source, and where warranted, continue closer toward the building, and finally, if indicated by the results of previous steps, structure sampling (indoor air, subslab vapour, building properties).

The development of a conceptual site model (CSM) and consideration of data adequacy are especially important when screening out a site from the vapour intrusion process. A comprehensive evaluation using of multiple lines of evidence is recommended before drawing conclusions. These lines of evidence include concentrations in different media and locations along the anticipated migration pathway, and information on site conditions and factors that could influence vapour migration.

A CSM is a visual representation and narrative description of the physical, chemical, and biological processes occurring, or that have occurred, at a contaminated site. The CSM should be able to tell the story of how the site became contaminated, how the contamination was and is transported, where the contamination will ultimately end up, and whom it may affect. To the extent possible, the CSM should provide information on the three-dimensional nature of contamination and physical characteristics of the site, as supported by maps, cross-sections, and site diagrams.

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

- information on the source and history of contamination – concentrations, distribution and extent of the chemicals of concern in at least one of soil, groundwater, soil vapour, or indoor air, although data from at least two media are likely to be necessary;
- receptors that could be exposed to the contamination (under both present and future land use scenarios); and
- information on historical and current land uses, potential sources and types of volatile or semi-volatile contamination, and known and suspected releases or spills that may have occurred at the site.

The following information is required to assess vapour intrusion using this guidance. Some precluding factors that

will rule out the use of the model exist for quantitative screening, so it is imperative that site conditions are assessed and described adequately to determine if these factors are present at the site:

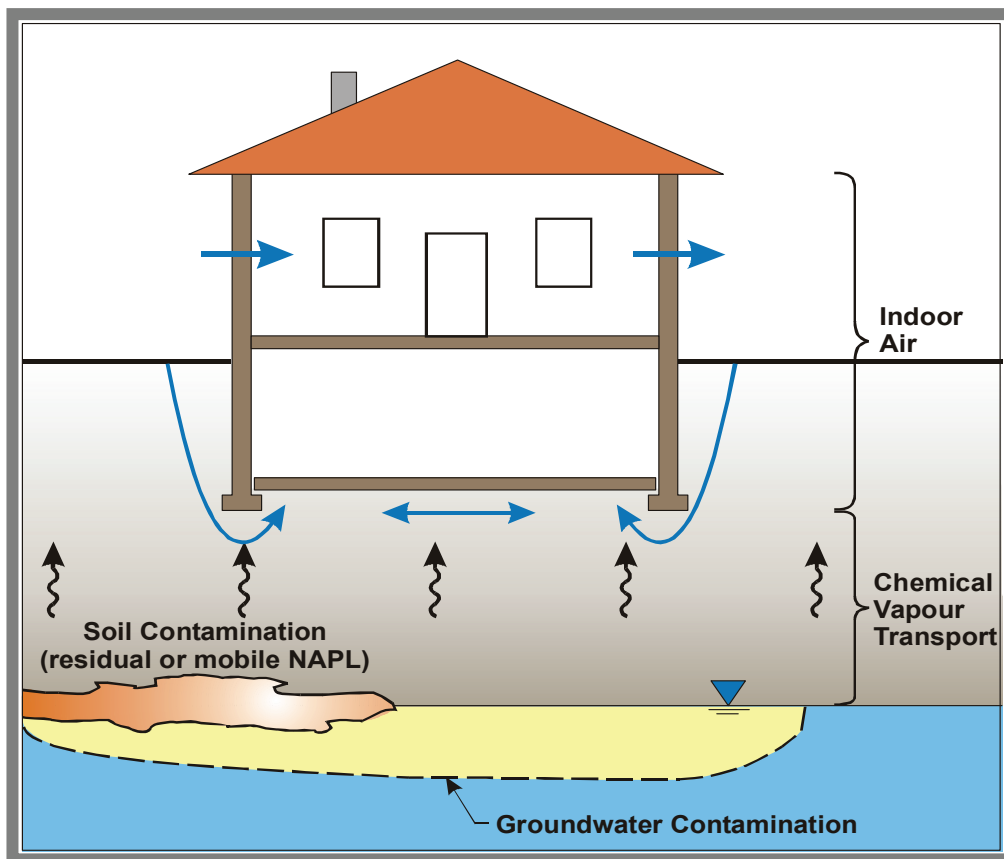
- form of contamination present (dissolved chemicals in groundwater, soil contamination, non-aqueous phase liquid [NAPL]);
- distance from the contamination to the building (vertical and lateral) – Shallow contamination (< 1 m from building foundation) should be noted. (To establish that contamination is at least 1 m from the building, concentration levels must be below the limit of detection at that distance. Professional judgment and experience may play a role in determining the edge of contamination.);
- sufficient information to determine if contamination is mobile;
- geological information, including soil units present at the site and type or textural classification for each soil unit (High permeability media, such as karst or cobbles should be noted.);
- location and characteristics of subsurface utilities, as these may form a preferential pathway from contamination to the building;
- land use (residential or commercial);
- information on buildings, including location, building size and height, foundation type (e.g. crawlspace, basement) and foundation characteristics (e.g. construction, utility penetrations, sumps) (Basements with earthen or wooden floors or foundations should be noted.); and
- information on background sources of volatile chemicals in indoor air, including indoor sources of volatile organic compounds (VOCs), and contaminated building materials.

Some additional information is likely to prove useful to describe fate and transport of contamination or plumes in a detailed quantitative risk assessment includes:

- hydrogeological information, including depth to groundwater, the groundwater flow direction, hydraulic conductivity, and lateral and vertical hydraulic gradients; and
- Vadose-zone soil properties, including water content, porosity, fraction organic carbon, bulk density, and soil-air permeability/

Figure 2.1 shows an example of a CSM for a residential site.

**Figure 2.1 Example Conceptual Site Model for Vapour Intrusion – Residential Site**



Note: NAPL, non-aqueous phase liquid.

Further guidance on site characterization is provided in the Health Canada *Guidance Manual for Environmental Site Characterization in Support of Human Health Risk Assessment* (HC, unpublished).

## 4.0 GUIDANCE FRAMEWORK

The guidance framework is presented in the flow chart in Figure 1.1. Note that even though Figure 1.1 gives a hazard quotient (HQ) < 1 as the acceptable risk level, this implies that all exposure pathways have been accounted for in the estimation of exposure.

### 4.1 Qualitative Screening

This screening step categorizes sites according to their potential for vapour intrusion. On the basis of this evaluation and the consideration of precluding factors, the user determines if the assessment should proceed to the quantitative assessment or if immediate action is needed to address unacceptable health risks at a site.

### 4.2 Quantitative Screening

The vapour attenuation ratio, predicted using the Johnson and Ettinger (1991) model, is used to predict indoor air concentrations. Concentrations measured in soil, groundwater, or soil vapour can be used to assess a site. **For the**

**quantitative screening attenuation charts to apply, the measurements must be taken at least 1 m depth below the building.**

If subslab vapour data are available, an appropriate subslab vapour attenuation factor (0.02) can be used to predict indoor air concentrations (Figure 1.1). Similarly, if indoor air quality measurements are available, these concentrations can be compared with acceptable air concentrations. However, due consideration should be given to the methodology and representativeness of the sampling and analysis program, and the possible effect of background sources of VOCs on indoor air concentrations. There can be background sources of the same chemicals either in ambient (outdoor) air or associated with indoor sources (e.g. building materials, consumer products, emissions) that are not due to subsurface contamination.

Standard equations are used to estimate health risk based on the predicted air concentration for carcinogenic and non-carcinogenic endpoints. Table 7.4 provides a matrix for risk management decisions based on predicted risks.

## 5.0 QUALITATIVE SCREENING

The qualitative screening is divided into two steps. The first step, comprising three questions, is designed to identify sites with a significant potential for human health or safety risks. Although beyond the scope of this guidance document, proper safety measures should be developed and implemented during site activities, as with any site assessment. The second step, comprising two questions, is designed to identify sites where the vapour intrusion pathway is not considered operable.

Sites that do not fall into either of the first two categories proceed to the quantitative screening step where a quantitative human health risk assessment is performed.

### Qualitative Screening – Questions 1, 2, and 3

These questions are used to identify sites with significant potential for adverse human health or safety risks, and where exposure controls are warranted.

**Question 1:** Are there buildings with wet basements or sumps in direct contact with contaminated groundwater, soil, and/or NAPL?

**Question 2:** Are there chemical odours reported by occupants that do not appear to be from indoor or ambient sources, and that could reasonably be originating from subsurface contamination?

**Question 3:** Have potentially explosive or acutely toxic gas concentrations been measured in the building or utility conduits, sumps, or drains connected to the building?

If the answer to any of the above questions is yes, immediate action should be taken to investigate and mitigate, if warranted, soil vapour risk and safety hazard. Based on the investigation, testing of indoor air quality, exposure controls, and/or relocation of receptors may be warranted. Where appropriate, emergency services should be contacted to deal with the immediate health hazard.

### Qualitative Screening – Questions 4 and 5

These questions identify sites where the soil vapour intrusion exposure pathway is not considered operable (i.e. potentially significant), based on the chemicals of potential concern, and where no quantitative risk assessment for vapour intrusion is warranted.

If the answer is no to Questions 4 and/or 5, then users should consider the vapour intrusion pathway inoperable.

**Question 4:** Are there volatile chemicals in groundwater or soil that could potentially pose an unacceptable risk based on their volatility and toxicity?

Table 5.1 lists chemicals commonly encountered at contaminated sites, along with their potential to be of concern for the vapour intrusion pathway. Compounds at contaminated sites that are classified as volatile/toxic in Table 5.1 should be considered contaminants of potential concern (COPCs) and be retained for further assessment. The list is not exhaustive, and users can conduct an assessment of toxicity and volatility using the methodology in Exhibit 1 if a chemical is not provided. The physical-chemical properties for a wide range of chemicals are provided in Table 4 within *Federal Contaminated Site Risk Assessment in Canada, Part II: Health Canada Toxicological Reference Values (TRVs) and Chemical-Specific factors, Version 2.0* (HC, 2010b) and in the *PQRA Spreadsheet Tool for Human Health Preliminary Quantitative Risk Assessment* (HC, 2008).

The screening method outlined in Exhibit 1 begins with prediction of the vapour concentration based on equilibrium partitioning theory using both the Henry's Law constant and pure chemical vapour pressure. The partitioning is described further in Section 7.0. The maximum vapour concentration predicted by these two approaches is divided by a dilution factor of 50 (alpha of 0.02), the minimum observed attenuation<sup>1</sup> between soil vapour and indoor air (U.S. EPA, 2008). The adjusted vapour concentration is compared with the target air concentration, based on conservative assumptions for exposure.

The target air concentration is calculated using the level of concern of an incremental cancer risk  $> 10^{-5}$  over a lifetime exposure or a hazard index for threshold toxicants  $> 0.2$  based on Health Canada guidance (HC, 2010a). It is assumed that the receptor is subject to a lifetime of exposure to the indoor air concentration predicted, using the maximum theoretical concentration in soil vapour and a conservative vapour attenuation factor.

**Question 5:** Are there current or potential future inhabited buildings within a 30 m distance of subsurface contamination?

Vapour concentrations decrease with increasing lateral or vertical distance from a subsurface vapour source until they reach negligible levels. The decrease in vapour concentrations is a function of contamination source size and geometry, soil properties, physical-chemical properties, and possible biological or chemical transformations within the subsurface environment.

In approximate terms, the available empirical data and modelling studies suggest that vapour concentrations will not

<sup>1</sup> 90th percentile value for filtered dataset.

be significant where contamination is beyond about 30 m lateral distance from inhabitable buildings (Mendoza, 1995; Lowell and Eklund, 2004; Abreu and Johnson, 2005).

**Contamination is defined here for screening purposes as detectable concentrations in groundwater or soil, and not necessarily above any guideline limit.**

There is little empirical data on vapour migration at sites with a deep vapour source below 30 m depth. For deep vapour sources, there will be vapour attenuation through diffusive and dispersive spreading of vapours. It is expected that a 30-m vertical distance criterion to determine when the vapour intrusion pathway is not operable is also reasonable.

The **distance criterion of 30 m should not be applied**, and buildings should be evaluated for vapour intrusion when at least one the following conditions exist at the site:

- **Significant preferential pathways** – Potentially significant preferential pathways are considered present at those sites where there is fractured bedrock, karst, vertical fissuring, or other media with unusually high gas permeability or sites where utility conduits directly connect the contamination source to the enclosed space of the building.
- **Gas under pressure** – The distance criterion does not account for the movement of gas under pressure; this is often the case at landfills where methane is produced and trace VOCs may move with the landfill gas.
- **Low permeability cover** – The distance criterion should not be applied when the ground surface between the contamination and building is covered with continuous or near-continuous concrete or asphaltic pavement of low permeability (or material with similar properties) because this barrier may prevent normal dissipation of the vapours and may enhance vapour migration toward the building. Frozen ground may also constitute a low permeability cover when a thaw bulb exists under buildings.
- **Expanding contamination zone** – It is assumed that the contamination plume or source zone is not expanding in size or migrating toward the building.

Table 5.1 Toxicity Factors and Results of Preliminary Screening for Volatility and Toxicity

Contaminant	Reference Dose (RfD)	Tolerable Concentration	Slope Factor		Unit Risk	Toxicological Reference Value Source	Classification	Target Indoor Air Concentrations: Non-Carcinogens	Target Indoor Air Concentrations: Carcinogens	Predicted Maximum Indoor Air Concentration	Exhibit 1 Determination
	mg/kg-day	note	(mg/kg-day) <sup>-1</sup>	note	(mg/m <sup>3</sup> ) <sup>-1</sup>	(mg/m <sup>2</sup> )		C <sub>air</sub> <sup>T</sup> (mg/m <sup>3</sup> )	C <sub>air</sub> <sup>T</sup> (mg/m <sup>3</sup> )	C <sub>air</sub> (mg/m <sup>3</sup> )	
Acetaldehyde	2.6E-03		7.7E-03		2.2E-03	RAIS	Carcinogen	-	4.5E-03	6.4E+04	Volatile/Toxic
Acetone	9.0E-01		1.79E+00		-	IRIS	Non Carcinogen	3.6E-01	-	3.2E+04	Volatile/Toxic
Acetonitrile	1.7E-02		3.40E-02		-	RAIS	Non Carcinogen	6.8E-03	-	1.6E+04	Volatile/Toxic
Acrolein	5.0E-04	oral	9.94E-04		-	IRIS	Non Carcinogen	2.0E-04	-	2.1E+04	Volatile/Toxic
Acrylonitrile	5.7E-04		1.13E-03		6.8E-02	RAIS	Carcinogen	-	1.5E-04	5.7E+03	Volatile/Toxic
Benzene	4.0E-03	oral	7.95E-03		3.3E-03	IRIS/Health Canada	Carcinogen	-	3.0E-03	8.3E+03	Volatile/Toxic
Benzyl chloride	1.7E-01	oral	3.38E-01		4.9E-03	IRIS/RAIS	Carcinogen	-	2.0E-03	1.8E+02	Volatile/Toxic
1,1-Biphenyl	5.0E-02	oral	2.22E-01		-	IRIS	Non Carcinogen	4.4E-02	-	1.8E+00	Volatile/Toxic
Bis(2-chloroethyl)ether			-	1.1E+00	2.5E-01	IRIS	Carcinogen	-	4.0E-05	2.5E+02	Volatile/Toxic
Bis(2-chloroisopropyl)ether	4.0E-02	oral	7.95E-02		-	RAIS	Non Carcinogen	1.6E-02	-	2.4E+03	Volatile/Toxic
Bis(chloromethyl)ether			-	4.1E+01	9.4E+00	Health Canada	Carcinogen	-	1.1E-06	3.6E+04	Volatile/Toxic
Bis(2-chloro-1-methylethyl)ether	4.0E-02	oral	1.77E-01		1.0E-02	IRIS/RAIS	Carcinogen	-	1.0E-03	1.6E+02	Volatile/Toxic
Bromobenzene	2.9E+00		5.69E+00		-	RAIS	Non Carcinogen	1.1E+00	-	1.4E+03	Volatile/Toxic
Bromodichloromethane	2.0E-02	oral	8.86E-02	6.2E-02	1.4E-02	IRIS	Carcinogen	-	7.1E-04	1.0E+04	Volatile/Toxic
Bromomethane	1.4E-03		2.84E-03		-	IRIS	Non Carcinogen	5.7E-04	-	1.7E+05	Volatile/Toxic
1,3-Butadiene	5.7E-04		1.13E-03		-	RAIS	Non Carcinogen	2.3E-04	-	1.3E+05	Volatile/Toxic
n-Butylbenzene			-		-		Not Evaluated	-	-	1.5E+02	Not Evaluated
sec-Butylbenzene			-		-		Not Evaluated	-	-	2.6E+02	Not Evaluated
tert-Butylbenzene			-		-		Not Evaluated	-	-	3.1E+02	Not Evaluated
Carbon disulfide	1.0E-01	oral	1.99E-01		-	IRIS	Non Carcinogen	4.0E-02	-	3.0E+04	Volatile/Toxic
Carbon tetrachloride			4.9E-02		1.1E-02	Health Canada	Carcinogen	-	9.0E-04	1.9E+04	Volatile/Toxic
2-Chloroacetophenone	8.6E-06		1.71E-05		-		Non Carcinogen	3.4E-06	-	1.4E+04	Volatile/Toxic
Chlorobenzene			1.00E-02		-	Health Canada	Non Carcinogen	2.0E-03	-	1.5E+03	Volatile/Toxic
2-Chloro-1,3-butadiene	2.0E-03		3.98E-03		-	IRIS	Non Carcinogen	8.0E-04	-	2.1E+04	Volatile/Toxic
Chloroethane			-		-		Not Evaluated	-	-	7.1E+04	Not Evaluated
Chloroform	1.0E-02	oral	1.99E-02		2.3E-02	IRIS/RAIS	Carcinogen	-	4.3E-04	2.6E+04	Volatile/Toxic
Chloromethane	2.6E-02		5.11E-02	6.3E-03	1.8E-03	RAIS	Carcinogen	-	5.6E-03	2.4E+05	Volatile/Toxic
beta-Chloronaphthalene	8.0E-02	oral	1.59E-01		-	IRIS	Non Carcinogen	3.2E-02	-	3.1E+00	Volatile/Toxic
o-Chloronitrobenzene	2.0E-05		3.98E-05		7.1E-04	RAIS	Carcinogen	-	1.4E-02	4.1E+01	Volatile/Toxic
p-Chloronitrobenzene	1.7E-04		3.40E-04		5.1E-04	RAIS	Carcinogen	-	2.0E-02	4.1E+01	Volatile/Toxic

Contaminant	Reference Dose (RfD)	Tolerable Concentration	Slope Factor		Unit Risk	Toxicological Reference Value Source	Classification	Target Indoor Air Concentrations: Non-Carcinogens	Target Indoor Air Concentrations: Carcinogens	Predicted Maximum Indoor Air Concentration	Exhibit 1 Determination
2-Chlorophenol	5.0E-03	oral	9.94E-03		-	IRIS	Non Carcinogen	2.0E-03	-	7.0E+03	Volatile/Toxic
2-Chloropropane	2.9E-02		5.69E-02		-	RAIS	Non Carcinogen	1.1E-02	-	4.5E+04	Volatile/Toxic
o-Chlorotoluene	2.0E-02	oral	3.98E-02		-	IRIS	Non Carcinogen	8.0E-03	-	1.3E+03	Volatile/Toxic
Crotonaldehyde			-		-		Not Evaluated	-	-	4.0E+03	Not Evaluated
Cumene (isopropylbenzene)	1.1E-01		2.27E-01		-	IRIS	Non Carcinogen	4.5E-02	-	6.0E+02	Volatile/Toxic
Cyanide (hydrogen)	2.0E-02	oral	3.98E-02		-	HC (provisional)	Non Carcinogen	8.0E-03	-	1.1E+05	Volatile/Toxic
Cyanogen	4.0E-02	oral	7.95E-02		-	RAIS	Non Carcinogen	1.6E-02	-	2.5E+05	Volatile/Toxic
Cyanogen bromide	9.0E-02	oral	3.99E-01		-	IRIS	Non Carcinogen	8.0E-02	-	3.6E+04	Volatile/Toxic
Cyanogen chloride	5.0E-02	oral	2.22E-01		-	IRIS	Non Carcinogen	4.4E-02	-	3.6E+04	Volatile/Toxic
Cyclohexane			-		-		Not Evaluated	-	-	9.1E+03	Not Evaluated
C6-C8 Aliphatics		oral	4.00E+02		-	TPHCWG	Non Carcinogen	8.0E+01	-	5.5E+03	Volatile/Toxic
C8-C10 Aliphatics		oral	1.84E+04		-	TPHCWG	Non Carcinogen	3.7E+03	-	7.0E+02	Volatile/Toxic
C10-C12 Aliphatics		oral	1.00E+03		-	TPHCWG	Non Carcinogen	2.0E+02	-	8.4E+01	Volatile/Toxic
C6-C8 Aromatics		oral	4.00E+02		-	TPHCWG	Non Carcinogen	8.0E+01	-	2.9E+03	Volatile/Toxic
C8-C10 Aromatics		oral	2.00E+02		-	TPHCWG	Non Carcinogen	4.0E+01	-	6.7E+02	Volatile/Toxic
C10-C12 Aromatics		oral	-		-	TPHCWG	Not Evaluated	-	-	7.3E+01	Not Evaluated
C12-C16 Aromatics		oral	-		-		Not Evaluated	-	-	1.1E+04	Not Evaluated
n-Decane	1.3E+00	inhal	2.64E+00			STAATS	Non Carcinogen	5.3E-01	-	2.0E+02	Volatile/Toxic
Dibenzofuran	4.0E-03	oral	7.95E-03		-	RAIS	Non Carcinogen	1.6E-03	-	4.7E-01	Volatile/Toxic
Dibromochloromethane	2.0E-02	oral	3.98E-02		-	IRIS	Non Carcinogen	8.0E-03	-	3.6E+03	Volatile/Toxic
1,2-Dibromo-3-chloropropane	5.7E-05		1.14E-04		6.9E-04	RAIS	Carcinogen	-	1.4E-02	1.5E+02	Volatile/Toxic
1,2-Dibromomethane	9.0E-03	oral	9.00E-03		6.0E-01	Health Canada	Carcinogen	-	1.7E-05	2.4E+03	Volatile/Toxic
1,2-Dichlorobenzene	4.3E-01	oral	8.55E-01		-	Health Canada	Non Carcinogen	1.7E-01	-	2.5E+02	Volatile/Toxic
1,3-Dichlorobenzene			-		-		Not Evaluated	-	-	3.6E+02	Not Evaluated
1,4-Dichlorobenzene	1.1E-01	oral	9.50E-02	inhal	2.1E-02	Health Canada	Carcinogen	-	4.7E-04	2.9E+02	Volatile/Toxic
Dichlorodifluoromethane	2.0E-01		3.98E-01		-	IRIS	Non Carcinogen	8.0E-02	-	6.5E+05	Volatile/Toxic
1,1-Dichloroethane	1.4E-10		2.84E-10		-	RAIS	Non Carcinogen	5.7E-11	-	2.5E+04	Volatile/Toxic
1,2-Dichloromethane	5.0E-02	oral	2.22E-01	inhal	2.3E-05	Health Canada	Carcinogen	-	4.3E-01	3.9E+04	Volatile/Toxic
1,1-Dichloroethylene	3.0E-03	oral	5.96E-03		5.0E-02	RAIS	Carcinogen	-	2.0E-04	6.8E+04	Volatile/Toxic
1,2-Dichloroethylene(cis)	1.0E-02		1.99E-02		-	IRIS	Non Carcinogen	4.0E-03	-	2.2E+04	Volatile/Toxic
1,2-Dichloroethylene(trans)	2.0E-02		3.98E-02		-		Non Carcinogen	8.0E-03	-	4.8E+04	Volatile/Toxic
1,2-Dichloropropane	1.4E-04		4.00E-04		1.5E-02	IRIS	Carcinogen	-	6.5E-04	6.5E+03	Volatile/Toxic



Contaminant	Reference Dose (RfD)	Tolerable Concentration	Slope Factor	Unit Risk	Toxicological Reference Value Source	Classification	Target Indoor Air Concentrations: Non-Carcinogens	Target Indoor Air Concentrations: Carcinogens	Predicted Maximum Indoor Air Concentration	Exhibit 1 Determination
1,3-Dichloropropene	3.0E-04	2.00E-02	1.8E-02	4.1E-03	IRIS	Carcinogen	-	2.5E-03	4.1E+04	Volatile/Toxic
Dicyclopentadiene	5.7E-03	1.14E-02		-	RAIS	Non Carcinogen	2.3E-03	-	1.6E+04	Volatile/Toxic
Dimethylamine		-		-		Not Evaluated	-	-	7.7E+04	Not Evaluated
Epichlorohydrin	2.9E-04	5.69E-04		1.2E-03	RAIS	Carcinogen	-	8.3E-03	1.7E+03	Volatile/Toxic
Ethyl acetate	9.0E-01	1.79E+00		-	IRIS	Non Carcinogen	3.6E-01	-	9.1E+03	Volatile/Toxic
Ethyl acrylate		-		1.4E-03	RAIS	Carcinogen	-	7.1E-03	4.3E+03	Volatile/Toxic
Ethylbenzene	1.0E-01	1.00E+00	-	-	Health Canada	Non Carcinogen	2.0E-01	-	1.2E+03	Volatile/Toxic
Ethyl chloride	2.9E+00	5.69E+00		-	RAIS	Non Carcinogen	1.1E+00	-	7.3E+04	Volatile/Toxic
Ethylene oxide		-	3.5E-01	1.0E-01	RAIS	Carcinogen	-	1.0E-04	6.2E+06	Volatile/Toxic
Ethyl ether	2.0E-01	3.98E-01		-	IRIS	Non Carcinogen	8.0E-02	-	4.4E+04	Volatile/Toxic
Ethyl methacrylate	9.0E-02	1.79E-01		-	RAIS	Non Carcinogen	3.6E-02	-	4.0E+03	Volatile/Toxic
Furan	1.0E-03	1.99E-03		-	IRIS	Non Carcinogen	4.0E-04	-	4.5E+04	Volatile/Toxic
n-Hexane		7.00E-01		-	Health Canada	Non Carcinogen	1.4E-01	-	1.4E+04	Volatile/Toxic
Isobutanol	3.0E-01	5.96E-01		-	IRIS	Non Carcinogen	1.2E-01	-	1.6E+03	Volatile/Toxic
Maleic hydrazide	5.0E-01	9.94E-01		-	IRIS	Non Carcinogen	2.0E-01	-	3.2E+04	Volatile/Toxic
Methacrylonitrile	1.0E-04	1.99E-04		-	IRIS	Non Carcinogen	4.0E-05	-	5.7E+03	Volatile/Toxic
Methomyl	2.5E-02	4.97E-02		-	IRIS	Non Carcinogen	9.9E-03	-	5.4E+06	Volatile/Toxic
Methyl acetate	1.0E+00	1.99E+00		-	RAIS	Non Carcinogen	4.0E-01	-	1.8E+04	Volatile/Toxic
Methyl acrylate	3.0E-02	5.96E-02		-	RAIS	Non Carcinogen	1.2E-02	-	1.2E+04	Volatile/Toxic
Methylcyclohexane	8.6E-01	1.70E+00		-	RAIS	Non Carcinogen	3.4E-01	-	5.0E+03	Volatile/Toxic
Methylene bromide	1.4E-03	5.00E-03		-	IRIS	Non Carcinogen	1.0E-03	-	8.9E+03	Volatile/Toxic
Methylene chloride	6.0E-02	3.00E+00	7.5E-03	1.7E-03	IRIS	Carcinogen	-	5.9E-03	4.1E+04	Volatile/Toxic
Methyl ethyl ketone	6.0E-01	1.19E+00		-	IRIS	Non Carcinogen	2.4E-01	-	7.3E+03	Volatile/Toxic
Methyl isobutyl ketone	8.6E-01	1.70E+00		-	RAIS	Non Carcinogen	3.4E-01	-	2.2E+03	Volatile/Toxic
Methyl methacrylate	1.4E+00	5.20E-02		-	IRIS	Non Carcinogen	1.0E-02	-	4.3E+03	Volatile/Toxic
Methyl styrene (mixture)	1.1E-02	2.27E-02		-	RAIS	Non Carcinogen	4.5E-03	-	5.6E+02	Volatile/Toxic
Methyl styrene (alpha)		-		-		Not Evaluated	-	-	5.6E+02	Not Evaluated
Methyl tertbutyl ether MTBE	1.0E-02	3.70E-02		-	Health Canada	Non Carcinogen	7.4E-03	-	7.2E+04	Volatile/Toxic
Nitrobenzene	5.0E-04	9.94E-04		-	IRIS	Non Carcinogen	2.0E-04	-	4.1E+01	Volatile/Toxic
N-Nitrosodi-n-butylamine	5.7E-04	1.14E-03		1.6E-01	RAIS	Carcinogen	-	6.3E-05	3.4E+02	Volatile/Toxic
m-Nitrotoluene	5.7E-04	2.53E-03		-	RAIS	Non Carcinogen	5.1E-04	-	4.1E+01	Volatile/Toxic
o-Nitrotoluene	5.7E-04	2.53E-03		-	RAIS	Non Carcinogen	5.1E-04	-	4.1E+01	Volatile/Toxic
p-Nitrotoluene	5.7E-04	2.53E-03		-	RAIS	Non Carcinogen	5.1E-04	-	4.1E+01	Volatile/Toxic
Polychlorinated Biphenyls (total)	1.3E-01	2.58E-01	2.0E+00	5.7E-01	Health Canada	Carcinogen	-	1.8E-05	4.2E+08	Volatile/Toxic
Polynuclear aromatic										

Contaminant	Reference Dose (RfD)	Tolerable Concentration	Slope Factor	Unit Risk	Toxicological Reference Value Source	Classification	Target Indoor Air Concentrations: Non-Carcinogens	Target Indoor Air Concentrations: Carcinogens	Predicted Maximum Indoor Air Concentration	Exhibit 1 Determination
<u>hydrocarbons</u>										
Acenaphthene	6.0E-02	1.19E-01		-	IRIS	Non Carcinogen	2.4E-02	-	6.0E-01	Volatile/Toxic
Acenaphthylene		-	-	-	-	Not Evaluated	-	-	1.6E+00	Not Evaluated
Anthracene	3.0E-01	5.96E-01		-	IRIS	Non Carcinogen	1.2E-01	-	2.0E-03	Not
Benzo[a]anthracene		-	3.1E-01	8.8E-02	RAIS	Carcinogen	-	1.1E-04	4.8E-04	Volatile/Toxic
Benzo[k]fluoranthene		-	5.5E-03	1.3E-03	Health Canada	Carcinogen	-	7.7E-03	3.8E-07	Not
Benzo[b]fluoranthene		-	8.2E-03	1.9E-03	Health Canada	Carcinogen	-	5.3E-03	1.4E-04	Volatile/Toxic
Benzo[g,h,i]perylene	-	-			RAIS	-	-	-	1.4E+07	Not Evaluated
Benzo[a]pyrene		-	1.4E-01	3.1E-02	Health Canada	Carcinogen	-	3.2E-04	6.1E-07	Not
Benzo[g,h,i]perylene		-	-	-	-	-	-	-	1.7E-06	Not Evaluated
Chrysene		8.80E-04	3.1E-03	8.8E-04	RAIS	Carcinogen	-	1.1E-02	8.6E-06	Not
Dibenz[a,h]anthracene		-	3.1E+00	8.8E-01	RAIS	Carcinogen	-	1.1E-05	1.1E-07	Volatile/Toxic
Fluoranthene	4.0E-02 oral	7.95E-02	-		IRIS	Non Carcinogen	1.6E-02	-	2.1E-03	Not
Fluorene	4.0E-02 oral	7.95E-02	4.0E-02	9.0E-03	IRIS	Carcinogen	-	1.1E-03	1.6E+00	Volatile/Toxic
Indeno(1,2,3-c,d)pyrene		-	3.1E-01	8.8E-03	RAIS	Carcinogen	-	1.1E-03	5.4E-08	Not
Naphthalene	2.0E-02	3.00E-03		-	Health Canada	Non Carcinogen	6.0E-04	-	1.2E+01	Volatile/Toxic
Phenanthrene		-				-	-	-	4.0E-02	Not Evaluated
Pyrene	3.0E-02	5.96E-02		-	Health Canada	Non Carcinogen	1.2E-02	-	1.3E-03	Not
Propylene oxide	8.6E-03	1.70E-02		3.7E-03	RAIS	Carcinogen	-	2.7E-03	3.5E+04	Volatile/Toxic
Styrene	1.2E-01 oral	9.20E-02		-	Health Canada	Non Carcinogen	1.8E-02	-	7.1E+02	Volatile/Toxic
1,1,1,2-Tetrachloroethane	3.0E-02	5.96E-02		7.4E-04	IRIS	Carcinogen	-	1.4E-02	5.9E+03	Volatile/Toxic
1,1,2,2-Tetrachloroethane	6.0E-02	1.19E-01		5.8E-03	IRIS	Carcinogen	-	1.7E-03	2.5E+03	Volatile/Toxic
Tetrachloroethylene (PCE)	1.4E-02 oral	3.60E-01		-	Health Canada	Non Carcinogen	7.2E-02	-	3.5E+03	Volatile/Toxic
Tetrahydrofuran		-		-		Not Evaluated	-	-	5.8E+04	Not
Toluene	2.2E-01 oral	3.80E+00		-	Health Canada	Non Carcinogen	7.6E-01	-	2.9E+03	Evaluated
1,2,4-Trichlorobenzene	1.6E-03 oral	7.00E-03		-	Health Canada	Non Carcinogen	1.4E-03	-	3.5E+02	Volatile/Toxic

Contaminant	Reference Dose (RfD)	Tolerable Concentration	Slope Factor	Unit Risk	Toxicological Reference Value Source	Classification	Target Indoor Air Concentrations: Non-Carcinogens	Target Indoor Air Concentrations: Carcinogens	Predicted Maximum Indoor Air Concentration	Exhibit 1 Determination
1,1,1-Trichloroethane	2.0E+00	3.98E+00		-	IRIS	Non Carcinogen	8.0E-01	-	1.8E+04	Volatile/Toxic
1,1,2-Trichloroethane	4.0E-03	7.95E-03	5.7E-02	1.3E-02	IRIS	Carcinogen	-	7.8E-04	3.3E+03	Volatile/Toxic
Trichloroethylene (TCE)	1.5E-03	2.90E-03	8.1E-04	1.8E-04	Health Canada	Carcinogen	-	5.5E-02	1.0E+04	Volatile/Toxic
Trichlorofluoromethane	3.0E-01	5.96E-01		-	IRIS	Non Carcinogen	1.2E-01	-	1.3E+05	Volatile/Toxic
1,1,2-Trichloropropane	5.0E-03	9.94E-03		-	IRIS	Non Carcinogen	2.0E-03	-	6.5E+04	Volatile/Toxic
1,2,3-Trichloropropane	6.0E-03	1.19E-02		-	IRIS	Non Carcinogen	2.4E-03	-	7.6E+02	Volatile/Toxic
1,2,3-Trichloropropene	6.0E-03	1.19E-02		-	Health Canada	Non Carcinogen	2.4E-03	-	3.9E+04	Volatile/Toxic
Triethylamine	2.0E-03	3.98E-03		-	RAIS	Non Carcinogen	8.0E-04	-	1.2E+05	Volatile/Toxic
1,2,4-Trimethylbenzene	1.7E-03	3.38E-03		-	RAIS	Non Carcinogen	6.8E-04	-	2.9E+02	Volatile/Toxic
1,3,5-Trimethylbenzene	1.7E-03	3.40E-03		-	RAIS	Non Carcinogen	6.8E-04	-	3.4E+02	Volatile/Toxic
Vinyl acetate	5.7E-02	1.14E-01		-	RAIS	Non Carcinogen	2.3E-02	-	8.6E+03	Volatile/Toxic
Vinyl bromide	8.6E-04	1.70E-03	1.1E-01	3.2E-02	RAIS	Carcinogen	-	3.1E-04	1.8E+05	Volatile/Toxic
Vinyl chloride		-	2.6E-01	8.8E-03	Health Canada	Carcinogen	-	1.1E-03	2.1E+05	Volatile/Toxic
Xylenes	1.5E+00	1.80E-01		-	Health Canada	Non Carcinogen	3.6E-02	-	9.8E+02	Volatile/Toxic

Note: Oral reference values were used in the absence of an inhalation value with no correction for bioavailability

#### Sources

Region 9 - US EPA Preliminary Remediation Goals Table of Physical and Chemical Properties

RAIS - Risk Assessment Information System on-line database searched 2004

Health Canada (HC, 2010b)

HEAST - Health Effects Assessment Summary Tables

IRIS - Integrated Risk Information System database searched 2004

TPHCWG - Total Petroleum Hydrocarbon Working Group

CCME Canada Wide Standards Technical Document

Mackay And Shiu 1991 -1992 (Volume I-III)

MSDS sheet

## 6.0 QUANTITATIVE SCREENING – PRECLUDING FACTORS

The vapour attenuation factors in this guidance are developed using the J&E model. When the conditions outlined below exist at a site, quantitative screening falls outside of the conceptual site model described by the J&E model. The quantitative screening process cannot be used to make any valid statements about vapour intrusion at sites with the following conditions:

**Shallow depth to contamination** – Sites with a contamination source within 1 m of the building foundation should be precluded from quantitative screening. When the contamination source is within 1 m of the building, the vapour attenuation factors used for this guidance are unreliable as a result of seasonal water-table fluctuations, the varying thickness of the tension-saturated zone (capillary fringe), which will depend on soil texture, and the possible presence of sumps in basements.

**Earthen basements** – Buildings with earthen or wooden basements that do not have an intact vapour barrier should be precluded from quantitative screening, unless the depth to the contamination source is greater than 5 m. This is a conservative estimate of the depth at which transport processes within the soil zone control the vapour flux into the building, as opposed to the building foundation characteristics.

**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 be precluded from the quantitative screening, 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 CSM described by the J&E model.

**Subsurface utility conduit connecting contamination source and building** – Common anthropogenic features such as floor drains, sewer lines, and utility conduits are not normally considered a precluding factor. However, if any of these features directly connects the contamination source to the enclosed space of the building, sites cannot be screened based on distance from contamination to building.

When the above precluding factors apply at a site, it will be necessary to perform a more in-depth assessment. For sites where high permeability media is the precluding factor, it may be appropriate to use a subslab-to-indoor air attenuation factor (0.02) to estimate indoor air concentrations, as indicated in Figure 1.1. Subslab vapour measurements alone will not be adequate to address sites with preferential pathways or earthen or wooden basements. Such sites will require a detailed risk assessment, typically comprising site-specific modelling and indoor air measurements in addition to subslab vapour measurements.

The presence or suspected presence of NAPL below or near to the building is not considered to be a precluding factor for quantitative screening, 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 location of the NAPL source and the NAPL distribution.

Care should be exercised when applying quantitative screening to **sites in Arctic or sub-Arctic** regions. Recent studies at Brochet, Manitoba (FSD, 2008) have shown that, even with deep frost penetration external to the building, there was a thaw bulb underneath the building and detectable vapours. In Arctic or sub-Arctic regions, thaw bulbs may form under any heated building without an insulated foundation, and may result in a preferential pathway.

**EXHIBIT 1. SCREENING PROCESS TO DETERMINE IF CHEMICAL IS VOLATILE****1. Estimate Maximum Vapour Concentration**

NAPL Present:  $C_v^{\text{NAPL}} = \text{UCF}_1 * \text{MW} * \text{P} / (\text{R} * \text{T})$   
 No NAPL Present:  $C_v^{\text{NO NAPL}} = \text{UCF}_2 * \text{S} * \text{H}'$   
 Maximum Vapour Concentration:  $C_v = \text{Max} (C_v^{\text{NAPL}}, C_v^{\text{NO NAPL}})$

Parameter	Default
$C_v^{\text{NAPL}}$ = Vapour concentration NAPL is present (mg/m <sup>3</sup> )	Calculated
$\text{UCF}_1$ = Unit conversion factor (mg/g)	1,000
MW = Molecular weight (g/mole)	Chemical specific
P = Pure chemical vapour pressure (atm)	Chemical specific
R = Gas constant (m <sup>3</sup> -atm/K-mole )	8.21 E-05
T= Absolute temperature (K, 273°C + T(°C))	298*
$C_v^{\text{NO NAPL}}$ = Vapour concentration NAPL not present (mg/m <sup>3</sup> )	Calculated
$\text{UCF}_2$ = Unit conversion factor (L/m <sup>3</sup> )	1,000
S = Pure chemical aqueous solubility (mg/L)	Chemical specific
H' = Dimensionless Henry's Law constant	Chemical specific
$C_v$ = Concentration in soil vapour (mg/m <sup>3</sup> )	Calculated

**2. Calculate Maximum Indoor Air Concentration**

$C_{\text{air}} = C_v * \alpha$  where  $\alpha = 0.02 = 1/\text{DL}$  and DL = dilution factor

**3. Calculate Target Air Concentration<sup>2</sup>**

*Carcinogen*

$C_{\text{air}}^{\text{T}} = \text{ILCR}^{\text{T}} / (\text{UR} * \text{t})$

**Note:** To convert from SF to UR, use:  $\text{UR} = \text{SF} (\text{mg/kg/day})^{-1} * \text{IR}/\text{BW}$  (use IR and BW for adult for screening purposes)

*Non-carcinogen* ( $\text{TC}_{\text{air}} = \text{RfC}$  ;  $\text{TDI} = \text{RfD}$ )

$C_{\text{air}}^{\text{T}} = \text{HQT} * \text{TC}_{\text{air}} / \text{t}$

<sup>2</sup> To simplify the process of estimating risk for screening, carcinogens are screened using a unit risk value and non-carcinogens are calculated using a tolerable concentration. It is recognized that this process is not necessarily applicable for all receptors (i.e. conversion assumes an adult for carcinogenic effects and a toddler for non-carcinogenic effects); however, it is used for screening. More detailed calculations are provided for estimating risk in the secondary screening process.

**Note:** To convert from TDI to TC, use:  $TC = TDI \text{ (mg/kg-day)} * BW/IR$  (use BW and IR for toddler for screening purposes)

**Note:** It is preferable to have the soil temperature match the temperature at which the Henry's constant is measured. Because most Henry's constants are measured at 25°C, this temperature was selected as the default for the partitioning equation.

Parameter	Default
$C_{AIR}^T$ = Target concentration of contaminant in air (mg/m <sup>3</sup> )	Calculated
$DR_{IHV}$ = Dose rate from inhalation of volatiles (mg/kg (BW)-day)	Calculated
$ILCR^T$ = Target incremental lifetime cancer risk (dimensionless)	10 <sup>-5</sup>
$UR$ = Unit risk factor (mg/ m <sup>3</sup> ) <sup>-1</sup>	Chemical specific
$t$ = Fraction of time exposed (dimensionless)	1.0
$HQ^T$ = Target hazard quotient	0.2
$SF$ = Slope factor (mg/kg-day) <sup>-1</sup>	Chemical specific
$IR$ = Receptor air intake rate (m <sup>3</sup> /day) (adult carcinogens)	15.8
$BW$ = Body weight (kg) (adult carcinogens)	70.7
$TDI$ = Tolerable daily intake (mg/kg-day)	Chemical specific
$BW$ = Body weight (kg) (toddler non-carcinogens)	16.5
$IR$ = Receptor air intake rate (m <sup>3</sup> /day) (toddler non-carcinogens)	9.3

#### 4. Determine If Chemical Is Volatile and Sufficiently Toxic

If  $C_{air} \geq C_{air}^T$  then chemical is considered volatile for purpose of vapour SLRA and is retained for the quantitative screening process

If  $C_{air} < C_{air}^T$  then chemical is not considered volatile for purpose of vapour SLRA and this pathway is not considered operable

## 7.0 QUANTITATIVE SCREENING PROCESS

The goal of quantitative screening is to estimate an indoor air concentration, for sites with no precluding factors, and use that estimate to calculate potential human health risk. A three-step process is followed to predict health risk.

1. The vapour concentration near the contamination source is either measured or estimated using partitioning relationships and the concentration in groundwater, soil, or NAPL.
2. The indoor air concentration is predicted using a vapour attenuation factor selected based on depth to vapour source, soil type, and building type. The vapour attenuation factor incorporates chemical transport in the unsaturated zone, vapour intrusion into the building, and mixing of vapours inside the building.
3. The HQs and/or incremental lifetime cancer risk is predicted, based on the predicted indoor air concentrations and chemical toxicity.

### Data Quality

Data adequacy is critical when evaluating vapour intrusion. Sufficient data should be obtained to characterize the spatial variability in groundwater and soil vapour concentrations such that a reasonably detailed CSM describing the distribution and extent of contamination can be developed. As a minimum:

1. Groundwater and soil vapour concentrations should be characterized on at least two sides of each individual building to be assessed at a site.
2. A minimum of two sampling events should take place to characterize seasonal variability.
3. Contamination source areas should be evaluated to characterize maximum concentrations. The quantitative screening of the site should be conducted using the maximum concentration.

The site investigation design and interpretation should establish multiple lines of evidence, including:

- source characterization;
- testing of the environmental quality of different media and locations (soil, groundwater, soil vapour, slab, and indoor air, as warranted); and

- obtaining information on hydrogeological, chemical, and biological conditions.

Hydrogeological and biological conditions can be of significant importance; for example, the potential for vapour intrusion may be limited when there is a freshwater lens at the water table (for a dissolved source), fine-grained soil layers with high moisture content in the vadose zone, or bioattenuation of hydrocarbon vapours.

Reasonably conservative parameters for source concentration, soil type and depth should be input into the model for estimating the vapour attenuation factor. For screening purposes, the maximum near-building concentration should generally be used as opposed to, for example, an average concentration for multiple samples obtained surrounding a building.

Further guidance on site characterization for evaluation of vapour intrusion is provided in the Health Canada *Guidance Manual for Environmental Site Characterization in Support of Human Health Risk Assessment* (HC, unpublished).

### 7.1 Step 1: Obtain Data Required for Quantitative

As shown in Figure 1.1, the first step in the screening process is site characterization. The preference of this guidance is for the use of both groundwater (when dissolved source) and soil vapour for evaluation of soil vapour intrusion. Use of soil data alone is not recommended for the quantitative screening process, but it will be accepted as part of the PQRA scoring process under the Federal Contaminated Sites Action Plan.

#### 7.1.1 Groundwater data

Groundwater samples should be taken near the water table. Transfer from groundwater to soil vapour occurs when chemicals in pore water volatilize into soil gas in the capillary transition zone above the water table.

The use of relatively short well screens, 1–2 m in length, situated across the water table is recommended when evaluating the soil vapour intrusion pathway. Longer well screens increase the blending of groundwater across the screened interval.

Because hydrogeologic systems can undergo changes, contaminants at depth within groundwater systems could pose future vapour intrusion potential. Ideally, groundwater characterization programs should also include investigation of vertical concentration variability either through the use of nested wells (at different elevations) or vertical profiling using a Geoprobe or similar groundwater sampling technique.

When small-scale discrete samples are analyzed (i.e. Geoprobe method), the concentration data for a sample taken at the water table could potentially be non-conservative if there are changes in the water-table elevation or the vertical concentration profile. For this reason, it is recommended that the maximum concentration measured in groundwater within 2 m of the water table be used for screening purposes.

Groundwater and soil vapour characterization programs should include analysis for transformation or degradation products associated with the COPCs (e.g. daughter products of tetrachloroethene [perchloroethylene]). Possible time-dependent variation in exposure concentrations for such COPCs should be considered when using this guidance.

### 7.1.2 Soil vapour data

Sampling soil vapour bypasses groundwater-/soil-to-air partitioning calculations, and provides a more direct indication of source vapour concentrations. Deeper soil vapour samples are least affected by spatial and temporal variability. The minimum depth for collection of external soil gas samples is 1 m below the foundation base (Figure 7.1), but it is recommended that external soil vapour samples be obtained at a depth equal to **at least** half the distance between the building foundation base and contamination source. A maximum lateral distance of 10 m from the building is recommended.

Whenever feasible, consideration should be given to the collection of soil vapour samples from below the building.

For both below- and beside-building samples, installing clusters of probes at multiple depths to evaluate vertical concentration profiles provides a means of corroborating the quality of the data and more fully developing the CSM.

Multiple lines of evidence should be used as a cross-check to assess the quality of soil vapour measurements. These can include the following:

- When there is a dissolved groundwater source, the measured deep soil vapour concentrations can be compared with those predicted from groundwater, accounting for attenuation of chemicals through the capillary transition zone. Much lower measured than predicted soil vapour concentrations may indicate negatively biased concentrations.
- Vertical soil vapour concentration profiles should indicate decreasing concentrations from a source zone.
- When there are sufficient data, contouring of the soil vapour concentrations may indicate anomalous data.

- Higher-than-expected oxygen concentrations and lower-than-expected carbon dioxide concentrations (i.e. based on expected biogeochemical conditions) may indicate a negatively biased sample through short-circuiting of atmospheric air.

The design of soil vapour characterization programs, particularly at sites with deep vadose zones and multiple depth samples, should consider possible temporal changes in vapour concentrations due to transient vapour migration or changing source concentrations. Sorption and biodegradation can delay the development of steady-state vapour concentration profiles. Nomographs that enable estimation of the approximate time for vapour concentrations to reach steady-state conditions are provided by Johnson et al. (1998) and the American Petroleum Institute (2004).

Recognizing that site characterization programs are often completed in stages, and that the first stage for a dissolved source is often limited to groundwater sampling (i.e. does not include soil vapour), the need for soil vapour testing may be assessed through comparison of predicted risks from groundwater to acceptable risk levels, as shown in Table 7.1.

**Table 7.1 Decision Matrix for Soil Vapour Sampling (for Dissolved Plume)**

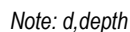
Predicted Risk from Groundwater Is:	Soil Vapour Recommendation
> AR*	Soil vapour characterization is warranted to evaluate attenuation between groundwater and soil vapour.
> 0.1 AR but < AR	Soil vapour characterization is recommended to confirm groundwater characterization results.
< 0.1 AR	Soil vapour characterization may not be warranted if there is a dissolved source and representative groundwater data were obtained.

\*Acceptable risk as defined in this guidance.

It is important that appropriate protocols are followed for sampling and analysis of soil vapour. These protocols are described in the Health Canada *Manual for Environmental Site Characterization in Support of Human Health Risk Assessment* (HC, unpublished).

When soil vapour concentrations are measured, partitioning calculations are not required and the user should proceed to Section 7.3.





A number of uncertainties are associated with use of soil data as a result of losses of volatile contaminants during soil sampling, handling, and chemical analysis. Depending on the contaminant type and geologic conditions, there may be significant spatial variation in soil concentrations, which may be difficult to detect based on conventional sampling programs. Finally, uncertainties are associated with soil partitioning calculations and predicted vapour concentrations

are sensitive to the partitioning coefficient between water and organic carbon, and the fraction organic content in soil – a parameter that can be difficult to accurately determine. If soil analyses results are to be used for the vapour pathway, it is recommended that the soil samples be field preserved (e.g. using methanol), where possible (e.g. U.S. EPA SW-846 Method 5035, 2008). **The practitioner is advised that the accuracy of the assessment will tend to be poor when soil matrix data are used, hence the preference for groundwater or soil vapour data.**

**Table 7.2 Comparison of Different Media for Vapour Intrusion Investigations**

Media Investigated	Indoor Air Evaluation Method	Principal Issues
Soil	Partitioning Model Soil vapour-to-indoor air fate and transport model	Partitioning model highly uncertain, significant spatial variability; possible negative bias due to losses during sampling; positive aspect is less temporal variability
Groundwater	Partitioning model Soil vapour-to-indoor fate and transport model	Partitioning model uncertain; imprecision of soil vapour transport model requires conservative attenuation factors; moderate to high spatial variability; generally moderate temporal variability
Deep Soil Vapour (beside building)	Soil vapour-to-indoor air fate and transport model	More direct indication of potential exposure, but high spatial variability (generally more so than groundwater); moderate to high temporal variability; method issues
Soil Vapour (below building)	Soil vapour-to-indoor air fate and transport model	More direct indication of potential exposure; spatial variability mitigated somewhat by being below building; moderate to high temporal variability; method issues
Subslab Vapour*	Subslab vapour-to-indoor air model (primarily dilution in indoor air) or empirical attenuation factor approach	Closest representation of potential vapours migrating into building, but intrusive, high spatial variability; also potentially high temporal variability; method issues; background air sources may confound results if building is positively pressurized
Indoor Air	Indoor air concentrations directly measured	Direct measurement but intrusive background sources may confound data interpretation; temporal variability likely high

\*Air within a crawlspace can be sampled as a substitute for subslab vapour. Depending on crawlspace ventilation and connection to house, there may be very little attenuation between the crawlspace and house (an attenuation factor of 1).

## **7.2 Step 2: Determine Contaminants of Potential Concern**

The chemicals identified as volatile and toxic in Table 5.1 represent a relatively comprehensive list of chemicals likely to be at a contaminated site. An initial list of COPCs would have been developed during qualitative screening steps given in Section 5.0 of this guidance; these would have been based on data from historical review and/or environmental testing, and compared with the chemicals listed in Table 5.1. An assessment of toxicity and volatility can be conducted using the methodology in Exhibit 1 if a chemical is not provided.

Surrogate chemicals may be identified to represent classes of compounds based on comparisons of relative toxicity and volatility. For example, for creosote contamination, naphthalene may be a reasonable surrogate for heavier molecular weight polycyclic aromatic hydrocarbons.

## **7.3 Step 3: Predict Source Vapour Concentrations (When Soil Vapour Data Not Available)**

Source soil vapour concentrations are estimated using the partitioning equations in Exhibit 2. When NAPL is not present,

a three-phase model is used. When NAPL is present, a two-phase model is used.

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. A linear absorption model based on the soil organic matter content predicts the partitioning between the sorbed and aqueous phases under equilibrium conditions. It is recommended that the fraction of organic carbon ( $f_{oc}$ ) be measured on a site-specific basis.

Presence or absence of NAPL can be determined using the solubility limit and soil saturation limit (U.S. EPA, 1996; ASTM, 1995). When a soil concentration is greater than the soil saturation limit and groundwater concentration is greater than the solubility limit, the two-phase model is used.

When NAPL is present, the vapour concentration is proportional to the vapour pressure of the compound, 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. There may, however, be other potential exposure pathways of concern when NAPL is present at a site.

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. It 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 on the mass and mole fraction of the chemical of interest within the mixture, the guidance partitioning equations can be adjusted to reflect the lower predicted vapour concentrations that will result (see Appendix A for details).

## 7.4 Step 4: Select Base Vapour Attenuation Factors

The selection of attenuation factors depends on land use, soil type, depth to contamination, and contamination source.

### 7.4.1 Introduction to vapour attenuation factor charts

The attenuation factors charts (Figures 7.2 to 7.5) were derived using the J&E model. They are based on four different soil types based on U.S. Soil Conservation Service soil texture classifications (sand, loamy sand, sandy loam, loam) and the depth to the contamination source. The attenuation factor charts are for two scenarios:

1. A groundwater contamination source with chemical transport through both the capillary transition zone and unsaturated zone; and
2. A 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 found to yield similar results compared with a basement scenario; therefore, only a basement scenario is included. Vapour intrusion is still expected to occur at a residence with slab-on-grade construction, and the model is applicable to these buildings as well as buildings with a basement or crawlspace. For the commercial scenario, a slab-on-grade scenario is assumed.

The attenuation factor charts apply the physical-chemical properties for benzene to all chemicals (see Appendix A, Section 5.4 for further justification). This is a reasonable assumption since the free-air diffusion coefficient, which is the main physical-chemical parameter affecting the attenuation factor, varies by about a factor of two for most volatile chemicals.

**EXHIBIT 2. PARTITIONING EQUATIONS****1. Groundwater Contamination Source (Preferred)**

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

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

**2. Soil Contamination Source (Not Recommended)**

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

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

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

Parameter	Default
$C_{w,i}$ = Ground water concentration (mg/L)	Measured site specific
$X_i$ = Mole fraction (no units) <sup>†</sup>	Estimated from chemical data
$S_i$ = Pure chemical aqueous solubility (mg/L)	Chemical specific
$C_{v,i}$ = Soil vapour concentration (mg/m <sup>3</sup> )	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 <sup>3</sup>
$MW_i$ = Molecular weight (g/mole)	Chemical specific
$P$ = Pure chemical vapour pressure (atm)	Chemical specific
$R$ = Gas constant (m <sup>3</sup> -atm/K-mole)	8.21E-05
$T$ = Absolute temperature (K, 273°C + T(°C))	Estimated
$C_{soil,i}$ = Total soil concentration (mg/kg)	Measured site specific
$C_{sat,soil,i}$ = Soil saturation concentration (mg/kg)	Calculated
$\rho_b$ = Dry bulk density (kg/L)	1.6
$\theta$ = Total porosity (dimensionless)	0.375 (coarse-grained soil) 0.399 (fine-grained soil)
$\theta_w$ = Water-filled porosity (dimensionless)	0.054 (coarse-grained soil) .148 (fine-grained soil)
$K_{oc}$ = Organic carbon-water partitioning coefficient (g/kg-OC per mg/L-water)	Chemical specific
$f_{oc}$ = Fraction organic carbon (dimensionless)	0.006 (recommend measure)
$\theta_a$ = Air-filled porosity (dimensionless)	$\theta - \theta_w$

Note: For chemicals that are solids at room temperature, the sub-cooled 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 3.

<sup>†</sup> See Appendix A for instructions on how to calculate the mole fraction of petroleum solutions.

## EXHIBIT 3. TEMPERATURE-CORRECTED VAPOUR PRESSURE AND HENRY'S CONSTANT

## 1. Temperature-Corrected Vapour Pressure

$$P' = P * e^{(\Delta H_1/R_1 * (1/T_r - 1/T_s))}$$

## 2. Temperature-Corrected Henry's Law

$$H'' = e^{(-\Delta H_{ts}/R_2 * (1/T_s - 1/T_r))} * H/(T_s * R_3)$$

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

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

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

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

Parameter	Default
P = Pure chemical vapour pressure (atm)	Chemical specific
P' = Temperature-corrected pure chemical vapour pressure (atm)	Chemical specific
$\Delta H_1$ = Enthalpy of vapourization at normal boiling point (J/mol)	Chemical specific
$\Delta H_2$ = enthalpy of vapourization at normal boiling point (cal/mol)	Chemical specific
$\Delta H_{ts}$ = Enthalpy of vapourization at average soil temp (cal/mol)	Chemical specific
H = Henry's Law constant (atm-m <sup>3</sup> /mol)	Chemical specific
H'' = Temperature-corrected dimensionless Henry's Law constant	Chemical specific
R <sub>1</sub> = Gas constant (J/mol-K)	8.3145
R <sub>2</sub> = Gas constant (cal/K-mol)	1.9872
R <sub>3</sub> = Gas constant (m <sup>3</sup> -atm/K-mol)	8.21 × 10 <sup>-5</sup>
T <sub>r</sub> = Reference temperature (K)	Specific to the temperature used for the derivation of the Henry's constant
T <sub>s</sub> = Average soil temperature (K)	Site specific
T <sub>c</sub> = Critical temperature (K)	Chemical specific
T <sub>b</sub> = Normal boiling point (K)	Chemical specific

The J&E model used to derive vapour attenuation factors assumes that contaminants are homogeneously distributed at their source, are present below the entire building, and source concentrations remain constant over time.

The base vapour attenuation factor charts developed for this guidance assume no biodegradation of hydrocarbon vapours. Because biodegradation of benzene, toluene, ethylbenzene, and xylenes (BTEX) vapours can be significant, there is provision to reduce the base (non-degrading) attenuation factors by a factor of 10, when conditions warrant, as outlined in Section 7.5.

### 7.4.2 Select soil type

Select the soil type, based on the coarsest soil at the site. If soil type is not known, it should be treated as coarse. For a PQRA, the only distinction of soil type allowed is between coarse- and fine-grained soil. Fine-grained soils are defined as having a median grain size  $< 75 \mu\text{m}$ , and coarse-grained soils are those with a median grain size  $> 75 \mu\text{m}$  (CCME, 2008a).

Vapour attenuation factors were also derived for four texture soil classes that are considered representative of most common soil types: sand, loamy sand, sandy loam, and loam. Clay was not chosen because unfractured homogeneous clay deposits are uncommon. The preferred method for determining the soil texture class are lithological descriptions combined with grain-size distribution tests. These soil types are integrated into the *Spreadsheet Tool for Detailed Quantitative Human Health Risk Assessment* (HC, 2009).

The soil textural triangle provided in Appendix A 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, Table 7.3 may be used to guide selection of the soil type.

### 7.4.3 Select land use

The two choices for land use for the quantitative screening process are a residential scenario and a commercial scenario.

**Residential** – A residential scenario should be selected if the site has a single-family or multi-family (townhouse or apartment) residential dwelling that is occupied for some or all of the time. A residential scenario would also apply to institutional land use (e.g. school, daycare) or operations where food is grown.

**Commercial** – A commercial land use should be selected for sites that are not residential and do not include operations where food is grown.

### 7.4.4 Estimate depth to vapour contamination source

The depth to vapour contamination source is the distance between the underside of the building foundation and vapour contamination source. The vapour contamination source is the water table when contamination is limited to dissolved constituents in groundwater. Allowance for water-table fluctuations should be made by selecting the minimum depth below the slab. When there is a soil contamination source, the distance is to the top of the contaminated zone.

### 7.4.5 Select vapour attenuation factor

Where contamination is limited to dissolved constituents in groundwater (saturated zone), the groundwater-to-indoor air pathway charts are used (Figures 7.2 and 7.4). Where there is a soil contamination source above the water table or when soil vapour is used to assess a groundwater or soil contamination source, the soil vapour-to-indoor pathway charts are used (Figures 7.3 and 7.5).

**Table 7.3 Selection of Soil Type**

If the coarsest soil type is:	Recommended soil texture
"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 7.2 Residential Groundwater-to-Indoor Air Attenuation Factors

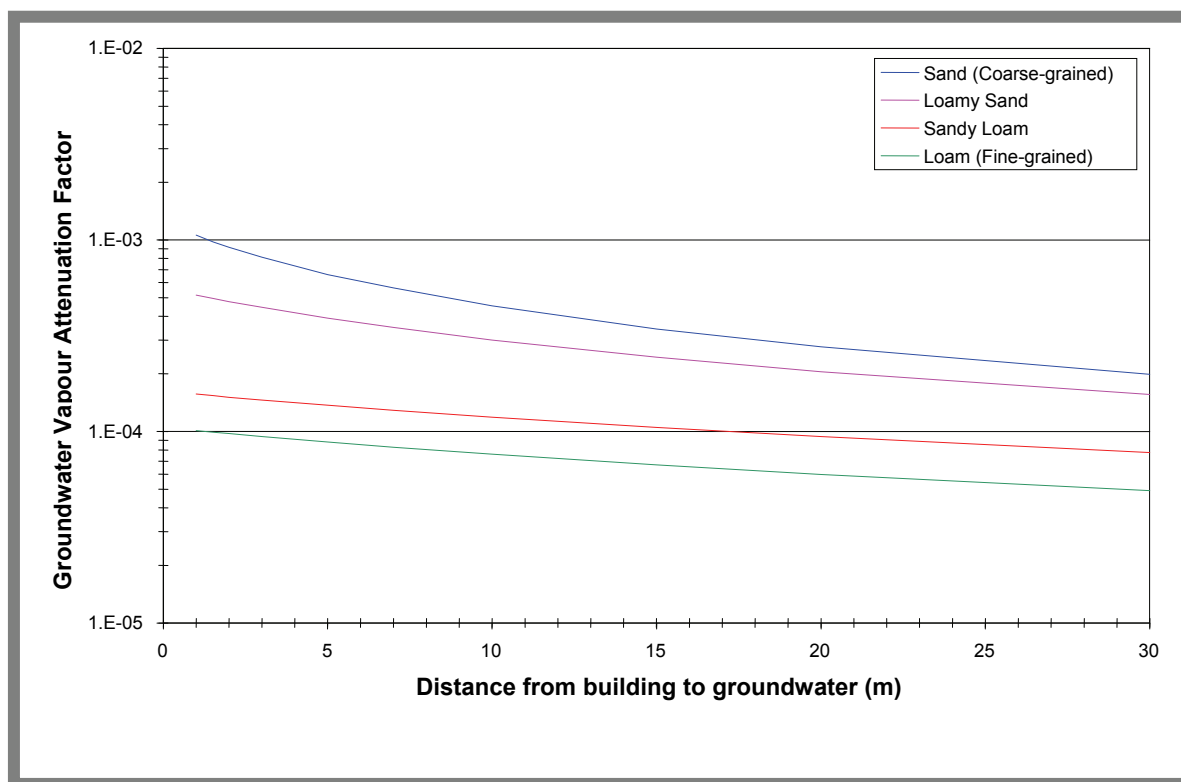


Figure 7.3 Residential Soil Vapour-to-Indoor Air Attenuation Factors

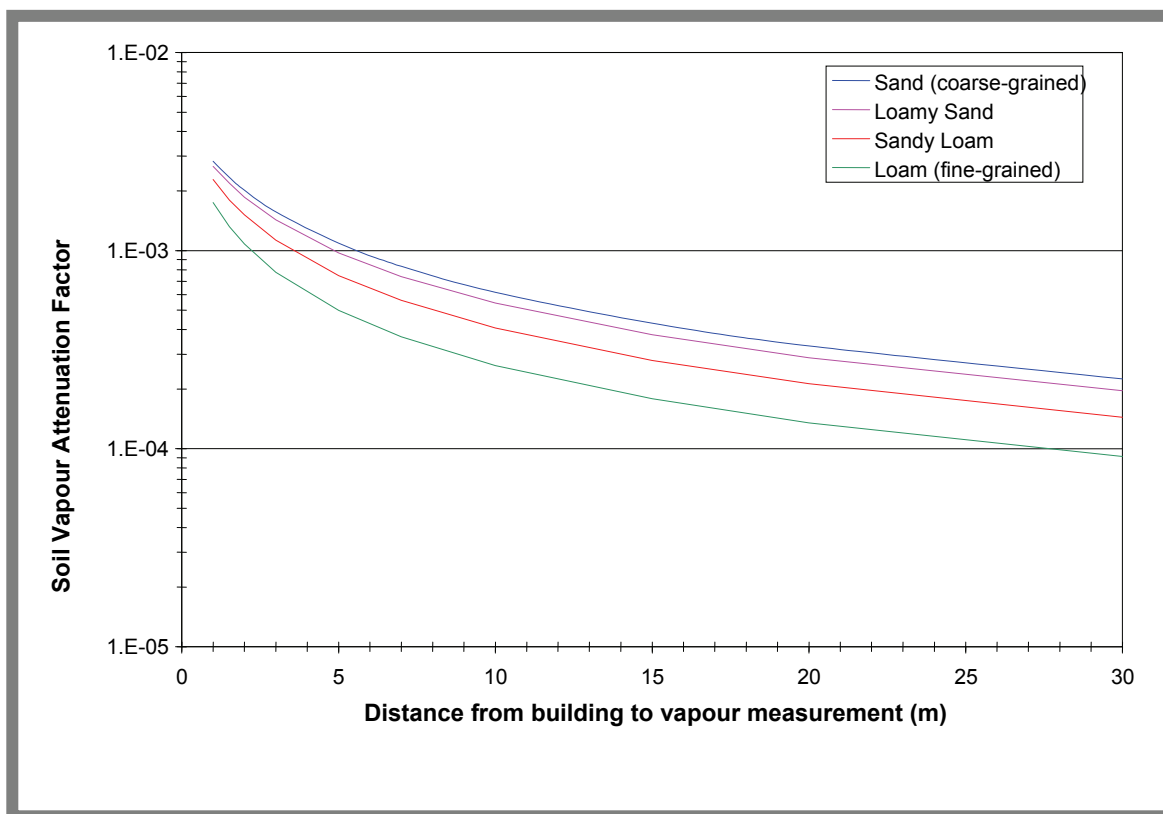


Figure 7.4 Commercial Groundwater-to-Indoor Air Attenuation Factors

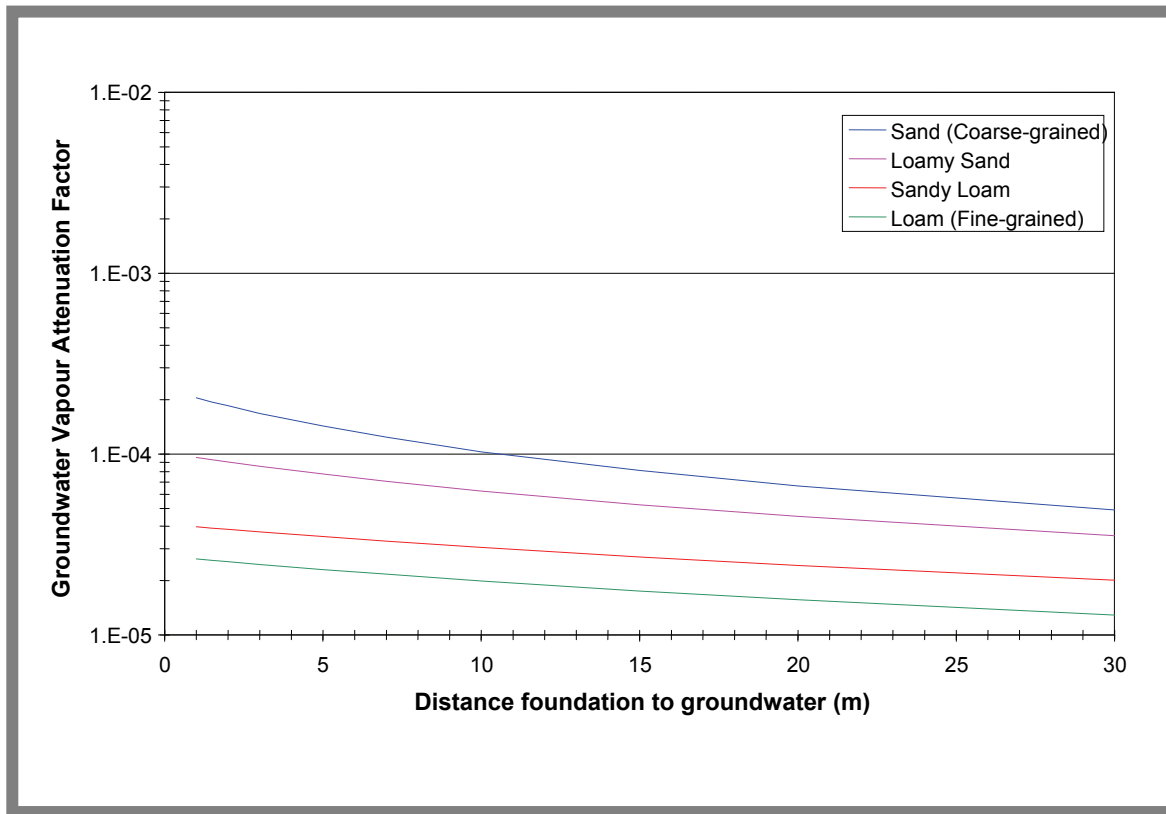
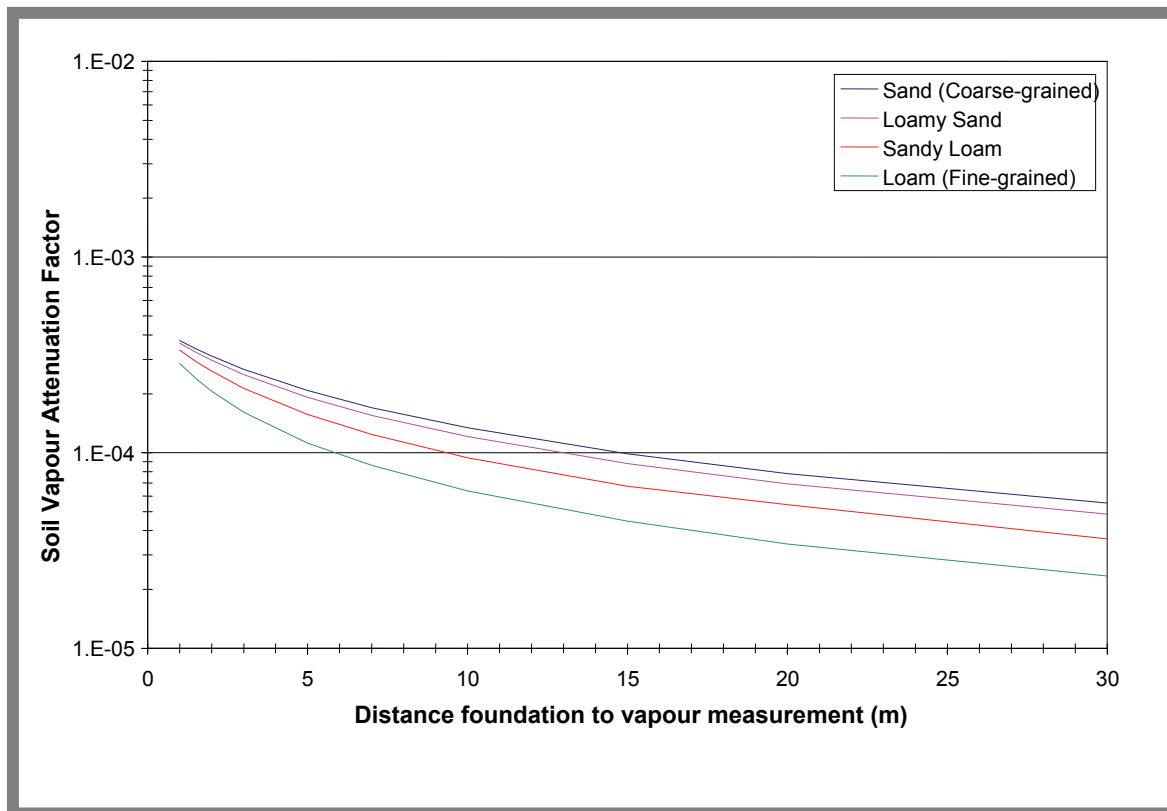


Figure 7.5 Commercial Soil Vapour-to-Indoor Air Attenuation Factors





## 7.5 Step 5: Adjust Attenuation Factor Based on Building Mixing Height

The vapour attenuation charts developed using the J&E model assume the following default building mixing heights:

- **Residential:** 3.6 m – complete mixing of vapours within first story, partial mixing within second story
- **Commercial:** 3.0 m – complete mixing within a single story office building

Although building height and mixing height are not equivalent, the mixing height for vapours within a building with high ceilings or a multi-storey building could be greater. If there is information indicating that the above default mixing heights are not representative, the attenuation factors can be scaled using a linear relationship. The attenuation factor is inversely proportional to the mixing height, as follows:

**Residential:** Adjusted Attenuation Factor = (3.6 m/Site-Specific Mixing Height) \* Vapour Attenuation Factor

**Commercial:** Adjusted Attenuation Factor = (3.0 m/Site-Specific Mixing Height) \* Vapour Attenuation Factor

## 7.6 Step 6: Adjust Attenuation Factor Based on Biodegradation

For hydrocarbon compounds that readily biodegrade under aerobic conditions such as BTEX and the F1 petroleum fraction, the vapour attenuation factor selected can be scaled by a factor of 10 where site conditions warrant, as follows:

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$$\text{Adjusted Attenuation Factor} = \text{Vapour Attenuation Factor}/10$$


---

### Rationale

There are empirical (field) data and laboratory studies indicating BTEX vapours are readily degraded in the presence of oxygen (Ostendorf and Kampbell, 1991; Fischer et al., 1996; Laubacher et al., 1997; Johnson et al., 1998; Hers et al., 2000; DeVaul, 2002). In addition, available empirical data indicate measured vapour attenuation factors for BTEX are generally lower than those measured for chemicals that either do not or only slowly degrade or transform, such as trichloroethene (trichloroethylene) and 1,1-dichloroethene. The vapour attenuation factors presented in Figures 7.2 to 7.5 are considered reasonable, based on empirical comparisons for non-degrading chemicals, but are overly conservative for

BTEX chemicals. Less empirical data exist on biodegradation for other petroleum hydrocarbon compounds.

### Requirements

Before the adjustment can be applied at a site, the following conditions must be met to establish that sufficient oxygen is present to ensure biodegradation of vapours.

- Adjustment can be applied only to hydrocarbon vapours that degrade under aerobic conditions.
- When soil vapour or groundwater data are used, depth to source below the building foundation must be > 3 m with non-contaminated soil between the source and the building.
- There must be no capping effect at the site. This is defined as sites where paved or other low-permeability surfaces represent > 80% of the area surrounding the building.
- If soil gas data are used, the samples must be near source. The adjustment cannot be used for shallow soil vapour concentrations.
- Concentration gradients of O<sub>2</sub>, CO<sub>2</sub>, and methane should provide evidence that aerobic biodegradation is occurring.

A protocol for soil gas testing for biodegradation assessment is provided in the Health Canada *Manual for Environmental Site Characterization in Support of Human Health Risk Assessment* (HC, unpublished). Further information about biodegradation of petroleum hydrocarbons vapours can be found in *Evaluation of Vadose Zone Biodegradation of Petroleum Hydrocarbons: Implications for Vapour Intrusion Guidance* (Golder Associates Ltd., 2008).

When measured soil concentrations are used to evaluate vapour intrusion, a 10 times downward adjustment of the alpha factor may be made for depths > 1 m below the foundation. The rationale for the 10 times factor for soil is two-fold. (1) The partitioning equation used to predict soil vapour concentrations appears to be conservative, based on a recent evaluation for CCME ([2008a,b]) where measured vapour concentrations in soil gas samples obtained near to soil contamination sources were in almost all cases much lower than the predicted concentrations. (2) Bioattenuation of hydrocarbon vapours will occur at many sites. Because it is unlikely that sufficient justification will be available at the PQRA level, the biodegradation adjustment is not included in the PQRA spreadsheet tool.

## 7.7 Step 7: Predict Indoor Air Concentration

The indoor air concentration is predicted using the measured or estimated soil vapour concentration and the vapour attenuation factor, as follows:

$$C_{\text{air}} = C_v * \text{Vapour Attenuation Factor}$$

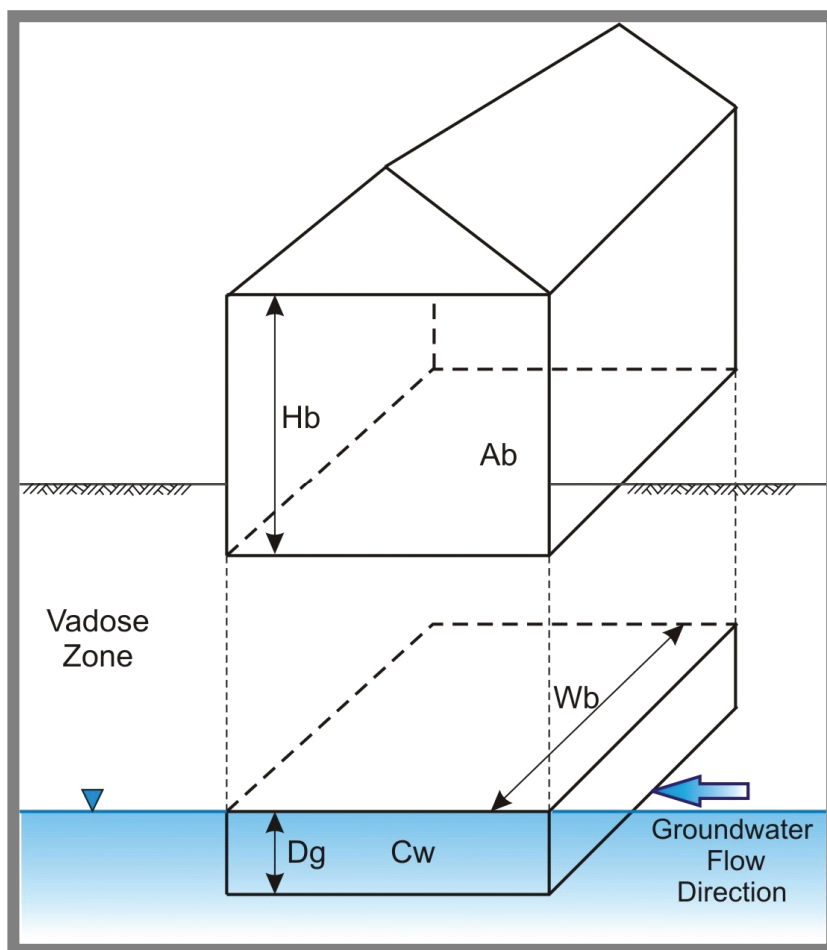
## 7.8 Step 8: Adjust Indoor Air Concentration Based on Mass Flux Considerations (Optional, Dissolved Groundwater Only)

The mass flux check can be used to ensure that the attenuation factor selected does not predict an indoor air concentration that is unrealistic compared with the available mass of the contaminant. The mass flux check is applicable when there is only a **dissolved contamination source**.

The mass of contaminant available for vapour intrusion, under steady-state conditions, is controlled by the mass flux in groundwater flowing below the building. The development of the guidance vapour attenuation factors assumes that the available mass in groundwater matches or exceeds the volatilization rate represented by the attenuation factor. In some cases, the attenuation factors presented in the guidance may assume a mass flux into the building that is unreasonable, based on the available mass of chemical in groundwater flowing under the building. As shown in Exhibit 4, if the predicted mass flux through volatilization is greater than the available mass flux in groundwater, then the **predicted indoor air concentration is scaled based on the available mass flux**.

The mass flux check is applicable when there is only a dissolved contamination source. The mass flux check, presented in Exhibit 4 and Figure 7.6, **requires an estimate of the Darcy velocity (specific discharge)**. The Darcy velocity can be estimated from the hydraulic conductivity and hydraulic gradient. Because it is unlikely that these values will be available for all sites at the PQRA level, the mass flux check is not part of the PQRA assessment.

Figure 7.6 Conceptual Model for Groundwater Mass Flux Calculation



The mass flux assumes that all dissolved chemicals within the top 1 m of groundwater flowing below the entire width of the building will volatilize and enter the building. In addition, it is assumed that the groundwater chemicals are not attenuated through biodegradation. These conservative assumptions were adopted for screening purposes because there is uncertainty in predicting the groundwater mass transport and concentration distribution in groundwater.

### **7.9 Step 9: Check Based on Contamination Source Depletion (Optional, Soil Contamination Only)**

In some cases, the semi-site-specific attenuation factors presented in the guidance assume a mass flux into the

building that is unrealistic based on the available mass in soil. To address possible mass limitations, the guidance includes a simple calculation to estimate the number of years it would take for the soil contamination source to be depleted (Exhibit 5). Data on the thickness of contaminated soil as well as soil bulk density are required. If the time for depletion is less than the assumed exposure duration, consideration should be given to conducting a detailed risk assessment. Also, for carcinogenic chemicals, consideration may be given to recalculating the carcinogenic dose using an adjusted exposure duration (see Exhibit 6). A great deal of care should be exercised in estimating both the exposure duration and the amortization period. Because the equation assumes that the vapour concentration would remain constant, it will likely underestimate the time for source depletion. Further detailed site-specific modelling would be necessary to estimate an appropriate exposure duration.

#### EXHIBIT 4. ADJUSTMENT OF PREDICTED INDOOR AIR CONCENTRATION BASED ON MASS FLUX CONSIDERATIONS – GROUNDWATER-TO-INDOOR PATHWAY

$$VR = ACH * A_b * H_b / UCF_4$$

$$Flux_v = C_{air} * VR$$

$$Flux_g = U * C_w * D_g * W_b * R_v * UCF_2 / UCF_3$$

$$\alpha' = Flux_v / Flux_g * \alpha \quad \text{if } Flux_v > Flux_g$$

$$C_{air}' = \alpha' * C_{air} \quad \text{if } Flux_v < Flux_g$$

Parameter	Default
VR = Building ventilation rate (m <sup>3</sup> /min)	Calculated
ACH = Air exchange rate (1/h)	0.35 residential
	1.0 commercial
A <sub>b</sub> = Area building (m <sup>2</sup> )	100 residential
	300 commercial
H <sub>b</sub> = Mixing height (m)	3.6 residential
	3.0 commercial
UCF <sub>4</sub> = Unit conversion factor (min/h)	60
Flux <sub>v</sub> = Predicted flux into building (mg/min)	Calculated
Flux <sub>g</sub> = Flux from groundwater (mg/min)	Calculated
U = Darcy velocity (specific discharge) (m/year)	Estimated
C <sub>w</sub> = Soil water (groundwater) concentration (mg/L)	Measured
D <sub>g</sub> = Mixing zone in groundwater for chemicals volatilizing (m)	1.0
W <sub>b</sub> = Width of building (m)	10 residential
	15 commercial
R <sub>v</sub> = Volatilization ratio for fraction of chemical mass in groundwater flowing below the building that volatilizes and enters buildings	1.0
UCF <sub>2</sub> = Unit conversion factor (L/m <sup>3</sup> )	1,000
UCF <sub>3</sub> = Unit conversion factor (min/year)	525,600
C <sub>air</sub> = Predicted air concentration based on Exhibit 1 (mg/m <sup>3</sup> )	Calculated
C <sub>air</sub> ' = Adjusted air concentration (mg/m <sup>3</sup> )	Calculated

**EXHIBIT 5. SOURCE DEPLETION CHECK BASED ON AVAILABLE MASS SOIL-TO-INDOOR AIR PATHWAY**

$$VR = ACH * A_b * H_b / UCF_4$$

$$Flux_v = C_{air} * VR$$

$$Mass_a = C_{soil} * \rho_b * T_s * A_b$$

$$Time_d = Mass_a / (Flux_v * UCF_3)$$

**For carcinogenic chemicals:** If  $Time_d < \text{Exposure Duration}$ , consideration can be given to recalculating carcinogenic dose using time for depletion (see Exhibit 6).

Parameter	Default
$C_{soil}$ = Total soil concentration (mg/kg)	Measured site specific
$\rho_b$ = Soil bulk density (kg/m <sup>3</sup> )	Estimated
$Mass_a$ = Available mass contaminant in soil ( )	Calculated
$T_s$ = Thickness of contamination source in soil (m)	Estimated
$UCF_3$ = Unit conversion factor (min/year)	525,60
$Time_d$ = Time for depletion of contamination source	Calculated

**Note:** Other parameters previously defined in Exhibit 4.

### 7.10 Step 10: Risk Characterization

Once the indoor air concentration has been estimated using vapour attenuation factors, calculation of human health risk can be done using the equations in the Health Canada PQRA guidance (HC, 2010a). The risk equations are provided in Exhibit 6.

Table 5.1 contains a list of TRVs; however, the Health Canada guidance on TRVs and chemical-specific factors (HC, 2010b) may be updated more often. The user should refer to the guidance (HC, 2010b) to identify appropriate TRVs. If Health Canada has no TRV for the chemical of potential concern, direction is provided in Health Canada (2010a) on appropriate alternate sources of regulatory TRVs.

If predicted health risks exceed acceptable levels, it does not necessarily indicate that an unacceptable risk actually exists. However, it does indicate that a more detailed and comprehensive risk assessment may be necessary.

### 7.11 Step 11: Evaluation of Data Consistency, Adequacy, and Uncertainty

A final critical step in the risk assessment process is to evaluate the results in terms of data consistency, adequacy, and uncertainty. The key questions that should be asked at this stage of the process include:

- Are predictions consistent with the CSM and internally consistent for different media?

- Are the data adequate to evaluate vapour intrusion potential, particularly when screening-level risk assessment indicates no further action is warranted?
- What is the overall uncertainty in the screening-level risk assessment and how should this influence decisions made?

Ideally, data from both soil vapour and groundwater (for a dissolved source) will be available for comparison. The confidence in the risk assessment is highest when both media indicate acceptable health risk. When one media indicates acceptable health risk and the other does not, the data quality and representativeness should be carefully reviewed. When significant differences between indoor air concentrations are predicted using different media, the data quality and representativeness should be carefully reviewed. The model will give lower (less conservative) predictions when soil vapour data are used; this is because the vapour intrusion model for groundwater-to-indoor air tends to overpredict the rate of chemical transport through the capillary fringe. However, **the results from soil vapour should not take precedence over groundwater.** If the indoor air concentration prediction from soil vapour are more than 10 times lower than those predicted using groundwater, there must be a compelling reason for soil vapour-to-indoor air predictions to take precedence. These may be factors that lead to significant attenuation such as an uncontaminated lens on the water table, fine-grained high-moisture content soil layers, or bioattenuation. The influence of these factors must be supported by site data.

The data adequacy evaluation involves the consideration of several factors, including the site complexity and distribution of contamination sources and plumes, the observed spatial and

temporal variability, and data quantity and quality. The adequacy of the data and the uncertainty in the data must be carefully assessed, particularly when the data are used to screen sites or buildings out of the assessment process. To guide the determination of appropriate follow-up actions, a decision matrix is provided in Table 7.4. As shown, follow-up actions may depend on consistency among predictions and the comparison of the predicted with acceptable risk levels. A “bright line” approach where the acceptable risk level defines whether or not action is taken should generally be avoided; instead, consideration should be given to how close the predicted risk level is to the acceptable risk level in light of uncertainty in the data.

It is not the purpose of this guidance to prescribe remediation measures; however, in the event that mitigation of contamination is necessary, *Vapour Intrusion Pathway: A Practical Guideline* (ITRC, 2007) and *Vapour Intrusion Guidance* (NJDEP, 2005) present possible remedies and can be consulted.

### 7.12 Step 12: Background Indoor Air Check

The human health risks from estimated vapour concentrations in air should be calculated without any correction for background. However, for risk management purposes, it may be instructive to compare the predicted indoor vapour concentrations with indoor or ambient background

concentrations, either those published in the literature or obtained from a site-specific study. For some chemicals, the target risk-based indoor concentration may be less than typical background levels. When calculating site-specific remediation objectives, it may be appropriate to use a representative background concentration (e.g. median background concentration) in place of the target risk-based indoor air concentration. Background sources of VOCs in air include building materials, consumer products, petroleum products, and emissions. It is recommended that the approximate mean background concentration be used for this determination. Information on background VOC concentrations in indoor air is available in CCME ([2008a,b), Hers et al. (2001), U.S. EPA (2003), Kurtz and Folkes (2003), and Foster et al. (2003). If the predicted vapour concentrations in indoor air are less than the background concentrations, then the contribution to risk from inhalation of vapour is less than that associated with background VOC sources. When predicted vapour concentrations in indoor air are less than background concentrations but still indicate unacceptable risk, consideration should be given to whether additional more in-depth risk assessment is required that may include collection of soil vapour or indoor air directly.

**Table 7.4 Decision Matrix for Interpretation of Risk Predictions**

Predicted risk from groundwater	Predicted risk from soil vapour	Recommended action*
< AR <sup>†</sup>	< 0.1 AR	No further testing typically warranted
> 0.1 AR but < AR	> 0.1 AR but < AR	Additional soil vapour testing or subslab/indoor air testing may be warranted, depending on how close predicted risk is to AR and data uncertainty
> AR	< 0.1 AR	Review CSM; additional soil vapour testing or subslab/indoor air testing may be warranted, depending on how close predicted risk is to AR and data uncertainty
> AR	> AR	Subslab/indoor air testing likely warranted
< AR <sup>‡</sup>	> AR	Review CSM and groundwater characterization; may be unsaturated zone source

\* For all cases, data adequacy (quality, quantity, representativeness) should be reviewed.

<sup>†</sup> Acceptable risk as defined in this guidance.

<sup>‡</sup> Or alternately, when risk predicted from soil vapour exceeds that predicted from groundwater.

## EXHIBIT 6. RISK EQUATIONS

### 1. Calculation of a Hazard Quotient (Non-Carcinogens)

1.1 Chemicals with an Tolerable Daily Intake (TDI) or RfD

$$HQ = DR_{IHV} / RfD$$

$$\text{where } DR_{IHV} = IR \times C_{AIR} \times AF \times D_1 \times D_2 \times D_3 / (BW)$$

1.2 Chemicals with a Tolerable Air Concentration ( $TC_{air}$ ) or RfC

$$HQ = C_{AIR} \times t / TC_{air}$$

$$\text{Where } t = D_1 \times D_2 \times D_3 / (BW)$$

$$\text{and } TC_{air} = TDI \text{ (mg/kg-day)} \times BW / IR$$

For PQRA: Typically use BW and IR appropriate to site receptor.

### 2. Calculation of an Incremental Lifetime Cancer Risk (ILCR)

2.1 Chemicals with a SF

$$ILCR = DR_{IHV} \times SF$$

$$DR_{IHV} = IR \times C_{AIR} \times AF \times D_1 \times D_2 \times D_3 \times D_4 / (BW \times LE)$$

2.2 Chemicals with a UR

$$ILCR = C_{AIR} \times t \times UR$$

$$\text{Where } t = D_1 \times D_2 \times D_3 \times D_4 / (BW \times LE)$$

$$\text{and } UR = SF \text{ (mg/kg-day)}^{-1} \times IR / BW$$

**For PQRA:** Typically use IR and BW for adult receptor.

If  $ILCR > 10^{-5}$ , there is potential unacceptable risk due to inhalation of volatiles.

If  $HQ > 0.2$ , there is potential unacceptable risk due to inhalation of volatiles.

Parameter	Default
$DR_{IHV}$ = Dose rate from inhalation of volatile contaminants (mg/kg(BW)-day)	Calculated
IR = Receptor air intake rate (m <sup>3</sup> /hour)	Scenario specific <sup>†</sup>
$C_{AIR}$ = Concentration of contaminant in air (mg/m <sup>3</sup> )	Calculated
AF = Inhalation absorption factor (no units)	1
$D_1$ = Hours per day exposed (hour/day)	Scenario specific <sup>†</sup>
$D_2$ = Days per week exposed/7 days (dimensionless)	Scenario specific <sup>†</sup>
$D_3$ = Weeks per year exposed/52 weeks (dimensionless)	Scenario specific <sup>†</sup>
$D_4$ = Total years exposed to site (years, carcinogens only)	Scenario specific <sup>†</sup>
BW = Body weight (kg)	Scenario specific <sup>†</sup>
LE = Life expectancy (years, carcinogens only)	‡
t = Fraction of time exposed (i.e. hours/day, days/year)	Scenario specific <sup>†</sup>
$TC_{AIR}$ = Tolerable air concentration (mg/m <sup>3</sup> ) ( $TC_{air}$ = RfC)	Chemical specific
TDI = Tolerable daily intake (mg/kg-day) (TDI = RfD)	Chemical specific
SF = Slope factor (mg/kg-day) <sup>-1</sup>	Chemical specific
UR = Unit risk (mg/m <sup>3</sup> ) <sup>-1</sup>	Chemical specific

<sup>†</sup> For default values see *Federal Contaminated Site Risk Assessment in Canada, Part I: Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA), Version 2.0* (HC, 2010a)

<sup>‡</sup> Health Canada is currently reviewing the validity and acceptability of exposure amortization for carcinogenic substances. The *Federal Contaminated Site Risk Assessment in Canada, Part I: Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA), Version 2.0* (HC, 2010a) should be consulted.

## 8.0 CONCLUSION

This guidance reflects the current state of knowledge on soil vapour intrusion. There still is relatively large uncertainty associated with models used to predict indoor air concentrations from subsurface contamination, although recent empirical data from sites have contributed to the partial validation of models and vapour attenuation factors adopted for this guidance, as described in Appendix B. Recently it has come to Health Canada's attention that caution should be used

when applying this model to chlorinated solvents in coarse soil because the model may underestimate risks. Professional judgment has played a role in the development of criteria used to screen sites and models used to derive vapour attenuation factors. The scientific basis for the approach and analysis embodied in this guidance will continue to be evaluated on the basis of future research, and will be refined and updated as warranted. Users of this guidance should exercise care in applying these models to ensure their appropriateness for the site under investigation and that human health is being protected.



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## 10.0 GLOSSARY

**Building depressurization** – pressure inside lower regions of building that is lower than ambient pressure caused by differences between indoor and outdoor air temperature (stack effect), wind loading on building, operation of the heating, ventilation, and air conditioning system or appliances (e.g. fans), and barometric pressure fluctuations or other factors

**Darcy velocity (specific discharge)** – estimated by multiplying the hydraulic conductivity by the hydraulic gradient

**Qualitative screening** – preliminary screening step to categorize sites according to their potential for vapour intrusion, and to determine whether the assessment should proceed to quantitative screening.

**Quantitative screening** – screening-level quantitative risk assessment where representative semi-site-specific vapour attenuation factors are used to estimate indoor air concentrations, which, in turn, are used to predict health risk

**Soil saturation limit (C<sub>sat</sub>)** – concentration above which NAPL is present in soil, based on solubility considerations

**Vapour attenuation factor (“alpha”)** – indoor air concentration divided by the soil vapour concentration at some depth (inverse of CCME dilution factor)

**Groundwater-to-indoor air vapour attenuation factor** – indoor air concentration divided by the soil vapour concentration predicted, using the groundwater concentration (typically based on the Henry’s Law constant)

**Soil vapour-to-indoor air vapour attenuation factor** – indoor air concentration divided by the measured soil vapour concentration

**Subslab vapour-to-indoor air vapour attenuation factor** – indoor air concentration divided by the measured subslab soil vapour concentration

## APPENDIX A

# DERIVATION OF VAPOUR ATTENUATION FACTORS FOR SCREENING-LEVEL RISK ASSESSMENT

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## A1.0 INTRODUCTION

This report describes the framework and methodology for the derivation of the vapour attenuation factor charts for screening-level risk assessment (SLRA) of soil vapour intrusion into buildings. This appendix is intended as a supporting document to the *Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites*. The vapour attenuation factor charts are a key part of this guidance document.

The vapour attenuation factors, defined as the indoor air concentration divided by the soil vapour concentration at some depth, are based on the results of model predictions using the Johnson and Ettinger (J&E) model. The attenuation factor charts enable a user of the SLRA guidance to select an attenuation factor based on four soil types and distance to contamination source for a residential or commercial land-use scenario. Attenuation factor charts are provided for a groundwater contamination source (groundwater-to-indoor air pathway) and soil or soil vapour contamination source (soil vapour-to-indoor air pathway). The use of two adjustable parameters (soil type and depth) allow for selection of an attenuation factor that is more representative of site conditions. The attenuation factors, when used with appropriate partitioning equations, are used to estimate indoor air concentrations associated with subsurface vapour sources. The indoor air concentrations are used to predict potential risk to human health via inhalation exposure.

The J&E model was chosen to develop the attenuation factor charts because it is commonly used, it is a relatively simple and easy to understand the model, and it incorporates the key processes for vapour intrusion into buildings. 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 modelling of vapour intrusion, it is not feasible to expect a model to provide a better match with empirical data.

This appendix describes the use of the J&E model for derivation of the vapour attenuation charts. The derived attenuation factors are compared with available empirical attenuation factors calculated from field measurements in Appendix B. The vapour attenuation factor charts developed for this guidance assume no biodegradation of hydrocarbon vapours such as benzene, toluene, ethylbenzene, and xylenes (BTEX). Because biodegradation of BTEX vapours has shown to be significant, based on soil vapour measurements and indirectly through evaluation of empirical vapour attenuation factors, there is provision in this guidance to reduce the base (non-degrading) attenuation factors by a factor of 10, when

conditions warrant. The supporting rationale for the adjustment for bioattenuation of hydrocarbon vapours is provided in Appendix C.

## A2.0 JOHNSON AND ETTINGER MODEL ASSUMPTIONS AND USE

### A2.1 Overview of Johnson and Ettinger Model

Johnson and Ettinger (1991) introduced a screening-level model for estimating the transport of contaminant vapours from a subsurface source into indoor air spaces. The 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” – the ratio of the vapour concentration in the indoor space to the vapour concentration at the contamination source. To facilitate use of the J&E model, in 1997 the U.S. EPA developed spreadsheet versions that also included additional calculations to estimate the partitioning between vapour source media (e.g. soil, groundwater) and soil vapour, and to estimate health risk based on the modelled indoor air concentration. A total of six spreadsheets were developed – including a screening-level model for uniform geology and a more advanced version that considers multiple geologic layers for each of three potential vapour sources: groundwater, bulk soil, and soil gas. The spreadsheets were updated in 2000, 2002, and 2003. Computer software that includes the J&E model or variants thereof (e.g. RISC, GSI Tool Kit) is also commercially available.

The J&E model was developed for use as a screening-level tool. Consequently, it is based on a number of simplified assumptions about contaminant distribution and occurrence, subsurface characteristics, transport mechanisms, and building construction.

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 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 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.

Contaminants are assumed to be homogeneously distributed at their source. The base version of the J&E model assumes an infinite contamination source that results in source concentrations that remain constant over time. Variations of the J&E model are available that include an option to consider a depleting soil contamination source when the groundwater or soil concentrations are below the aqueous solubility limit or soil saturation concentration. Partitioning relationships commonly used with the J&E model are described in Section 4.0.

## ***A2.2 Johnson and Ettinger 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. When site-specific data are properly used and constrained to reasonable ranges, the overall variation in attenuation factors predicted by the J&E model is about one order of magnitude, 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 A1. Model parameters with moderate to high variability include:

- water-filled porosity and capillary transition height for contaminated groundwater vapour sources;
- $Q_{\text{soil}}$  and soil-air permeability for shallow contamination and 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 foundation area, depth to base of foundation, and foundation slab thickness.

As described in Johnson (2002), 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  $Q_{\text{soil}}$  to the building ventilation rate ( $Q_{\text{soil}}/Q_{\text{build}}$ ). Both these parameters typically vary over a defined range depending on soil properties and building conditions.



Table A1. Qualitative Uncertainty and Sensitivity Analysis for Inputs Used for Johnson and Ettinger Model

Input Parameter	Parameter Sensitivity and Uncertainty			
	Building Underpressurized		Building Not Underpressurized	
	Shallow Contamination	Deeper Contamination	Shallow Contamination	Deeper Contamination
<b>Soil Properties</b>				
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 (single chemical)	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Free-Air Diffusion Coefficient (single chemical)	Low	Low	Low	Low
<b>Building Properties</b>				
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 (from surface)	Low	Low	Low	Low

Note: Attenuation factor inversely proportional to building mixing height and building air change rate N/A, not applicable

## A3.0 PRECLUDING FACTORS FOR SECONDARY SCREENING

When site-specific conditions fall outside of the conceptual site model (CSM) described by the J&E model, the screening-level attenuation factor charts should not be used. Instead, the assessment should proceed to a detailed risk assessment. This is because the J&E model is based on a simplified representation of physical processes that cause the model to be less accurate when the site-specific conditions are different from the CSM described by the J&E model. The screening-level vapour attenuation factors should not be used when the following “precluding factors” apply:

**Shallow depth to contamination** – Sites with a contamination source within 1 m of the building foundation should be precluded from secondary screening. When the contamination source is within 1 m of the building, the vapour attenuation factors used for this guidance are unreliable as a result of seasonal water-table fluctuations, the varying thickness of the tension-saturated zone (capillary fringe), which will depend on soil texture, and the possible presence of sumps in basements.

**Earthen basements** – Buildings with earthen basements should be precluded from secondary screening, unless the depth to the contamination source is sufficiently deep such that transport processes within the soil zone control the vapour flux into the building, as opposed to the building foundation characteristics. The depth where the earthen basement property is no longer important will depend on site-specific conditions. A conservative value for this depth is 5 m, when other precluding factors are taken into consideration. Therefore, buildings with earthen basements where contamination is less than 5 m from the building should be precluded from secondary screening.

**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 be precluded from the secondary screening, 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 CSM described by the J&E model.

**Subsurface utility conduit connecting contamination source and building** – Common anthropogenic features such as floor drains, sewer lines, and utility conduits are present at most sites. The presence of these features is not normally considered a precluding factor. However, if there are utility conduits that directly connect the contamination source to the enclosed space of the building, then this should be taken as a precluding factor.

The presence or suspected presence of non-aqueous phase liquid (NAPL) is not considered to be a precluding factor for secondary screening provided that soil vapour samples are obtained from above the NAPL zone (i.e. vapour source alpha charts should be used). 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.

## A4.0 PARTITIONING RELATIONSHIPS

### A4.1 Partitioning Model When Non-Aqueous Phase Liquid Not Present

Source soil vapour concentrations can be predicted using either groundwater or soil chemistry data or directly measured. A **three-phase** model describing partitioning between the sorbed soil-water and soil-air phases is typically assumed when no NAPL is present. 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:

(A1)

$$C_v = UCF * H' * C_w$$

where  $C_v$  is the soil vapour concentration (mg/m<sup>3</sup>),  $H'$  is the dimensionless Henry's Law constant,  $C_w$  is the soil-water concentration (mg/L), and UCF (1000 L/m<sup>3</sup>) is a unit conversion factor. Henry's Law is applicable for most organic contaminants that are sparingly soluble (the mole fraction of that contaminant in water is < 0.001).

(A3)

$$C_v = 1000 * C_{soil} * H' * \rho_b / (\rho_w + K_{oc} * f_{oc} * \rho_b + H' * \theta_a)$$

where  $C_{soil}$  is the total soil concentration (mg/kg) (all phases),  $\rho_b$  is the dry bulk density (g/cm<sup>3</sup>), and  $\theta_w$  and  $\theta_a$  are the water- and air-filled porosities (dimensionless).

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:

(A2)

$$C_s = K_{oc} * f_{oc} * C_w$$

where  $C_s$  is the sorbed concentration (mg/kg),  $K_{oc}$  is the organic carbon-water partitioning coefficient (mg/kg-OC per mg/L-water) and  $f_{oc}$  is the fraction organic carbon. This linear sorption model has been experimentally verified for common non-polar or slightly polar organic compounds (Chiou et al., 1983; Karickhoff et al. 1979) when fraction organic carbon ( $f_{oc}$ ) is greater than about 0.001 (Schwarzenbach et al., 1981).

Based on a phase mass balance, the soil-air concentration is related to the total soil concentration using the equation (A3) below.

#### A4.2 Partitioning Model When Non-Aqueous Phase Liquid Present

For a pure chemical, NAPL will not be present at concentrations below the soil saturation limit. The soil saturation limit is estimated by the following equation (ASTM, 1995) using the equation (A4) below.

(A4)

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

where  $C_{\text{sat,soil}}$  is the soil saturation limit for a particular compound (mg/kg), and  $S$  is the pure-chemical solubility (mg/L),  $\theta_w$  is the water-filled porosity,  $K_{\text{oc}}$  is the organic carbon-water partitioning coefficient (mg/kg-OC per mg/L-water),  $f_{\text{oc}}$  is the fraction organic carbon,  $\rho_b$  is the dry bulk density (g/cm<sup>3</sup>),  $H'$  is the dimensionless Henry's Law constant, and  $\theta_a$  is the air-filled porosity.

When NAPL is present, a **two-phase** partitioning model is used. The partitioning between NAPL and air phases is proportional to the vapour pressure of the compound, which for a pure chemical is:

(A5)

$$C_v = 10^6 * MW * P / RT$$

where  $C_v$  is the vapour concentration (kg/m<sup>3</sup>),  $P$  is the vapour pressure (atm),  $MW$  is the molecular weight (g/mole),  $R$  is the gas constant (0.08205 L-atm/K-mole), and  $T$  is the absolute temperature (°K).

#### A4.3 Partitioning Models for Multi-Component Mixtures

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, as follows:

(A6)

$$C_{w,i} = X_i * S_i$$

where  $i$  denotes component  $i$  in the mixture and  $X_i$  is the mole fraction of the component  $i$  in the NAPL mixture. The mole fraction can be estimated as follows:

(A7)

$$X_i = W_i / MW_i / \sum W_j / MW_j$$

where  $W_i$  is the mass fraction (kg/kg) and  $MW_i$  is the molecular weight. For petroleum hydrocarbons, the mole fraction can be approximated through the following relationship:

(A8)

$$X_i = C_{\text{soil},i} / \text{TPH} * MW_{\text{TPH}} / MW_i$$

where  $C_{i,\text{soil}}$  is the concentration of the individual compound in soil (mg/kg),  $\text{TPH}$  is the total petroleum hydrocarbon concentration in soil (mg/kg),  $MW_{\text{TPH}}$  is the average molecular weight of the petroleum hydrocarbon, and  $MW_i$  is the molecular weight of the compound.

For mixtures of miscible chemicals that are fractionally soluble in water, the concentration at which NAPL will be present is a function of the mixture composition. The soil saturation limit for the mixture is (Brost et al., 2000) using equation (A9) below:

where  $C_{\text{sat,soil,T}}$  is the soil saturation limit for the NAPL mixture,  $\rho_b$  is the dry bulk density ( $\text{g/cm}^3$ ),  $\theta_w$  is the water-filled porosity,  $K_{\text{oc}}$  is the organic carbon-water partitioning coefficient ( $\text{mg/kg-OC per mg/L-water}$ ),  $f_{\text{oc}}$  is the fraction organic carbon,  $H'$  is the dimensionless Henry's Law constant, and  $\theta_a$  is the air-filled porosity. The soil saturation limit for an individual compound using equation (A10) below:

*For chemicals that are solids at room temperature, the subcooled liquid solubility should be used in place of the solid solubility.*

#### A4.4 Summary of Two- and Three-Phase Partitioning Models

In summary, a **three-phase** partitioning model is used when NAPL is not present, and a **two-phase** model for partitioning between NAPL and vapour is used when NAPL is present. When there are site-specific data on mass and mole fraction, the partitioning equations can be adjusted to reflect the lower predicted vapour concentrations that will result.

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 solubility limit. When a soil concentration is greater than the  $C_{\text{sat}}$  and the groundwater concentration is greater than the solubility limit, the NAPL to vapour partitioning relationship is used, and vapour concentrations are constant regardless of concentration. If the predicted vapour concentration 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.

#### A4.5 Four-Phase Model

A **four-phase** model for partitioning between the sorbed aqueous soil-air and NAPL phases has recently been developed and applied to the vapour intrusion pathway (Park and San Juan, 2000). This model is not used for this guidance, but has been adopted by some regulatory jurisdictions in the United States (State of Washington, U.S. EPA Region 9). The four-phase model accounts more for mass and volume conservation among all four phases and enables more accurate estimation of mole fraction in the NAPL phase, for a multi-component mixture. The disadvantage is that it is more computationally complex. Comparisons among the three- and two-phase models, described above, and the four-phase model indicate that the three- and two-phase models, in almost all cases, provide for conservative predictions.

(A9)

$$\Sigma [ C_{\text{sat,soil,T}} * W_i * \rho_b / S_i * (\theta_w + K_{\text{oc}} * f_{\text{oc}} * \rho_b + H' * \theta_a) ]$$

(A10)

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

## **A5.0 DERIVATION AND USE OF VAPOUR ATTENUATION FACTORS**

### ***A5.1 General Considerations***

The vapour attenuation factor charts for SLRA are based on two different soil types (fine- and coarse-grained), and the depth to the contamination source. The attenuation factor charts are for two scenarios:

1. a groundwater contamination source with chemical transport through both the capillary transition zone and unsaturated zone, and
2. a 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. As described below, a slab-on-grade scenario was also considered as part of the development process, and was found to yield similar factors compared with a basement. For the commercial scenario, a slab-on-grade scenario was assumed.

The attenuation factors charts were derived using the J&E model and input values provided in Table A2. 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; this is because 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 conditions precluded from the secondary screening). However, to avoid the compounding effect of choosing conservative values for all input parameters, “typical” or mean values were chosen for some input parameters.

**Table A2. Johnson and Ettinger Model Input Values for Derivation of Attenuation Factor Charts**

Input Parameter	Units	Residential	Commercial
Coarse-Grained Sand (U.S. SCS* Sand)			
Unsaturated Zone Water-Filled Porosity	cm <sup>3</sup> /cm <sup>3</sup>	0.054	0.054
Total Porosity	cm <sup>3</sup> /cm <sup>3</sup>	0.0375	0.375
Capillary Transition Zone Water Porosity	cm <sup>3</sup> /cm <sup>3</sup>	0.253	0.253
Capillary Transition Zone Height	cm	17	17
Fine-Grained (U.S. SCS Loam)			
Unsaturated Zone Water-Filled Porosity	cm <sup>3</sup> /cm <sup>3</sup>	0.148	0.148
Total Porosity	cm <sup>3</sup> /cm <sup>3</sup>	0.399	0.399
Capillary Transition Zone Water Porosity	cm <sup>3</sup> /cm <sup>3</sup>	0.332	0.332
Capillary Transition Zone Height	cm	37.5	37.5
Effective Soil Gas Permeability	cm <sup>2</sup>	Not Used	1 × 10 <sup>-7</sup>
Q <sub>soil</sub>	L/min	5 (empirical)	4.3 (calculated)
Soil Temperature	°C	15	15
Henry's Law Constant†		Chemical specific	Chemical specific
Free Air Diffusion Coefficient		Chemical Specific	Chemical Specific
Building Depressurization	Pa	Not Used	2
Building Air Change Rate	hr <sup>-1</sup>	0.3	1
Building Mixing Height – Basement	m	3.66	N/A‡
Building Mixing Height – Slab-on-Grade	m	2.44	3
Building Footprint Area – Basement	m <sup>2</sup>	100	N/A
Building Footprint Area – Slab-on-Grade	m <sup>2</sup>	100	300
Subsurface Foundation Area	m <sup>2</sup>	180	N/A
Subsurface Foundation Area – Slab-on-Grade	m <sup>2</sup>	106	370
Depth to Base of Foundation – Basement	m	2	N/A
Depth to Base of Foundation – Slab-on-Grade	m	0.15	0.5
Perimeter Crack Width	mm	1	1
Building Crack Ratio	Dimensionless	0.00038 (calculated)	0.0002 (calculated)
Building Crack Ratio – Basement	Dimensionless	0.0002 (calculated)	N/A
Crack Dust Water-Filled Porosity	cm <sup>3</sup> /cm <sup>3</sup>	Dry	Dry
Building Foundation Slab Thickness	m	0.1	0.15

\* U.S. Soil Conservation Service.

† Henry's Law Constant adjusted for temperature based on method provided in *User's Guide for Evaluating Vapor Intrusion into Buildings* (U.S. EPA, 2004).

‡ Not applicable.

The suggested minimum site characterization information needed for use of the vapour attenuation charts 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 if precluding factors apply. The number of samples and measurements needed to establish the above information varies by site.

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

## **A5.2 Justification for Input Parameters**

### **A5.2.1 Residential and commercial soil-dependent properties**

The soil-dependent properties for the coarse- and fine-grained soil fractions were derived using a sand and loam as representative soil types. Test data according to the U.S. Soil Conservation Service (SCS) system of soil texture

classification were used to obtain soil properties for sand and loam. Coarse-grained soils (sand) are defined as having a mean grain size larger than 75 µm, whereas fine-grained soils (loam) are defined as having a mean grain size smaller than 75 µm.

The vapour attenuation factors are derived for four soil textures based on the U.S. SCS classification system. The properties of each soil texture class were derived using the water-retention model described in this appendix. The soil texture classes – 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 because unfractured homogeneous clay deposits are uncommon.

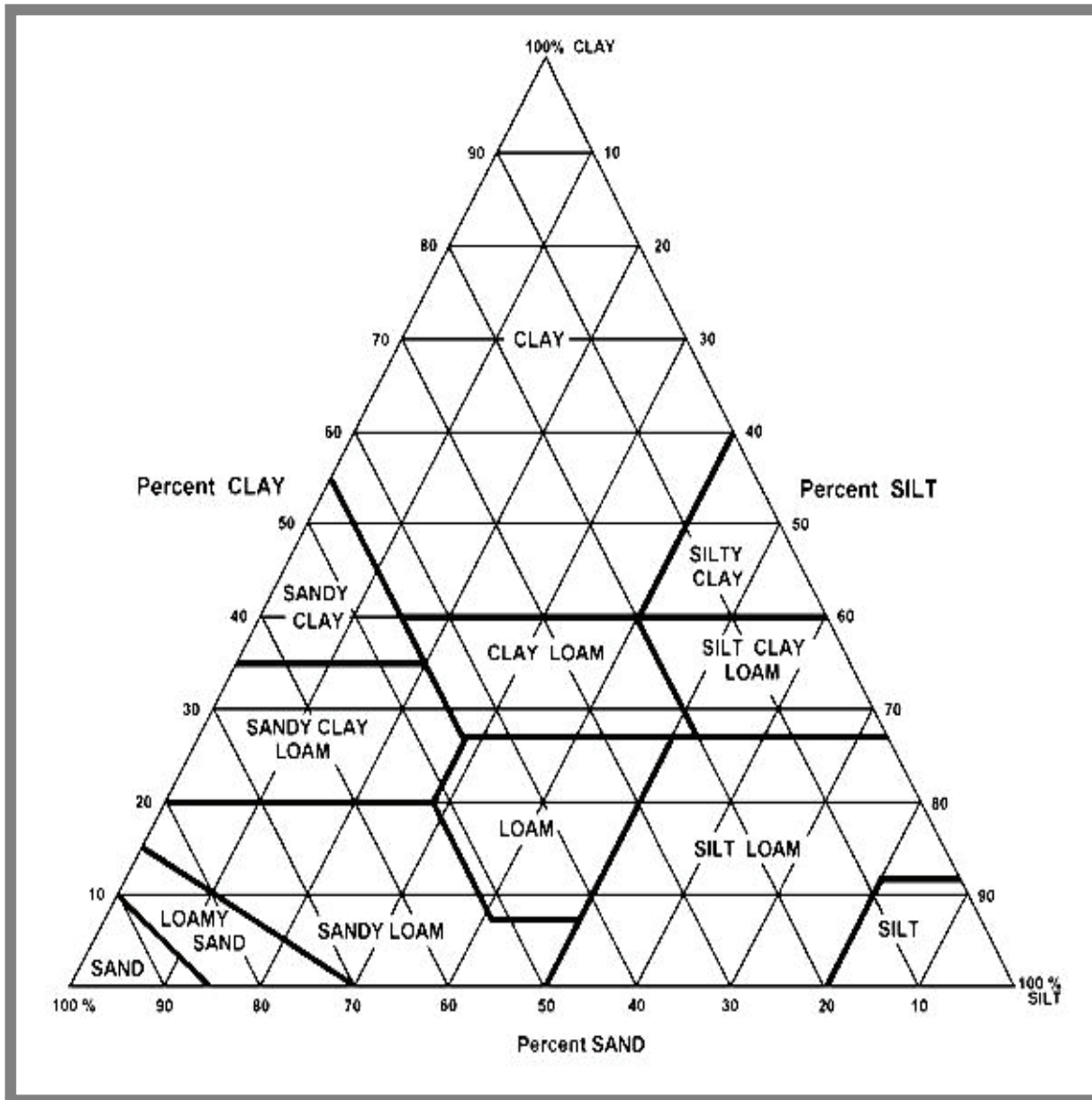
The preferred method for determining the soil texture class are lithological descriptions combined grain-size distribution tests. The soil textural triangle provided in Figure A1 may be used to determine the soil texture. If the soil plots on a soil texture class are not addressed in the guidance, the next coarsest soil type should be chosen. If no grain-size distribution tests are available, Table A3 may be used to guide selection of the soil type.

**Table A3. Selection of Soil Type**

<b>If the coarsest soil type is:</b>	<b>Recommended Soil Texture</b>
"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 A1. Soil Textural Triangle



The coarsest grain size present below the building should dictate selection of soil texture; however, if the coarsest layer represents less than 5% of the distance between the foundation and vapour contamination source, then the next coarsest layer can be selected.

The method used to estimate the soil moisture was the van Genuchten water-retention model (van Genuchten, 1980) to approximate moisture contents based on fitted parameters for test data on U.S. SCS soils. Soil above the water table is divided into two zones for the purposes of estimating soil moisture: the unsaturated zone and the capillary transition zone.

For the unsaturated zone, the default value for soil moisture was a value equal to halfway between the residual saturation

value and field capacity, using the van Genuchten model-predicted values that were derived from model curve-fit parameters computed by Schaap and Leij (1998) for U.S. SCS soil types.

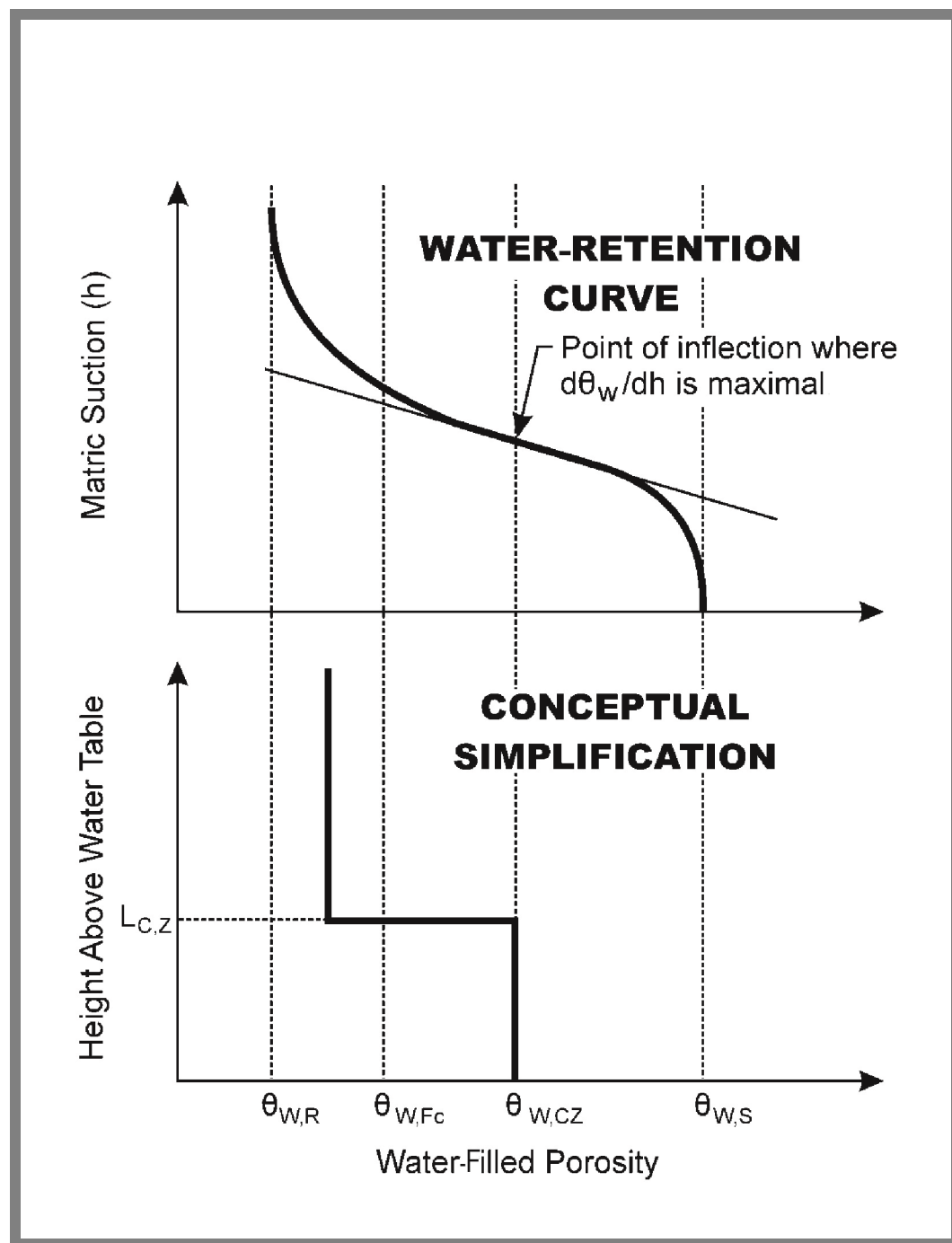
For the capillary transition zone ( $\theta_{w,cz}$ ), the moisture content is the water-filled porosity at the inflection point in the water-retention curve where  $d\theta_w/dh$  is maximal, and where  $\theta_w$  and  $h$  equal the water-filled porosity and matrix suction, respectively. Vapour-phase 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 U.S. SCS soil textural classifications (Nielson and Rogers, 1990). The bi-

linear model for estimation of moisture content is graphically shown in Figure A2.

Soil types coarser than U.S. 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 the 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; this reflects the good drainage characteristics of sand.

Figure A2. Model Used to Estimate Water-Filled Porosity in Soil



### ***A5.2.2 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, and 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; this causes 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); this can be from leaking supply air ducts, restricted or insufficient return air, or unbalanced exhaust systems. Building depressurization values are compiled in Table A4.

Table A4. Survey of Building Depressurization Relative to Atmospheric Pressure \*

Reference**	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Depressurization (Pa)	Comments
19	Measured	Netherlands	Houses with crawlspaces	N/A		~2	Between indoor spaces and crawlspaces
14	Measured	Canada	Houses: Halifax (12), Ottawa/Hull (16), Winnipeg (12), Vancouver (12)	Winter 1993	Range: average for house	~2  ~5 to 15 0.5 to 8.5	Between crawlspace and soil  Mix older and newer houses. most houses had forced-air heating system and basement, depressurization correlated to house construction (full, partial basement, slab-on-grade) and climate
9	Measured	Spokane River Valley, Wash., U.S.A.	House (14)	Winter	Average	2 to 6	
7	Measured	Chicago, Ill., U.S.A.	House (1)	Feb. 17 to June 1, 1982	Range	0.6 to 4.3	Basement pressure differential decreased between Feb. 17 and June 1
20	Predicted	Alameda, Calif., U.S.A.	Small commercial building (1)	N/A	Range	1 to 4	Predicted based on wind loading
8	Predicted	Portland, Ore., U.S.A.	2 storey house with basement	N/A		~2	Predicted based on wind
47	General reference	N/A	Houses	N/A		~2	Predicted based on stack effect
18	Guidance	Canada	slab-on-grade house slab-on-grade house 1–2 storey house 1–2 storey house 3 storey house 3 storey house	N/A		up to 10	Upper range associated with extreme weather conditions
					Range	1 to 3	Mild to severe winter, without chimney
					Range	3 to 5	Mild to severe winter, with chimney
					Range	4 to 6	Mild to severe winter, without chimney
					Range	8 to 10	Mild to severe winter, with chimney
					Range	7 to 9	Mild to severe winter, without chimney
					Range	13 to 15	Mild to severe winter, with chimney

\*\* References from Put and Meijer, 1989 (In Dutch)

\* If the house has 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.

The method often used with the J&E model for estimating  $Q_{\text{soil}}$  through the building envelope is an analytical solution for two-dimensional soil-gas flow to a small horizontal drain (Nazaroff 1992). The use of this model (i.e. Perimeter Crack Model) can be problematic because  $Q_{\text{soil}}$  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  $Q_{\text{soil}}$  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,  $Q_{\text{soil}}$  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 (Fischer et al. 1996; Garbesi and Sextro, 1989; Hers et al. 2002; Garbesi et al. 1993; Rezvan et al., 1991;). The  $Q_{\text{soil}}$  values measured using tracer techniques were compared with 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., 2002). Although the  $Q_{\text{soil}}$  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 provide insight into the extent of the advective flow zone. For example, Garbesi et al. (1993) report a pressure coupling between soil and 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%. 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.

Because the advective flow zone is relatively limited in extent, the soil type adjacent to the building foundation is important. In many cases, coarse-grained imported fill is placed below foundations, 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  $Q_{\text{soil}}$  value of 10 L/min was to obtain a  $Q_{\text{soil}}$  to building ventilation-rate ( $Q_{\text{build}}$ ) ratio that was representative of the available tracer-test data (Table A5) and empirical subslab soil vapour attenuation factors.<sup>1</sup> When advection is the main process for vapour intrusion, the subslab vapour attenuation factor is approximately equal to  $Q_{\text{soil}}/Q_{\text{build}}$ . The  $Q_{\text{soil}}/Q_{\text{build}}$  ratio chosen ( $4.7 \times 10^{-3}$ ) is only slightly higher than the median empirical subslab ratio ( $2.8 \times 10^{-3}$ ). The  $Q_{\text{soil}}/Q_{\text{build}}$  ratios are also consistent with those recommended by Johnson (2002). Because the building ventilation rate is approximately proportional to the building size, the use of  $Q_{\text{soil}}/Q_{\text{build}}$  indirectly takes into account the building size. A  $Q_{\text{soil}}$  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 width, soil-air permeability representative of sand ( $k = 10^{-7} \text{ cm}^2$ ), and building depressurization of about 8 Pa.

<sup>1</sup> As indicated in Appendix B, an in-progress U.S. EPA study indicates that the subslab vapour attenuation factors for filtered data (417 data points) range from 6.2E-04 (10<sup>th</sup> percentile) to 1.4E-2 (90<sup>th</sup> percentile) with a median value of 2.8E-03 (personal communication, Dr. Helen Dawson, USEPA).

**Table A5. Measured Soil-Gas Advection Rate into Buildings from Tracer Studies**

Study	Building	Soil Type	Tracer	$\Delta P$	$Q_{\text{soil}}/Q_{\text{build}}$	$Q_{\text{soil}}$ (L/min)	$Q_{\text{soil}}/\text{Area}$ (L/m <sup>2</sup> )	$Q_{\text{soil}}/\text{Area} \cdot \Delta P$ (L/m <sup>2</sup> -Pa)
Sanders et Hers (2006)	House with basement	Medium Sand	PHCs*		0.00729927	3.3	N/A**	N/A
Hers (ongoing study)	House with basement and crawlspace	Sand	MTBE† cyclohexane, 2,2,4-trimethylpentane	0.6	0.0039 to 0.0084	N/A	N/A	N/A
Hers (ongoing study)	Houses with basement	Sand and Gravel	TCE‡	4 (average)	0.001 TO 0.0064	N/A	N/A	N/A
Olson and Corsi (2001)	House with basement, Paulsboro	Sand (some silt)	SF <sub>6</sub> §	3.6 to 6.2	0.003 to 0.01	5.8 to 6.7	0.18 (6.2 Pa)	0.03
Mose and Mushrush (1999)	Houses, Virginia	N/A	Radon	N/A	0.003 to 0.02	N/A	N/A	N/A
Hers (1998)	Experimental greenhouse, Chatterton	Medium 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	Fine Sand	SF <sub>6</sub>	10	0.0002 to 0.0004	4.5	0.018	0.006
Garbesi et al. (1993)	Small experimental basement	Fine Sand	N/A	20	N/A	20		0.04
Little et al. (1992)	Houses, U.S.A.	N/A	Radon	N/A	0.0016 (average)	N/A	N/A	N/A
Garbesi and Sextro (1989)	House with basement	Sandy Loam to Loamy Sand	SF <sub>6</sub>	30	~0.001	67 (best estimate)	N/A	0.01 (best estimate)
Rezvan et al. (1989)	Houses	Gravel	Radium	N/A	0.0079 to 0.045	17 to 96††	N/A	N/A

\* Petroleum hydrocarbons.

† Methyl *tert*-butyl ether.

‡ Trichloroethylene.

§ Sulfur hexafluoride.

# Benzene, toluene, and xylenes.

\*\* Not applicable.

†† Estimated, using assumed values for house volume (366 m<sup>3</sup>) and air exchange AEH (0.35/hr)

### A5.2.3 Commercial $Q_{soil}$ (default value = 4.3 L/min)

For commercial buildings, there is a large variation in size, design, and construction. As a result, prediction of soil-gas advection is highly uncertain. There are also little, 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 or 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. Several case studies indicate 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, 2005) indicates that significant negative pressures (several hundred pascals) can theoretically develop in multi-storey buildings unless controlled through building ventilation and measures that control 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 because of the influence of environmental factors such as temperature and wind. Although there is significant uncertainty for building pressurization and  $Q_{soil}$ , it is clear that the potential for negatively pressurized commercial buildings exists, and that predictive modelling of vapour intrusion into commercial buildings should include a soil-gas advection component.

Empirical data for commercial sites that would enable estimation of  $Q_{soil}$  are limited. In general, a lower  $Q_{soil}/Q_{build}$  ratio would be expected for commercial buildings compared with residential houses, based on the building construction (typically slab-on-grade or subsurface parking garage) and typically better quality foundation construction for commercial buildings. 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 ( $4.7 \times 10^{-4}$ ) than the residential value was chosen, based on best professional judgment. The corresponding  $Q_{soil}$  based on the default building size and ventilation rate is 7 L/min.

Although modelling 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 Pa to 4 Pa) and sandy soils. The other defaults used for the modelling are provided in Table A2. Using a building depressurization of 2 Pa to 4 Pa, a  $Q_{soil}$  of 4.3 L/min to 8.6 L/min and  $Q_{soil}/Q_{build}$  of  $2.9 \times 10^{-4}$  to  $5.8 \times 10^{-4}$  is calculated. The  $Q_{soil}/Q_{build}$  chosen is within the range calculated using the model suggesting it is reasonable.

### A5.2.4 Residential building air-change rate (default value = 0.35 hr<sup>-1</sup>)

Ventilation has three components (Nazaroff, 1992):

1. infiltration, or uncontrolled leakage of air into a building through openings in the building envelope ,
2. natural ventilation through open windows and doors, and
3. mechanical ventilation provided by fans.

Ventilation rates reported in the literature vary significantly, with results from 27 studies summarized in Table A6. 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 "airtight" houses with reduced ventilation rates to minimize energy consumption and costs (e.g. R-2000 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).

Table A6. Survey of Building Ventilation Rates

Reference	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Air Exchange (ACH)	Comments
Borman and Lyberg (1986)	Measured	Sweden	Detached and row houses	1974–1982	Average	0.17	No mechanical ventilation, 1975 and later
			3 storey apartments		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, 4 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 meteorological conditions, extended use of doors caused ACH to exceed 3
ASHRAE (1985)	Measured	USA	Houses	N/A	Typical range	0.20–2	Median values for two studies
					Median	0.5, 0.9	
Grimsrud et al. (1982)	Mostly predicted	North America	Houses (312)	N/A	Average	0.63	Mostly predicted using Lawrence Berkeley Laboratory model (stack and 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	



Reference	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Air Exchange (ACH)	Comments
CMHC (1997)	Guidance	Canada	Wood frame pre–1945	N/A	Typical range	0.5–1	Estimated heating season, natural ventilation
			Wood frame 1946–1960	N/A	Typical range	0.2–0.4	Estimated heating season, natural ventilation
			Wood frame 1961–1980	N/A	Typical range	0.15–0.3	May be 0.2 intermittent
			Airtight new house	N/A	Typical range	0.05–0.1	0.3 installed capacity
Olson et al. (1996)	Guidance	Canada	Houses	N/A	Low	0.1	
					Typical range	0.3	
Commercial Buildings							
Ekberg (1994)	Measured SF <sup>6</sup>	Sweden	Office buildings (4)	Jan. 1990, to Dec. 1991	Range	3.2 to 4	Measured during periods of mechanical ventilation
Sheldon et al. (1988)	Measured SF <sup>6</sup>	Washington D.C., U.S.A.	Old–age home	Winter 1983		1.72 +/- 0.41	High ACH attributed to excessive heating and cold outdoor temperatures
			School	1983		0.85 +/- 0.31	
			Office	Jul.1, 1983		0.61 +/- 0.32	
			Office	Sept. 1983		0.52 +/- 0.25	
Dols and Persily (1995)	Measured SF <sup>6</sup>	Portland, Ore., U.S.A.	Office building (7 stories, floor area of 34,600 sq. m <sup>2</sup> )	Aug. 6,1991	Measured @ minimum intake fresh air ~10th to 90th	0.45	Designed to ASHRAE 62–1981, which is approximately 0.18 ACH for and office building

Reference	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Air Exchange (ACH)	Comments
Fang and Persily (1995)	Measured SF <sub>6</sub>	Overland, Mo., U.S.A.	Office building (7 stories, floor area of 32,500 sq. m <sup>2</sup> )		percentile building air change		
				Jan. 13, 1992		0.6–1.9	Percent outdoor air generally ranged between 70% and 100% of total building air exchange rate
					Measured @ minimum intake fresh air	0.3	
					Measured @ maximum intake fresh air	2.6	
Table 5: Survey of Building Ventilation Rates							
<b>Residential Houses</b>							
Hancock et al. (2002)	Measured SF <sub>6</sub>	San Antonio, Tex., U.S.A.	2 houses	Aug. 1, 2000	Range	0.2–0.3 0.05–0.15	When AC on (summer) When AC off (summer)
					Range		
Lawrence Berkeley National Laboratory (2001)	Measured SF <sub>6</sub>	Florida, U.S.A.	11 houses	Fall 1997 to Spring 1998	Range	0.14–0.78	Lower ACH were obtained in homes with Heat Recovery Ventilator
Olson and Zhu (1997)	Measured PFT	Greater Toronto, Ont., Canada	Houses (44)	Feb. 12 to Apr. 9, 1996	Average Median	0.45 0.4	
Murray and Burmaster (1995)	Measured PFT	U.S. EPA Region 1	Houses (467)	All seasons	Mean	0.4	5th and 95th percentiles = 0.1, 0.95
		U.S. EPA Region 2	Houses (1,496)	All seasons	Mean	0.55	5th and 95th percentiles = 0.14, 1.38
		U.S. EPA Region 3	Houses (332)	All seasons	Mean	0.55	5th and 95th percentiles = 0.15, 1.25

Reference	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Air Exchange (ACH)	Comments
		U.S. EPA Region 4	Houses (1,549)	All seasons	Mean	0.98	5th and 95th percentiles = 0.21, 2.82
		U.S. EPA Region 1	Houses (161)	Winter	Mean	0.36	5th and 95th percentiles = 0.08, 0.90
		U.S. EPA Region 1	Houses (254)	Spring	Mean	0.44	5th and 95th percentiles = 0.14, 1.06
		U.S. EPA Region 1	Houses (5)	Summer	Mean	0.82	5th and 95th percentiles = 0.27, 2.01
		U.S. EPA Region 1	Houses (47)	Fall	Mean	0.25	5th and 95th percentiles = 0.1, 0.58
Saskatchewan Research Council (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)	1992–1993	Average	0.34	Most measurements in fall and winter months
Saskatchewan Research Council (1992)	Measured PFT	Saskatoon and Regina, Sask., and Tillsonburg, Ont., Canada	Houses (44)	Jan. 14 to Feb. 11, 1991	Average	0.34	
					Median	0.31	
Rothweiler et al. (1992)	Measured N <sub>2</sub> 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	U.S.A.	Houses (4,000)	Mostly 80s early 90s	Average	2	All regions (standard deviation = 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

Reference	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Air Exchange (ACH)	Comments
Lewis and Zweidinger (1992)	Measured SF <sub>6</sub>	Boise, Idaho,, U.S.A.	Houses (10)	Nov. 15, 1986, to Feb. 4, 1987	Average	5.4	Summer, all regions
					Average	0.4	Fall, all regions
					Average	0.45	
Mailahn et al. (1989)	Measured PFT and HFB	Berlin, Germany	Houses (10)	Sept. 1986, to Apr. 1987	Median	0.45	
					Average	1.01	Older houses had statistically significant higher ACH (1.2) than newer houses (0.88)
					Median	1.02	
Mueller et al. (1998)	Measured	U.S.A.	Houses	N/A	Typical range	0.5–1.5	Typical houses
						0.5–0.8	New/energy efficient house, as low as 0.2
Walkinshaw (1987)	Measured	Ont., Canada	Houses (70)		Range	0.06–0.77	Lowest ACH in summer with windows closed
			R–2000 Houses		Range	0.34–0.37	R–2000 houses

Standards in Canada and the United States 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 United States, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) 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. It appears that mechanical ventilation systems are quite frequently operated at less than the design or installed capacity (Figley, 1997; Hamlin and Gusdorf, 1995).

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 ACH for energy-efficient “air-tight” houses (built in cold climates) (Fellin and Otson, 1996) to over 2 ACH (upper range; ASHRAE, 1985). 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. One of the most comprehensive studies of American 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, respectively. 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 U.S.A.), the 10th, 50th, and 90th percentile values were 0.11, 0.27, and 0.71 ACH, respectively. In contrast, for the winter season and warmest climatic area (Region 4, southern California, Texas, Florida, and Georgia), the 10th, 50th, and 90th percentile values were 0.24, 0.48, and 1.13 ACH, respectively. Although 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  $0.35 \text{ hr}^{-1}$  was selected to represent the lower end of these distributions.

#### ***A5.2.5 Commercial building air-change rate (default value = $1 \text{ hr}^{-1}$ )***

The data set for commercial buildings is relatively limited (Table A6). 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.

The ASHRAE Standard 62-2001, entitled *Ventilation for Acceptable Indoor Air Quality*, provides minimum ventilation rates for different types of commercial and institutional buildings. For example, for offices, the minimum outdoor air ventilation requirement for office space is 10 L/s (20 cfm) per person; this corresponds to an air-change rate of about 0.72 ACH. An earlier ASHRAE Standard 62-1981 had a lower ventilation requirement that corresponded to an air change of about 0.18 ACH. The default ventilation rate selected for a commercial building was 1 ACH.

#### ***A5.2.6 Residential building mixing height (default value = 2.44 m for slab-on-grade scenario; = 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 mixing height will depend on a number of factors, including the building height, the HVAC system operation, environmental factors (e.g. 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 electrical baseboard heaters. It is likely that the mixing height, to some degree, is correlated to the building air-change rate.

Little data that provide for direct inference of mixing height are available. 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 (Colorado Department of Transport); Redfields Eau Claire; Juniper). 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 levels. For the CDOT site apartments, there was an approximate five-fold reduction between the concentrations measured for the first-floor and second-floor units (Jeff Kurtz, EMSI Inc., pers. comm., 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). Less mixing would be expected for an apartment because there are less cross-floor connections than for 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.

### ***A5.2.7 Commercial building mixing height (default value = 3 m)***

The default commercial building 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.

As part of an SLRA, little detailed information on building conditions is likely to be available. However, if information clearly indicates that the default mixing height is not representative, the attenuation factors in the guidance can be easily scaled using a linear relationship; this is because the attenuation factor is inversely proportional to the mixing height.

- For example, if the building under evaluation is a warehouse structure with high ceilings with no significant thermal stratification, there is the option to adjust the attenuation factor, as follows:

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

$$\text{Crack Ratio} = \text{Crack Width} \times 4 \times (\text{Subsurface Foundation Area})^{0.5} / \text{Subsurface Foundation Area}$$

There is a slight difference in crack ratio for the two scenarios based on the slight difference in subsurface foundation area. However, this difference has no effect on the calculated attenuation factors.

Little information is 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 10 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, whereas the total crack length per house ranged from 2.5 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

- Adjusted Attenuation Factor = (3.0 m/Site-Specific Mixing Height) × Attenuation Factor
- This scaling procedure is also addressed in the example calculation section.

### ***A5.2.8 Residential crack width (default value = 1 mm) and crack ratio (default value = 0.0002 for basement house; = 0.00038 for slab-on-grade 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:

0.01. The selected default values (Table A2) fall within the ranges observed.

### ***A5.2.9 Commercial crack width (default value = 1 mm) and crack ratio (default value = 0.0002 for slab-on-grade building)***

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

### ***A5.2.10 Residential building area (default 10 m × 10 m) and subsurface foundation area for basement (default value = 180 m<sup>2</sup>)***

The residential building area, corresponding to a building with a 1,076 ft<sup>2</sup> footprint, is a subjectively chosen default value. However, the building area chosen is considered appropriate based on the  $Q_{\text{soil}}$  input selected, which is linked to building area through the  $Q_{\text{soil}}/Q_{\text{build}}$  relationship.

The default building area chosen is similar to the default values used in the Superfund User's Guide (Environmental Quality Management, Inc., 2004) for the J&E Model (9.61 m × 9.61 m or 92.4 m<sup>2</sup>) and the default values used by the State of Michigan's Part 1, Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria: Technical Support Document

(10.5 m × 10.5 m or 111.5 m<sup>2</sup>). The State of Michigan guidance document indicates that the 111.5 m<sup>2</sup> 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 and the U.S. Department of Housing and Urban Development.

**A5.2.11 Commercial building area (default 20 m × 15 m) and subsurface foundation area (default value = 310.5 m<sup>2</sup>)**

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 in the CCME Canadian Wide Standards (PHCs) (CCME, 2008a,b).

**A5.3 Considerations Relating to Foundation Type**

Vapour attenuation factors were calculated for both a basement and slab-on-grade scenario for the input parameters in Table A2. Both scenarios assumed a  $Q_{\text{soil}}$  of 5 L/min because cracks, drains, and other foundation openings may exist for both foundation types. There was little difference in attenuation factor between the basement and slab-on-grade scenarios (<10%). The reason relates to the building foundation area and volume. The mass flux into the building is approximately proportional to the foundation area (180 m<sup>2</sup> for basement and 106 m<sup>2</sup> for slab-on-grade). The indoor air concentrations are proportional to the flux divided by the building mixing volume (366 m<sup>3</sup> for basement and 244 m<sup>3</sup> for slab-on-grade). Although the flux is higher for the basement scenario, there is also greater dilution; this results in attenuation factors similar to the slab-on-grade scenario. Provided that the  $Q_{\text{soil}}$  for each scenario is the same, the balancing effect of flux area and dilution volume can also be expressed through the foundation area to enclosed space ratio. Because there was little difference between the basement and slab-on-grade scenarios, only attenuation factors for the basement scenario are provided.

**A5.4 Considerations Relating to Use of Benzene as Surrogate Chemical**

The guidance attenuation factor charts are based on physical-chemical properties for benzene, but are applied to all chemicals with the assumption that their properties are sufficiently similar to benzene for screening purposes.

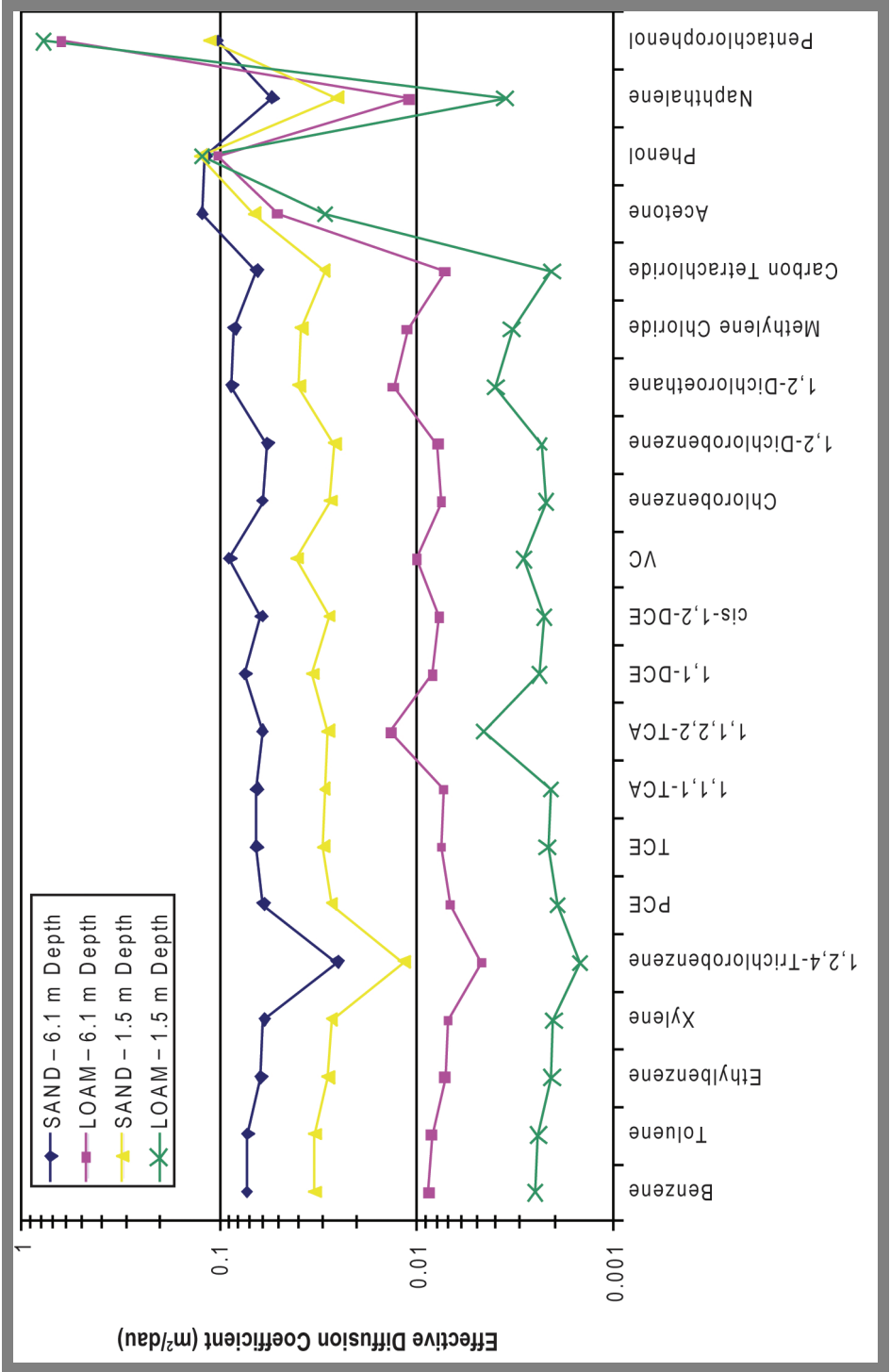
Diffusive transport is the only process incorporated in the attenuation factor estimation affected by chemical-specific properties (free-air diffusion coefficient and Henry's Law constant). Advective transport of soil gas is not affected by chemical-specific properties. The diffusion rate (i.e. flux) is directly proportional to the attenuation factor when there is no advective transport into the building (i.e. a two-fold increase in

diffusion rate results in a two-fold increase in the attenuation factor). When there is advective transport, the relative importance of diffusion diminishes. Fortunately, the chemical-specific variation in the effective diffusion coefficient is, in most cases, not significant relative to other sources of uncertainty; this is because the free-air diffusion coefficients generally vary by only a factor of two for most volatile organic compounds. This is small relative to the order-of-magnitude range of values expected from a screening-level model.

To further evaluate the significance of physical-chemical properties on diffusion, the depth-integrated effective diffusion coefficient, calculated for a two-layer soil profile (capillary transition zone and unsaturated zone), was compared for several volatile organic compounds (VOCs) (Figure A3). The "overall" depth-integrated effective diffusion coefficient was calculated for four scenarios with two different U.S. SCS soil types (sand and loam) and two different depths to contamination source (1.5 m and 6.1 m). The effective diffusion coefficient is less for a smaller depth to contamination because the relative effect of the capillary fringe on the overall effective diffusion coefficient is greater. The effective diffusion coefficient for the capillary fringe is low because of high-moisture content, and the fact that aqueous diffusion coefficients are typically about four orders of magnitude lower than gaseous diffusion coefficients.

The results indicate that for most VOCs, the effective diffusion coefficient is less than a factor of two greater than or less than that for benzene; consequently, the change in vapour attenuation ratio would also be less than a factor of two. Chemicals with significantly higher effective diffusion coefficients, such as phenol ( $H' = 1.6 \times 10^{-5}$ ), acetone ( $H' = 1.6 \times 10^{-3}$ ), and pentachlorophenol ( $H' = 1 \times 10^{-6}$ ) could have significantly higher effective diffusion coefficients; however, the low Henry's Law constants result in very low source-vapour concentrations compared with health-based reference concentrations; therefore, these chemicals will, in most cases, not be of concern. For comparison, the dimensionless Henry's Law constant for benzene is 0.23. When NAPL is present, the relevant physical-chemical property affecting the source-vapour concentration is the vapour pressure. Therefore, at sites where NAPL is present, it may be appropriate to compare the vapour concentration from the Henry's Law constant calculation to that based on vapour pressure as a final check for chemicals that have significantly different properties compared with those of benzene.

Figure A3. Comparison Effective Diffusion Coefficient for Selected Chemicals





### ***A5.5 Considerations Relating to Transport Through Capillary Transition Zone***

The derivation of the attenuation factor chart for a groundwater contamination source assumed that the top boundary for contamination was the water table. This is the typical assumption when the J&E model is used for a groundwater source. Chemical transport through the capillary transition zone is limited to diffusion in both soil vapour and pore water.

There are other potential mechanisms for chemical mass transport through the capillary transition zone that could result in greater chemical flux than that predicted through diffusion alone. They include fluctuations in the water-table level and lateral flow of contaminated groundwater through the capillary fringe. These mechanisms are not part of the J&E model.

It was hypothesized that the potentially non-conservative aspects associated with not including other chemical mechanisms for transport in the capillary transition zone (i.e. in addition to diffusion) are counterbalanced by input values for the J&E model that underestimate moisture content, and hence overestimate the diffusive transport rate. To test this hypothesis, model predictions for different boundary conditions and input parameters were compared with predictions using the conventional model described above. Specifically, (1) the top boundary for the contamination source was assumed to be the top of the capillary fringe, and (2) the more realistic moisture contents were used to estimate diffusive flux rates by integrating the water-retention curve, as opposed to the approximation based on the bi-linear water-filled porosity profile. The results indicated similar diffusive flux rates for the conventional model with a contamination source at the water table, and the alternate model described above with the contamination source at the top of the capillary fringe.

### ***A5.6 Considerations Relating to Mass Flux in Groundwater***

When contamination is limited to dissolved chemicals migrating in groundwater, the only source of vapours are

chemicals that volatilize from groundwater. The available mass that could potentially volatilize under steady-state conditions is controlled by the mass flux in groundwater flowing below the building. The development of the vapour attenuation factors did not take into consideration possible mass flux considerations and instead assumed an infinite mass of chemicals is always present below the building.

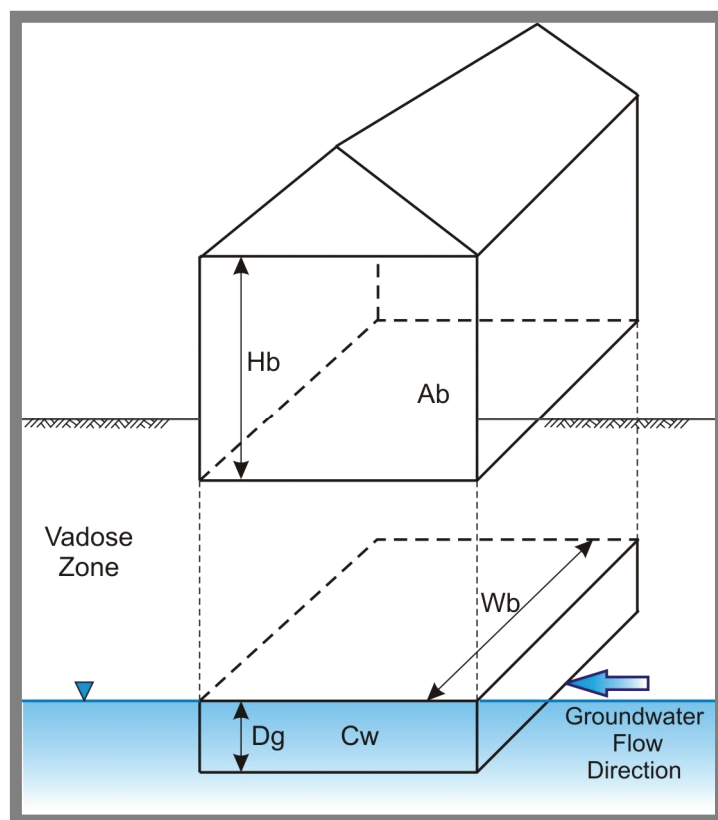
Mass flux calculations indicate that in some cases the semi-site-specific attenuation factors presented in the guidance assume an unrealistic mass flux into the building, based on the available mass of chemical in groundwater. A preliminary evaluation of mass flux was conducted based on a simplified modelling scenario with results presented in Table A7. The calculation assumes that all dissolved chemicals within the top 1 m of groundwater flowing below the entire width of the building will volatilize and enter the building (i.e. leaving no chemicals in groundwater down-gradient of the building) (Figure A4). In reality, dissolved plumes only lose a small portion of their mass through volatilization. The assumed Darcy velocity (specific discharge) was 100 m/year; this corresponds to a groundwater velocity of about 400 m/year, or about 1 m/day. The assumed groundwater velocity is representative of relatively fast-moving groundwater at sites with coarse-grained soils. The assumed groundwater-to-indoor air attenuation factor was 0.001. Both the mass flux entering the building through volatilization and available mass through groundwater transport to below the building were compared. The example calculation results indicate that for TCE, the mass volatilized is less than the available mass; however, for hexane, the available mass in groundwater is insufficient. The results suggest that based on the upper bound attenuation factor of 0.001, there could be mass flux restrictions for volatile chemicals, even when the rate of groundwater flow is relatively fast.

Based on the rationale listed above, this guidance includes a simple mass flux check to ensure that the predicted indoor air concentration, based on the attenuation factor selected, is not unrealistic based on the available mass. The mass flux check is applicable when there is only a dissolved contamination source.

**Table A7. Example Calculations Illustrating Mass Flux Limitations for Dissolved Contamination Source\***

Parameter	Trichloroethylene	n-Hexane
Assumed groundwater concentration ( $C_w$ , mg/L)	0.1	0.1
Assumed Darcy velocity ( $U$ , m/year)	100	100
Maximum available groundwater flux for volatilization ( $\text{Flux}_m$ , mg/min)	0.19	0.19
Assumed vapour attenuation factor	0.001	0.001
Temperature-corrected Henry's Law constant ( $H^1$ , dimensionless)	0.22	2.81
Predicted soil vapour concentration ( $C_a$ , mg/m <sup>3</sup> )	22	281
Predicted indoor air concentration ( $C_{air}$ , mg/m <sup>3</sup> )	0.022	0.281
Predicted vapour flux into building ( $\text{Flux}_p$ , mg/min)	0.046	0.59
Ratio predicted/available flux ( $\text{Flux}_p/\text{Flux}_m$ )	0.24	3.1

\* Calculations are for defaults provided in Exhibit 4, and conservatively assume all dissolved chemicals in top 1 m of groundwater flowing below building volatilize and enter the building.

**Figure A4. Conceptual Model for Groundwater Mass Flux Calculation**

### ***A5.7 Considerations Relating to Contaminant Source Depletion in Soil***

The time for depletion of the contamination source can be calculated when the available mass in soil can be reasonably estimated. The development of the guidance vapour attenuation factors did not take into consideration possible mass flux considerations and instead assumed an infinite mass of chemicals is present below the building. Mass flux calculations indicate that in some cases the semi-site-specific attenuation factors presented in the guidance assume an unrealistic mass flux into the building, based on the available mass in soil and partitioning equations used to predict vapour concentrations from a soil contamination source.

A preliminary evaluation of source depletion was conducted, based on a simplified modelling scenario with results presented in Table A8. The scenario assumes that there is a uniform 3-m thick soil contamination layer above the water

table. Based on the predicted mass flux into the building for the assumed vapour attenuation factor, the time for mass depletion is calculated for TCE and hexane. The calculated time for source depletion is about 2 years for TCE and 2 months for hexane. The short time for source depletion highlights the conservative nature of the partitioning model used to estimate soil vapour concentrations from a soil source, and why the guidance gives preference to use soil vapour to estimate potential health risk from vapour intrusion.

To address source depletion limitations, the guidance includes a simple calculation to estimate the number of years it would take for the contamination source to be depleted (Exhibit 5). It should be noted that this equation assumes a constant vapour flux into the building; this is another reason that source depletion times are short in the examples provided below. If the time for depletion is less than the assumed exposure duration, consideration should be given to conducting a detailed risk assessment that includes soil vapour samples.

**Table A8. Example Calculations Illustrating Source Depletion Calculation for Soil Contamination Source**

Parameter	Trichloroethylene	n-Hexane
Assumed soil concentration ( $C_{\text{soil}}$ , mg/kg)	10	10
Assumed thickness soil contamination ( $T_s$ , m)	3.0	3.0
Available contaminant mass	$4.8 \times 10^6$	$4.8 \times 10^6$
Assumed vapour attenuation factor	0.001	0.001
Predicted soil vapour concentration ( $C_a$ , mg/m <sup>3</sup> )	2,047	29,563
Predicted indoor air concentration ( $C_{\text{air}}$ , mg/m <sup>3</sup> )	2.05	29.6
Predicted vapour flux into building ( $\text{Flux}_p$ , mg/min)	4.3	62
Time for source depletion ( $\text{Time}_d$ , year)	2.1	0.15

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## APPENDIX B

### EVALUATION OF EMPIRICAL VAPOUR ATTENUATION FACTORS (ALPHAS)

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## B1.0 INTRODUCTION

This appendix provides an in-depth evaluation of empirical vapour attenuation factors (“alphas”) at sites with measurements of volatile chemical concentrations in indoor air, and either groundwater, soil vapour, and/or subslab vapour. The purpose of this evaluation is to compare empirical data with model-predicted alphas used to derive the quantitative screening guidance alpha charts for the Health Canada guidance. The ultimate goal of this process is to help define alphas that are reasonably protective of human health based on the best science and currently available data. Because the objective is to protect individuals and the guidance has wide geographic application, the focus of this evaluation has been the upper range of the observed distribution in empirical alphas.

Soil vapour transport and intrusion into buildings can be quantified through use of a vapour attenuation factor (**alpha**) – the ratio of the indoor air concentration divided by soil vapour concentration ( $C_{\text{air}}/C_{\text{vapour}}$ ) at the point of interest (i.e. “ $\mu\text{g}/\text{m}^3/\mu\text{g}/\text{m}^3$ ” or dimensionless ratio), as defined below.

- **Groundwater-to-indoor air alpha** – This alpha is based on the soil vapour concentration estimated from groundwater concentration data using the Henry’s Law constant, and represents chemical transport through both the capillary fringe immediately above the water table and higher regions of the unsaturated zone.
- **Soil vapour-to-indoor air alpha** – This alpha is based on the measured soil vapour concentration within the unsaturated zone, and represents transport through the unsaturated zone.
- **Subslab vapour-to-indoor air alpha** – This alpha is based on the measured subslab vapour concentration measured immediately below a building foundation, and represents transport through the foundation.

The vapour attenuation factor (**alpha**), by definition, is not a constant, and it varies with depth at every site. The three alphas defined above (groundwater, soil vapour, and subslab vapour) represent three points along that spectrum; therefore, alphas promulgated for regulatory guidance should be internally consistent. The main focus of this appendix is groundwater-to-indoor air (**groundwater alpha**) and soil vapour-to-indoor air (**soil vapour alpha**) alphas.

The database on vapour attenuation factors presented in this appendix derives largely from a comprehensive multi-year study conducted in support of the development of the U.S. EPA VI Guidance, with additional data provided through work for Health Canada and research programs completed by Golder Associates for other agencies. The evaluation of vapour attenuation factors is dynamic and ongoing because many vapour intrusion sites have only recently been investigated and new data sets are being generated, and because methods for investigating sites and analyzing the empirical data are evolving.

The compiled database provides measured concentrations for various media (groundwater, soil vapour, and air) and numerous other site data needed for the interpretation of alpha values. The groundwater and soil vapour alpha database, as of May 2006, contained information from 419 sites, comprising 37 residential and four commercial sites, with approximately 1,500 paired measurements of data that enable the calculation of an alpha value. There are both data for sites contaminated with chlorinated solvent chemicals (29 sites) and petroleum hydrocarbon compounds (10 sites).

The evaluation begins with a discussion of issues and challenges for empirical alpha analysis and discussion of background issues. Next, the data-screening and filtering process that was used for this study is described. The appendix concludes with the results of the empirical database and key trends, based on chemical type and site properties.

## B2.0 EMPIRICAL APPROACH – ISSUES AND CHALLENGES

Several issues and challenges for the empirical determination of alpha values from vapour intrusion data in the context of guidance development are described below.

The scope and number of data points at individual sites varies greatly, and ranges from a single measurement in a single building to multiple measurements in hundreds of buildings. Consequently, a relatively high percentage of data points come from a relatively small group of sites.

There are variations in the type of data collected. For example at some sites, only groundwater measurements are available, meaning soil vapour concentrations must be estimated to obtain an alpha value, whereas at other sites, only soil vapour measurements are available. The soil-gas sampling location also varies, and ranges from just above the water table to just below the building foundation.

For sites where groundwater is used for alpha evaluations, screen lengths are often variable, with only a few sites where measurements are taken at discrete depths at the base of the capillary fringe.

There is significant variability with respect to data quality and methods used to investigate vapour intrusion, and also with respect to various levels of available documentation.

Most volatile chemicals of potential concern at contaminated sites are also found indoors as “background” chemicals. As empirical and background studies have progressed over the past several years, it has become clear that some of the empirical data are influenced by background volatile organic compound (VOC) sources.

For the above reasons, data reliability and uncertainty have become critical issues as well as concepts for screening of empirical data used to evaluate vapour intrusion. As subsequently documented in this appendix, the process used to evaluate and filter non-reliable data is an important step in the process of deriving empirical alphas.

## B3.0 SOURCES OF UNCERTAINTY FOR VAPOUR ATTENUATION FACTORS

Factors that contribute to uncertainty in vapour attenuation factors that should be considered when calculating and interpreting empirically defined alpha values include:

1. Groundwater and soil vapour concentrations are not directly measured below buildings, but are either measured external to and some distance from the building or are interpolated values below the building when there were sufficient data.
2. spatial variability in groundwater and soil vapour concentrations, including often relatively steep concentration gradients over short distances;
3. lateral migration of soil vapour away from groundwater contamination sources;
4. spatial variability in subslab soil vapour concentrations;
5. temporal variability, which tends to be least for groundwater measurements and greatest for indoor air measurements, and for which there are varying time scales;
6. transient effects caused by seasonal (or similar time-scale) variability in source concentrations and consequent time lag in observed response in indoor air concentrations;
7. variability caused by sampling and analysis procedures; and

8. background sources of VOCs (ambient air, building materials, consumer products, and occupant-related sources).

The first seven sources of uncertainty listed above can result in either a positive and negative bias in the empirical alpha. The eighth source of uncertainty, background sources of VOCs, will always result in a positive (upward) bias in the vapour attention factor.

As a result of the sources of uncertainty, some alpha values in the database are biased high. For this reason, it is important to screen out or qualify data that may be biased, particularly when data could be influenced by background sources of VOCs. As subsequently described in this appendix, a statistical approach has been followed where upper percentiles of the data (90th percentile) are calculated to provide conservative, yet non-extreme values for regulatory comparison purposes, to account for possible errors and bias in the data.

The empirical alphas presented in this appendix are single point-in-time alphas. For the purposes of human health risk assessment, longer-term mean indoor air concentrations tend to be most relevant. There are a limited number of studies where repeat measurements of source (groundwater) and indoor air measurements have enabled variability because of seasonal or other factors being evaluated. For example, Folkes (2006) calculated time series alphas (4 to 21 points) for five buildings and found that the variance about the mean was approximately plus or minus 1/3 to 1/2 order of magnitude. Although data to quantify these effects (e.g. through analysis of variance approach) are insufficient, the suggestion is that that near maximum empirical alphas overestimate long-term mean alphas.

## B4.0 EVALUATION OF POSSIBLE INFLUENCE OF BACKGROUND VOLATILE ORGANIC COMPOUNDS ON EMPIRICAL ALPHAS

An empirical alpha is calculated by dividing the measured indoor air concentration by the source-vapour concentration. When the subsurface vapour and potential background contributions are explicitly considered, the following relationship is obtained:

(B1)

$$\alpha_{\text{emp}} = (C_{\text{air}}^{\text{vapour}} + C_{\text{air}}^{\text{background}}) / C_{\text{vapour source}}$$

Through rearrangement of equation (B1), the following equation is obtained:

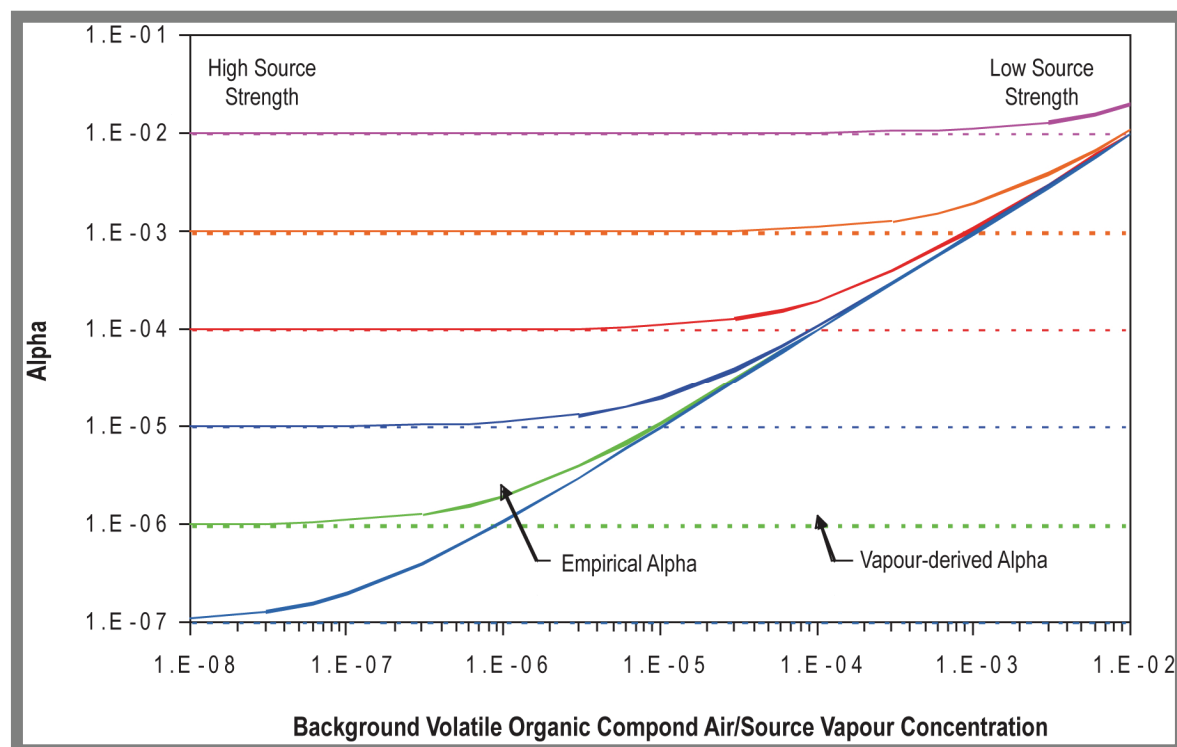
(B2)

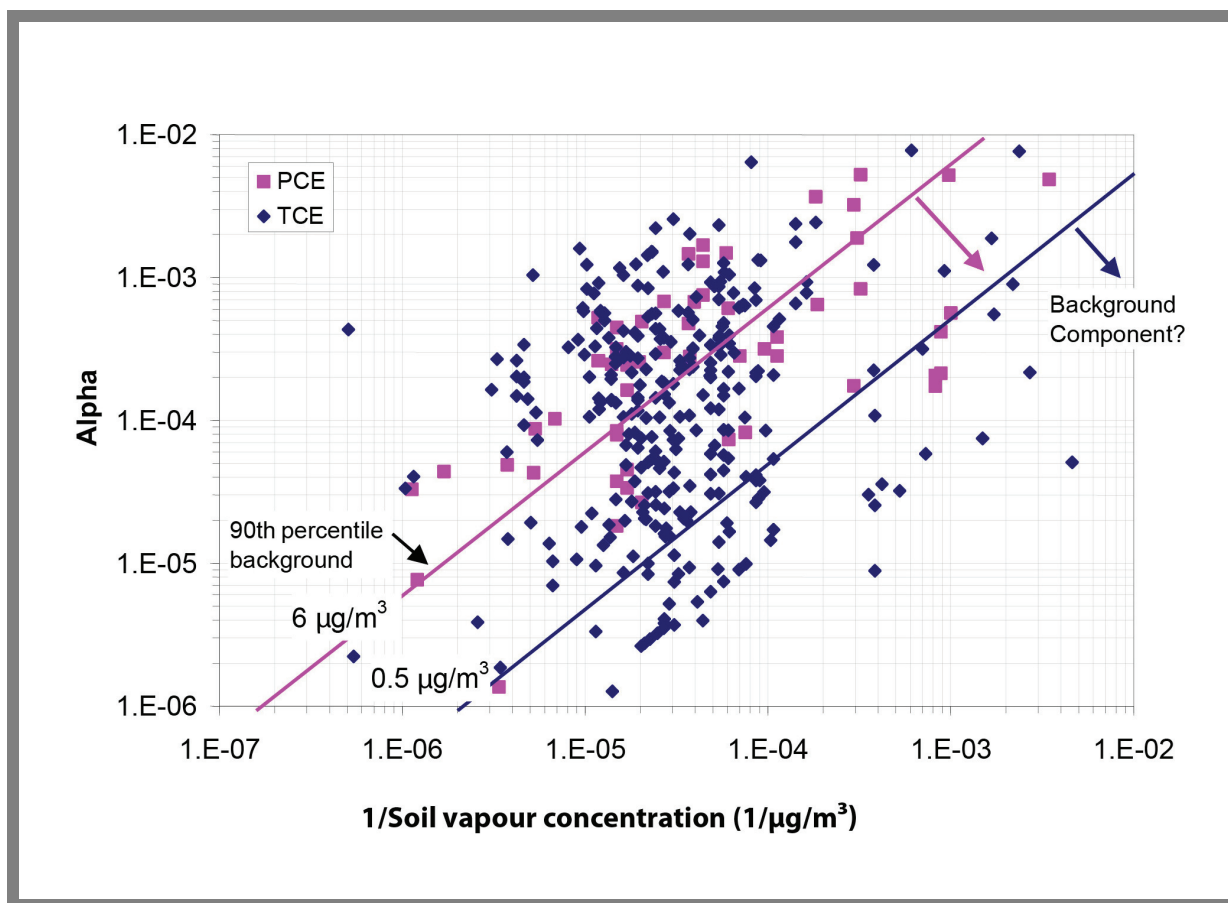
$$\alpha_{\text{emp}} = C_{\text{air}}^{\text{background}} / C_{\text{vapour source}} + \alpha_{\text{inherent}}$$

where  $C_{\text{air}}^{\text{vapour}}$  is the subsurface vapour component in indoor air ( $\mu\text{g}/\text{m}^3$ ),  $C_{\text{air}}^{\text{background}}$  is the background indoor air component ( $\mu\text{g}/\text{m}^3$ ). The ratio of background air to source-vapour concentrations must be about 1/10 of the inherent alpha value for there not to be an influence of background on the empirical determination, or in other words, the indoor air vapour concentration must be at least 10 times the background level. A plot of alpha versus the ratio of the background/source concentrations shown in Figure B1 provides further insight into the influence of background, as shown by the contrast in empirical alpha (curved line at higher background/source concentration ratios) and inherent vapour-derived alphas (straight line).

An example calculation is provided for benzene to illustrate how background can influence the empirical alpha determination. The median background concentration of benzene in indoor air, based on published studies, is approximately  $4 \mu\text{g}/\text{m}^3$  (Table B1). A realistic source-vapour concentration for benzene at gasoline-contaminated sites is about  $400,000 \mu\text{g}/\text{m}^3$  (Fischer et al., 1996; Laubacher et al., 1997; Ririe and Sweeney, 1998), resulting in a background/source ratio of  $1 \times 10^{-5}$ . Therefore, the inherent alpha would need to be greater than  $1 \times 10^{-4}$  for there not to be a significant influence from background on the alpha calculation. As subsequently indicated in this appendix, reliable alphas are, for almost all buildings, less than  $1 \times 10^{-4}$ ; therefore, it is expected that in many cases empirical alphas for benzene will be biased by background sources of benzene in indoor air.

Figure B1. Theoretical Influence of Background on Empirical Alpha



**Figure B2. Influence of Background on Empirical Alpha**

The influence of background on the empirical groundwater alpha was further evaluated using data for multiple sites and two chemicals, trichloroethene (TCE) and perchloroethylene (PCE), by plotting the inverse of the predicted soil vapour concentration ( $1/C_{\text{vapour}}$ ) against the empirical alpha (Figure B2). For PCE, there is a steadily increasing trend in the empirical alpha as  $1/C_{\text{vapour}}$  increases (similar trends were also observed for benzene, toluene, ethylbenzene, and xylenes [BTEX]). As shown in Figure B1, a linear increase would

theoretically be expected if the empirical alpha primarily reflects a background component. An empirical alpha was also calculated assuming only a background component and a 90th percentile background air concentration based on published literature (Table B1). As shown on Figure B2, for PCE, a significant proportion of the alpha values falls below the 90th percentile empirical alpha line, suggesting a background component to many of these data points. For TCE, fewer data points fall below the 90th percentile line, suggesting less of an influence of background on alpha.

Table B1. Literature Background Indoor Air Concentrations and Filter Criteria

Chemical	Background Data					Filter Criteria (see Section B5.2.1)			
	No. of Studies	Median Of Median ( $\mu\text{g}/\text{m}^3$ )	Average of 90th Percentile ( $\mu\text{g}/\text{m}^3$ )	Median of 90th Percentile ( $\mu\text{g}/\text{m}^3$ )	Value for filtering ( $\mu\text{g}/\text{m}^3$ )	Ground Water Filter	Ground Water Concentration ( $\mu\text{g}/\text{L}$ )	Soil Vapour Filter	Subslab Vapour Filter
Benzene	12	4	15	14	14	10,000	959	1,000	100
Ethylbenzene	7	4	14	10	10	10,000	400	1,000	100
Toluene	8	12	84	60	60	10,000	3,659	1,000	100
<i>m</i> - and <i>p</i> -xylenes	7	11	36	37	37	10,000	2,176	1,000	100
<i>o</i> -xylene	7	4	12	11	11	10,000	647	1,000	100
PCE*	12	2	12	6	6	10,000	135	1,000	100
TCE†	12	< 1	4.4	< 1	0.5	5,000	10	1,000	100
1,1,1-TCA‡	6	3	25	5	5	10,000	109	1,000	100
1,1-DCA§	3	< 0.1	INS**	INS	0.1	10,000	6.5	1,000	100
1,1-DCE#	3	< 0.1	INS	INS	0.1	10,000	1.32	1,000	100
<i>cis</i> -1,2-DCE	3	< 5	INS	INS	0.2	10,000	18.2	1,000	100

\* Perchloroethylene.

† Trichloroethene.

‡ Trichloroethane.

§ Dichloroethane.

# Dichloroethene.

\*\* INS, insufficient data.

The relationships in Figures B1 and B2 indicate that empirical alphas for chemicals with elevated background concentrations (e.g. BTEX, PCE) will be influenced by background, unless the source strength and/or the inherent attenuation factor are very high. In contrast, empirical vapour alphas are more reliable for chemicals with typically low background indoor air

concentrations, such as 1,1-dichloroethene (1,1-DCE) and TCE. Because there are few, if any, background sources of 1,1-DCE, this chemical can be an effective tracer for measuring soil vapour intrusion. The above concepts were subsequently used to guide the filtered process described in Section B5.0.

Table B2 Groundwater Empirical Alphas

	Reliability	Depth to Vapour Contamination Source (m)	Groundwater Concentration (mg/L)	Number	Minimum	25th	Median (50th)	75th	90th	95th	Maximum	Guidance SLRA (J&E Model) Alpha
<b>Chlorinated Solvents Sites</b>												
Alliant – 11 DCE & TCE – C	Low	3	0.0019 – 0.096	10	1.2E-06	N/A	8.6E-06	N/A	N/A	N/A	3.8E-05	9.4E-05
Bay Area 1 – TCE – L	Low to moderate	3.66	0.080 – 0.260	4	1.3E-06	N/A	9.2E-06	N/A	N/A	N/A	1.9E-05	9.20E-05
Bay Area 2 – TCE – L	Low	3.66	0.039 – 0.066	3	9.1E-06	N/A	3.8E-05	N/A	N/A	N/A	3.9E-05	9.20E-05
CDOT – TCE, 111 TCA, 11 DCE – SI	Moderate to high	3.7	TCE: 0.25–1.4; TCA: 0.61–2.4, DCE: 0.014–4.9	12	1.8E-06	9.1E-06	1.8E-05	2.8E-05	1.4E-04	2.0E-04	2.7E-04	9.20E-05
Davis – TCE, cis – 12 – DCE – S	High	1.7	3.6 – 9.1	2	4.7E-05	N/A	2.4E-04	N/A	N/A	N/A	4.3E-04	9.50E-04
Eau Claire – TCE – S	Moderate	0.6 – 1.2	0.3 – 8.1	6	2.2E-06	N/A	2.6E-04	N/A	N/A	N/A	9.3E-04	<1E-03
Endicott – TCE – S&G	Moderate to high	4.32 – 11.32	0.047 – 0.350	21	1.2E-04	1.2E-04	6.4E-04	9.3E-04	1.2E-03	1.4E-03	1.5E-03	4.2E-04 – 7.2E-04
HamiltonSunstrand – 11 DCE – S&G	High	9	0.015 – 0.03	32	9.6E-06	6.0E-05	1.1E-04	1.5E-04	2.0E-04	2.6E-04	5.2E-04	5.20E-04
Hopewell Precision – TCE – S&G	High	0.8 – 1.3	0.049 – 0.22	13	2.6E-05	2.4E-04	3.9E-04	1.1E-03	1.3E-03	1.8E-03	2.4E-03	1.00E-03
LAFB – TCE & 11DCE – LS	Moderate to high	4.7 – 5.7	TCE: 0.075–0.170; DCE: 0.0017–0.0018	19	3.7E-06	8.3E-06	1.7E-05	3.7E-05	1.2E-04	1.6E-04	2.3E-04	6.2E-04 – 6.7E-04
Lockwood – TCE & PCE – SL	Moderate to high	2.4	TCE: 0.066–0.631, PCE: 0.237–2.92	27	7.6E-06	3.5E-05	1.0E-04	3.8E-04	6.7E-04	1.1E-03	1.8E-03	1.50E-04
MADEP 1 TCE – S	Moderate	2.1	0.89 – 1.5	2	1.6E-04	N/A	6.0E-04	N/A	N/A	N/A	1.0E-03	8.20E-04
MADEP 2 TCE – S	Moderate	2.7	4	1	4.0E-05	N/A	4.0E-05	N/A	N/A	N/A	4.0E-05	8.10E-04
Mountain View TCE – LS	Low to moderate	10.3	3.3	5	4.8E-07	N/A	3.3E-06	N/A	N/A	N/A	3.3E-05	
Redfields 11 DCE – S – SI	High	0.09–12 (Avg = 4.0)	0.010 – 1	330	1.7E-06	2.8E-05	7.3E-05	1.5E-04	2.9E-04	4.7E-04	1.8E-03	1E-04 – 4E-04
Twins Inn TCE, cis – DCE, 11 DCE – S	Moderate	3.3 – 4.6	TCA: 1.9; DCE: 0.27, TCE 1.0	3	4.1E-06	N/A	1.5E-05	N/A	N/A	N/A	2.0E-05	7.00E-04
Uncasville PCE – S	Moderate	2.4	0.19	4	2.6E-04	N/A	3.9E-04	N/A	N/A	N/A	5.2E-04	8.40E-04
Site 1 TCE – S&G	Moderate to	3.5 – 4.5	0.050 – 1.3	169	2.6E-06	5.3E-05	1.5E-04	3.9E-04	7.9E-04	1.2E-03	6.4E-03	6.7E-04 –

	Reliability	Depth to Vapour Contamination Source (m)	Groundwater Concentration (mg/L)	Number	Minimum	25th	Median (50th)	75th	90th	95th	Maximum	Guidance SLRA (J&E Model) Alpha
	high											8E-04
Harcros – Tri State PCE – S	Low to high	3.4 – 4.3	0.17 – 1.4	4	1.4E-06	N/A	6.5E-05	N/A	N/A	N/A	2.5E-04	7E-04 – 8E-04
Wall Township PCD – S	Moderate to high	~3.2	0.1 – 0.45	33	1.7E-06	2.7E-05	8.2E-05	3.1E-04	5.1E-04	1.1E-03	1.4E-03	8.0E-04
Rapid City – L	Low	4.4	51 – 64	3	9.9E-06	2.1E-05	3.1E-05	3.6E-05	3.8E-05	3.9E-05	4.0E-05	9.9E-05
Cortlandville – S	Low to moderate	1.5	0.1 – 18.5	23	5.1E-05	6.0E-05	1.3E-04	1.2E-03	2.2E-03	3.0E-03	3.7E-03	9.8E-04
<b>All Sites</b>				724	4.8E-07	3.0E-05	8.6E-05	2.3E-04	5.8E-04	9.3E-04	6.4E-03	4.3E-04 – 7E-04
<b>Petroleum Hydrocarbon Sites</b>												
BP – BTEX – LS	Low	3.2	0.98 – 11	4	2.6E-06	N/A	9.2E-06	N/A	N/A	N/A	1.7E-05	8.00E-04
MADEP 3 – BTEX – S	Moderate	2.4	0.37 – 0.70	4	3.6E-06	N/A	1.4E-05	N/A	N/A	N/A	2.9E-05	8.90E-04
MADEP 4 – BTEX – S	Low	3.4	4.6 – 8.6	2	8.0E-06	N/A	1.0E-05	N/A	N/A	N/A	1.3E-05	7.80E-04
MADEP 6 – BTEX – S	Low	0.8	0.03 – 7.1	4	3.4E-05	N/A	1.0E-04	N/A	N/A	N/A	2.1E-04	<1E-03
MADEP 7 – BTEX – S	Low	2.7	3.5 – 15.7	3	5.9E-07	N/A	9.6E-07	N/A	N/A	N/A	2.4E-06	8.30E-04
Stafford MTBE – S	High	1.5 – 3.2	156 – 590	1	1.3E-05	N/A	1.3E-05	N/A	N/A	N/A	1.3E-05	9.80E-04
Stafford BTEX – S	Low	1.5 – 3.2	1.1 – 43	8	6.9E-07	N/A	1.4E-06	N/A	N/A	N/A	5.1E-06	9.80E-04
Mount Holly BTEX	Low	0.8	0.31 – 2.1	4	2.7E-06	N/A	6.7E-06	N/A	N/A	N/A	1.7E-05	<1E-03
<b>All Sites</b>				30	5.9E-07	2.4E-06	4.9E-06	1.6E-05	3.7E-05	1.0E-04	2.1E-04	

Note: Depth to vapour source is from base of foundation.



## B5.0 EMPIRICAL DATA- SCREENING PROCESS

The approach adopted for the evaluation of empirical alpha data consisted of three main parts:

**Data Quality Screening** – This step consisted of removal of poor quality data.

- **Data Filtering** – Several filters were applied to remove less reliable data.
- **Data Reliability Assessment** – A data reliability assessment was performed for remaining data based on a comparative ranking system where data were classified as higher, medium, and lower reliability data.

The screening process is described in the following text.

### B5.1 Data-Quality Screening

The first step of the screening process was to filter data of poor quality. There are a number of possible reasons for poor quality data including improper or outdated sampling or analysis methods, or specific instances where quality control testing and checks indicate that the precision and/or accuracy of the data are outside generally accepted limits. For some case study sites, limited documentation of methods made it difficult to evaluate data quality. The minimum criteria adopted for the data-quality screening step were:

1. concurrent or near-concurrent (i.e. within a few months) paired groundwater or soil vapour and indoor air data (An exception was made for a few sites' groundwater data when groundwater concentrations were not expected to vary seasonally.) ;

2. indoor air analysis conducted according to U.S. EPA Method TO-15 (i.e. Summa canister samples); and
3. no obvious background sources of VOCs of concern, such as open solvent or gas containers, or recent, significant use of chemicals.

Specific data points for buildings, or in a few cases, entire data sets for a particular site, were excluded from the study based on these criteria.

### B5.2 Data Filtering

The second step of the screening process was to apply several data filters to remove unreliable or less reliable data. The applied filters involved consideration of source strength, concentration ratios, minimum alpha values and detection limits, and an additional filter for large data sets.

#### B5.2.1 Vapour source strength filter

The most important filter was to remove data representing "low source strength," where source soil vapour concentrations were too low to distinguish indoor vapour concentrations from typical background levels, based on conservatively high alpha values. The unfiltered residential alphas for groundwater range from  $3.4 \times 10^{-7}$  to  $8 \times 10^{-1}$  and for soil vapour from  $1.0 \times 10^{-6}$  to 5.4 (Figures B3 to B5). For groundwater, the chemicals shown represent over 95% of the data points; for soil vapour, all data are shown. The alphas show a declining trend with increasing vapour concentration divided by the background concentration; the data for key chemicals is shown on Figures B4 and B5. The primary reason for the decline in alpha for most chemicals is considered to be the influence of background. Other reasons include a negative bias in soil vapour concentrations due to non-representative data (i.e. collected in the wrong location) or improper sampling techniques. Typically, there will be greater uncertainty associated with estimation of source concentrations near the periphery of a plume. At high source strength concentrations, the decrease in alpha for houses above dissolved plumes may be due to mass flux limitations because the available flux for vapour intrusion is limited by the flux transported by groundwater.

Figure B3. Unfiltered Groundwater Alphas

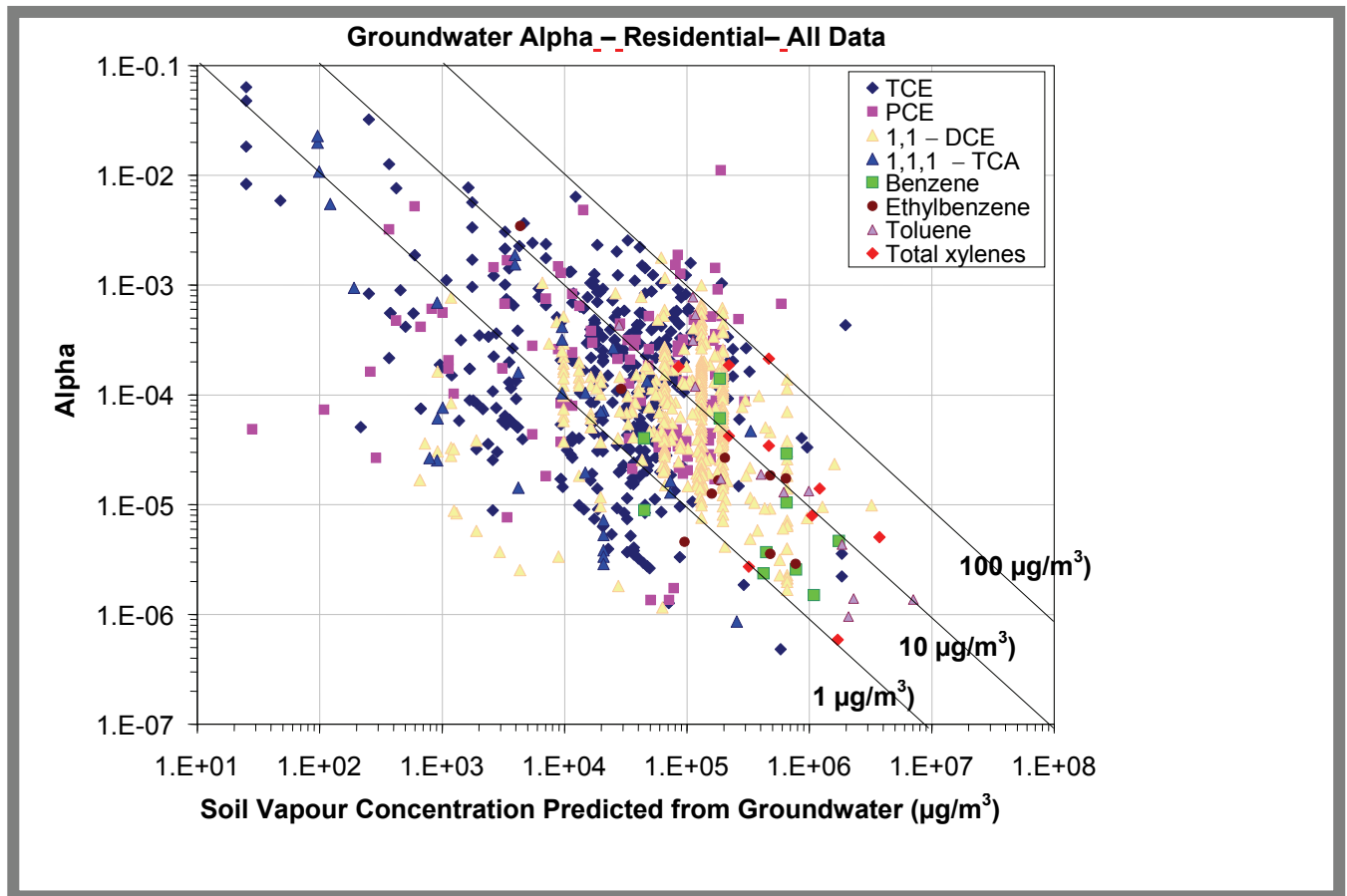


Figure B4. Unfiltered Groundwater Alphas Normalized to Background

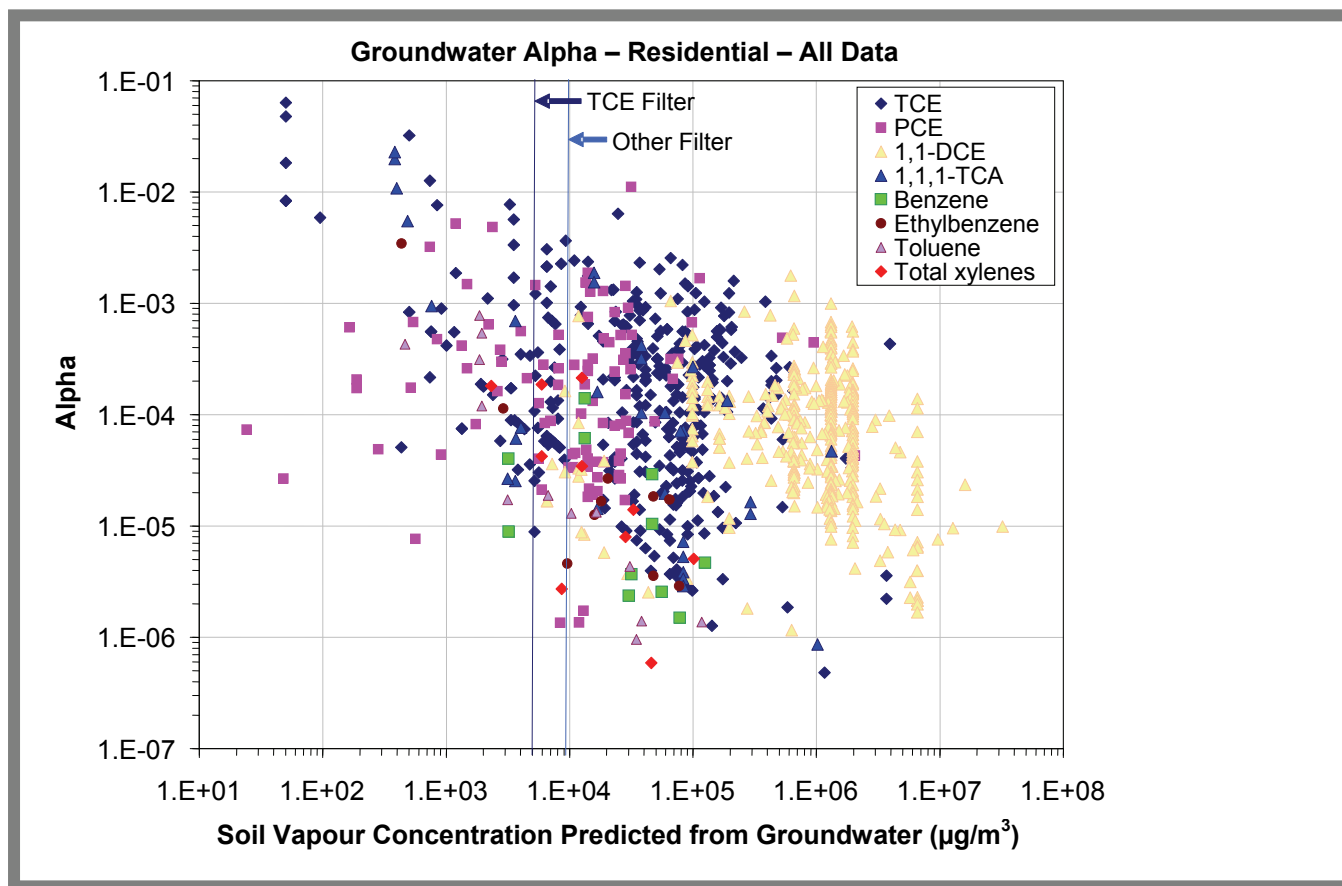


Figure B5. Unfiltered Soil Vapour Alphas Normalized to Background

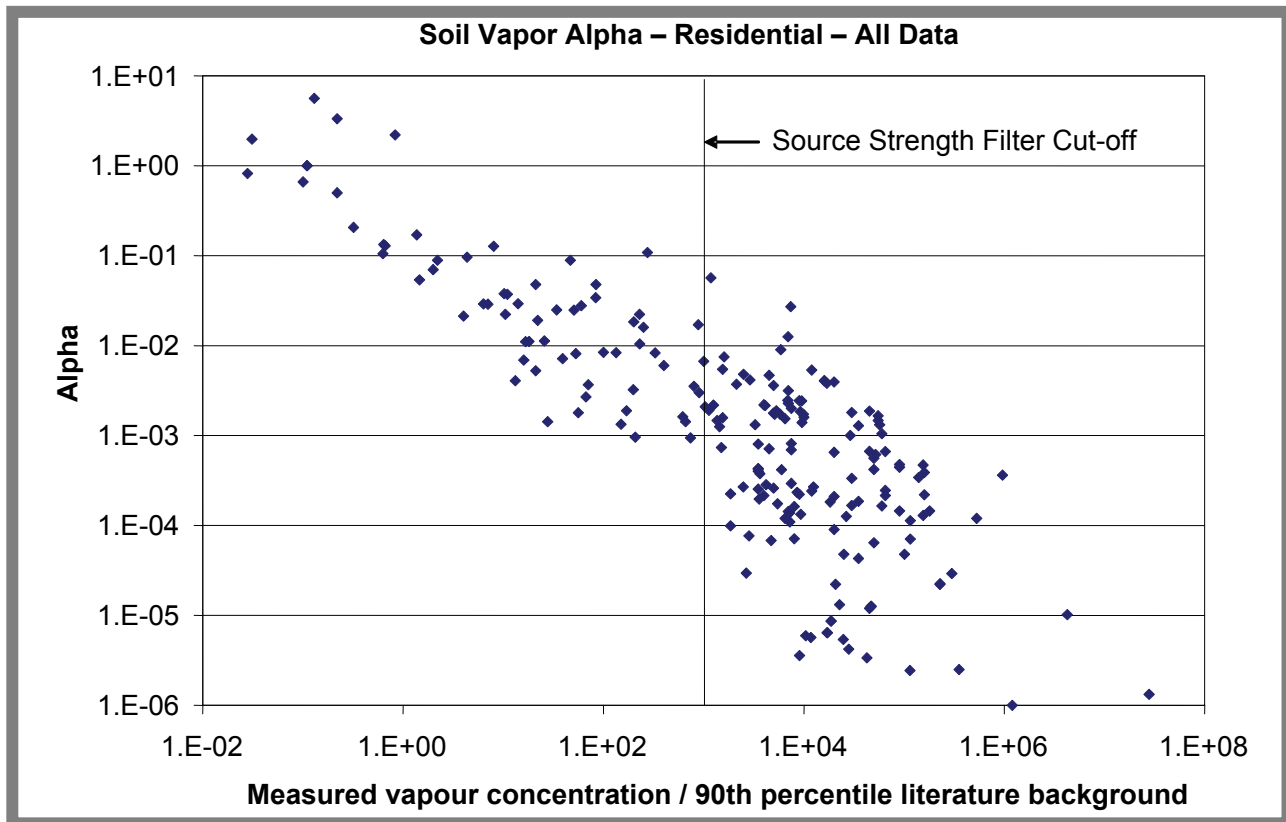
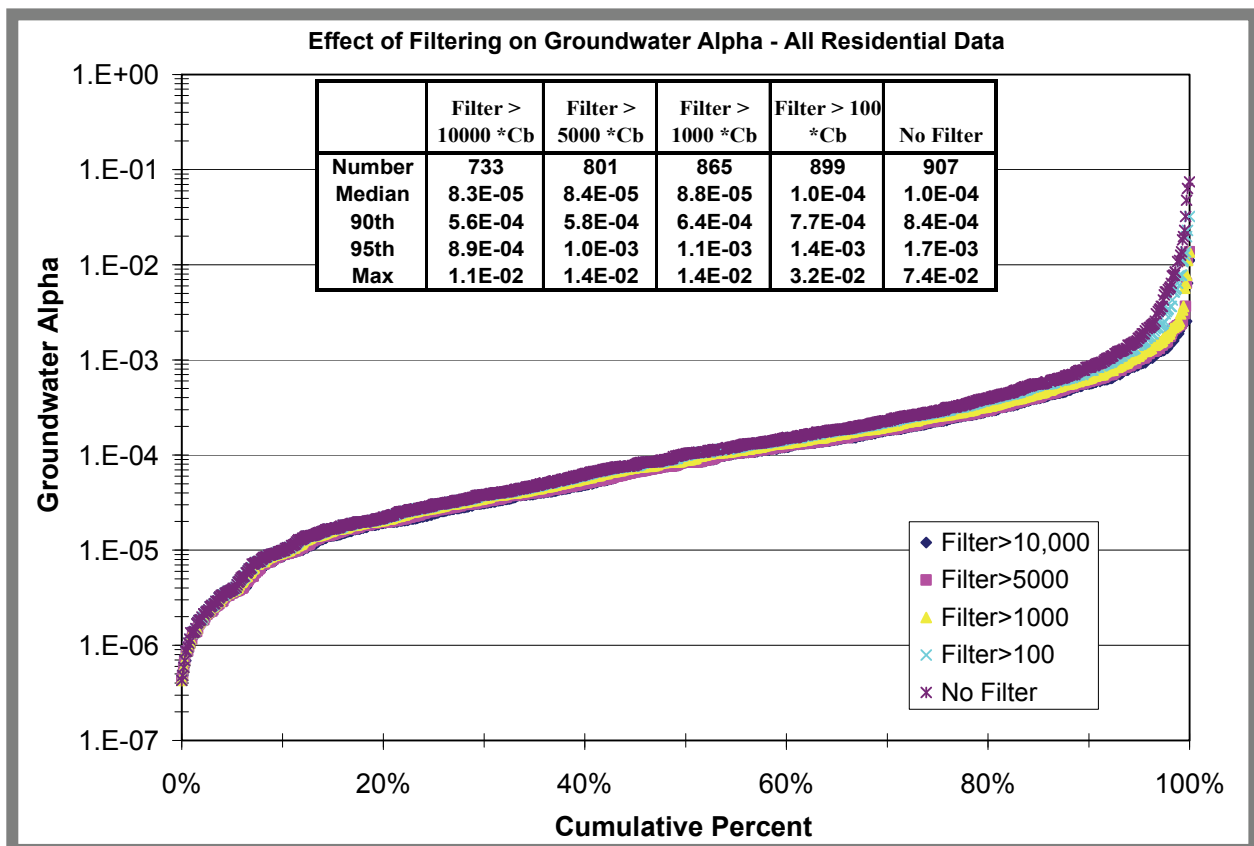


Figure B6. Effect of Filter Criteria on Groundwater Alpha



The data screening was performed using measurements for individual buildings. Data were retained for the attenuation factor study only when the following conditions were met:

(B3)

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$$\text{Subslab Alpha: } C_{\text{subslab vapour}} > 100 \times C_{\text{background}}$$


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(B4)

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$$\text{Soil Vapour Alpha: } C_{\text{measured soil vapour}} > 1,000 \times C_{\text{background}}$$


---

(B5)

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$$\text{Groundwater Alpha: } C_{\text{predicted soil vapour}} > 10,000 \times C_{\text{background}}$$


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For TCE, a groundwater filter criteria of 5,000 times background was used (Table B1). The  $C_{\text{background}}$  is the median of the 90th percentile background concentration for multiple studies based on a review of published literature values for buildings not believed to be impacted by soil vapour intrusion. It is recognized that there is uncertainty in background VOC levels; however, because the goal is to filter data, the use of approximate 90th percentile values was considered reasonable.

The rationale for the above filter criteria is to remove alpha values that are potentially influenced by background, based on source strength considerations.<sup>1</sup> An evaluation of different filter criteria for groundwater indicated a decrease in alpha values as the filter criteria were increased (Figure B5). The difference in percentiles and maximum values was relatively small for filter criteria of 5,000 and 10,000, suggesting this criterion was reasonable.

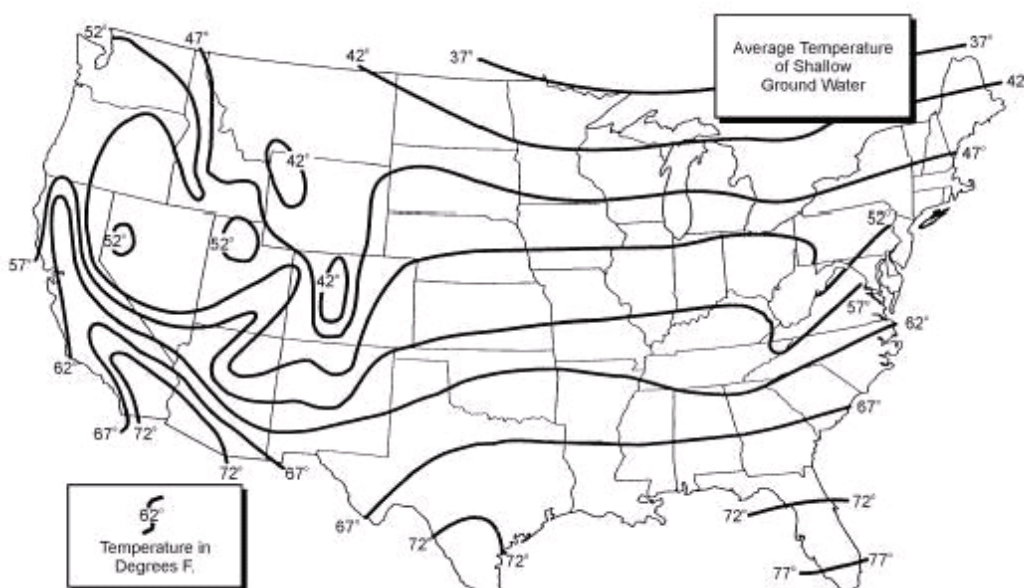
A filter involving the screening of data with indoor air concentrations less than an upper value based on background (e.g. 90th percentile literature value) was also evaluated. However, this filter has an inherent bias to it because it removes low alpha values. In addition, this filter was not as

effective in removing the downward trend in alpha for increasing soil vapour concentrations as the filter based on source strength (e.g. for TCE, this filter would result in groundwater alphas as high as 0.05; see Figure B3).

An important but subtle point is whether or not the filtering process introduces a bias in the subset of empirical alphas used for development of guidance alphas. As demonstrated in this appendix, for very low source strength data, background and detection limit clearly result in alphas that are biased high and should not be used. However, there is borderline data (i.e. where the concentration is just below the filter cut-off) where it is not clear that the data are potentially biased or the degree to which the above factors influence alpha. The issue of non-representative data, which means the external groundwater or soil vapour data used are not representative of those below the building, is perhaps the most difficult to address because there is variability in subsurface vapour concentrations and practical limitations in field sampling programs. To some degree, the collection of non-representative data is difficult to avoid. Although one could argue that non-representative data should be included in the empirical alpha analysis to reflect real-world variability, the emphasis of this guidance is to appropriately characterize sites and delineate concentrations near buildings. For this reason, it was considered appropriate to use a relatively aggressive data filter that would remove low source strength data.

The predicted vapour concentration from groundwater was calculated with a temperature-corrected Henry's Law constant using the method described by Environmental Quality Management, Inc. (2004) (Figure B7).

<sup>1</sup> In a few cases, borderline data points that did not meet the above criteria were retained; however, these data points are clearly flagged in subsequent tables and figures.

**Figure B7. Average Shallow Groundwater Temperatures for United States**

Source: Environmental Quality Management, Inc., 2004.

### **B5.2.2 Concentration (alpha) ratio**

When there were multiple chemicals of potential concern with similar fate and transport properties, the ratio of the soil vapour to indoor air concentration (i.e. alpha) for different chemicals was compared to determine if data should be filtered. The vapour attenuation factor is expected to be similar for chemicals with similar fate and transport properties. Groups of chemicals with similar properties are BTEX for a petroleum hydrocarbon-contaminated site, and PCE and TCE for a chlorinated solvent site. Comparisons of the alpha for 1,1-DCE to other chemicals can also provide useful insight into data reliability because of the absence of background sources for 1,1-DCE. For example, much higher alphas for PCE or TCE than 1,1-DCE suggest possible background sources of PCE or TCE in indoor air. Because there may be different attenuation rates due to biodegradation or biotransformation processes, only large (i.e. order of magnitude) differences in concentrations ratios suggest data-consistency problems.

The screening based on concentration (alpha) ratio that was adopted involved the calculation of the alpha ratios for the chemicals of potential concern for each building measurement. The alpha ratio was calculated using the lowest alpha for multiple chemicals. For example, if the PCE and TCE alphas were  $5 \times 10^{-4}$  and  $1 \times 10^{-4}$ , respectively, the alpha ratio would be five for PCE (and one for TCE). The data filtering that was applied in most cases involved removal of data points with an alpha ratio in excess of 10. The rationale for using a factor of 10 is that some variability in the alpha ratio would be expected, based on slight differences in fate and transport properties and

analytical testing precision. In a few cases, the alpha-ratio filter was not applied when there were anomalous data.

Concentration plots can also be used to evaluate data trends and identify possible outliers associated with background VOC sources. One data analysis method involves calculation of a "Super Ratio":

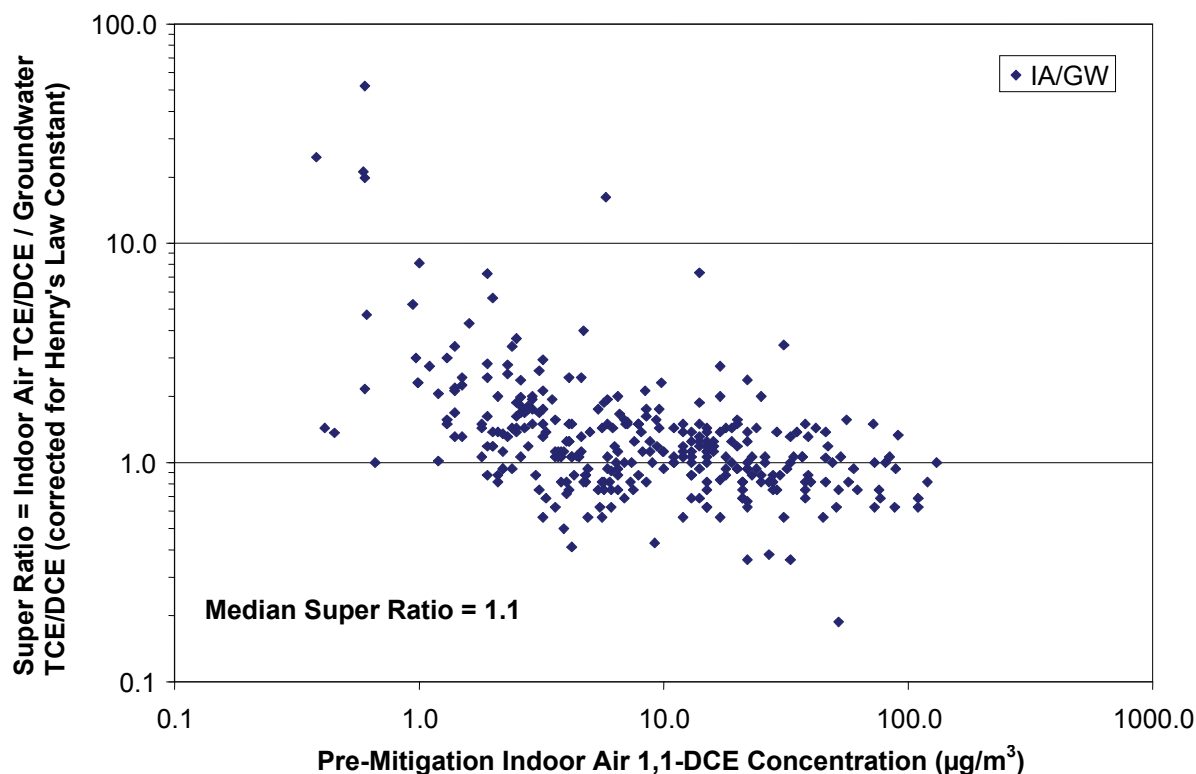
(B6)

$$\text{Super Ratio} = \frac{(C1/C2)_{\text{air}}}{[(C1/C2)_{\text{gdw}} * (H2/H1)]}$$

where  $(C1/C2)_{\text{air}}$  is the ratio of the indoor air concentration for chemicals 1 and 2,  $(C1/C2)_{\text{gdw}}$  is the ratio of the groundwater concentration, and  $(H2/H1)$  is the ratio of the Henry's Law constant. The Super Ratio was calculated for the Redfields, Colorado, site where a large groundwater plume consisting primarily of 1,1-DCE and TCE migrated below a residential area (Figure B8).

Super Ratios significantly above one indicate the indoor air TCE concentration may have been influenced by background sources, assuming similar fate and transport characteristics for 1,1-DCE and TCE.

Figure B8. Evaluation of Possible Background Influence Using Concentration Ratios



Note: IA/GW, ratio of indoor air concentration to groundwater concentration N = 344; data provided by Jeff Kurtz, Envirogroup.

### B5.2.3 Minimum alpha and detection limit filters

Indoor air concentrations that exceed soil vapour concentrations, or that are only slightly lower than the soil vapour concentrations, suggest background sources of the chemical under consideration and not a subsurface vapour source. This is because a minimum dilution of soil vapour due to building ventilation would be expected. The following filter was adopted:

If  $C_{\text{vapour}} < 10 * C_{\text{air}}$ , data were filtered and removed from the data set.

All data points where the groundwater, soil vapour, or subslab vapour concentration was below the analytical reporting limit were filtered. However, data points were not filtered where the indoor air concentration was below the reporting limit. Instead, the below-detection limit data were replaced with the analytical reporting limit. Data pairs with indoor air concentrations below the detection limit were not removed because removing this low-alpha data would have resulted in an upwardly biased alpha distribution.

### B5.2.4 Optional additional filter for large data sets

At sites with a large number of buildings with indoor air measurements (i.e. several hundred), a second data filter was applied in addition to a source strength filter where additional low concentration data were removed. The rationale is that low-concentration data near the periphery of a dissolved plume would tend to be less reliable, and therefore interpolated groundwater concentrations below buildings would be more uncertain. This screening step was implemented only for sites where, after the source strength-screening step, there were still sufficient data points for determination of a representative alpha. This screening step was performed only for the CDOT (Colorado Department of Transport) and Redfields sites, where only data for houses with interpolated 1,1-DCE groundwater concentrations greater than 10 µg/L were retained.

### B5.2.5 Considerations relating to multiple chemicals and monitoring events

The filtered database consisted primarily of a single chemical alpha value per building. For the chlorinated solvent database, there were multiple chemical alphas for five of 21 sites and

multiple monitoring events for one site. However, the number of buildings represented by these sites was small, and ranged from one to eight buildings. For petroleum hydrocarbon sites, most sites had multiple chemical alphas (i.e. BTEX chemicals); however, there were alpha values for only one to two buildings per site. Additional filtering was not performed to remove data for multiple chemicals and monitoring events (i.e. determine a single alpha for a building) because the number of sites with multiple alphas was limited, and because data regarding multiple chemicals and events provide insight into the natural variability expected when determining alpha values.

### ***B5.3 Data Reliability Assessment***

Data reliability for the purposes of this assessment is defined as the consistency and usefulness of the data. The first step of the reliability assessment comprised an analysis of the relationships among data to determine if there was evidence for soil vapour intrusion. This integrated analysis of data is referred to as **vapour pathway analysis**, and included the following aspects:

1. spatial relationships between the groundwater plume, soil vapour plume, and measured indoor air concentrations in buildings (Is there a consistent pattern?);
2. correlation between estimated groundwater or soil vapour concentrations below a building and measured indoor air concentrations (If vapour intrusion from groundwater volatilization is occurring, then a relationship, to some extent, should be observed.); and
3. concentration ratio trends for different chemicals with similar fate and transport properties at sites with multiple contaminants (Are the concentration ratios similar in groundwater, soil vapour, and indoor air?).

When available, soil vapour profiles can also be used to evaluate the potential for vapour intrusion. For example, significant vertical bioattenuation of vapour concentrations beside a building may indicate low potential for vapour intrusion, providing there is supporting evidence that biodegradation is also occurring below the building.

As a result of the inherent uncertainty in alpha data, statistically significant correlations among data are not expected. For example, for sites where multiple buildings above a groundwater plume have been tested, there typically is considerable scatter in the data, when the paired groundwater and indoor air data are compared, and a statistically weak correlation. However, for sites where soil vapour intrusion is occurring, a qualitative relationship among data points suggests that vapour intrusion is generally observed.

In a few cases, the reliability assessment also incorporated other complementary test data. For example, at several sites, indoor air concentrations (before and after measures were taken to prevent soil-gas advection, i.e. subslab

depressurization) were used to infer if vapour intrusion was occurring. If there are significant changes between concentrations measured in air before and after such measures, it is likely that vapour intrusion is occurring, assuming no other conditions change. The testing of air directly above cracks and other openings can also be used to help determine whether vapour intrusion is occurring.

The second step of the reliability assessment involved comparison of the measured indoor air concentrations to the 90th percentile background indoor concentrations in Table B1. If indoor air concentrations exceeded the 90th percentile concentration, there is a relatively high probability that the indoor air concentration represents, at least in part, a vapour source. Project-specific studies involving control buildings outside of the contaminated area, if available, were also considered for evaluation of background data.

The reliability rankings were based on the following criteria:

- **Higher reliability** – Evidence for vapour intrusion based on vapour pathway analysis (i.e. positive relationships observed for the data) and indoor air concentrations > 90th percentile background;
- **Moderate reliability** – No evidence for vapour intrusion, based on vapour pathway analysis but indoor air concentrations > 90th percentile background; and
- **Lower reliability** – No evidence for vapour intrusion, based on vapour pathway analysis and indoor air concentrations < 90th percentile background.

The lower reliability data represent upper bound values for alphas in that the true alpha is likely lower due to background indoor air concentrations. The lower reliability data are retained because the number of data measurements for petroleum hydrocarbon chemicals are limited.

The analysis presented in subsequent sections of this report indicates that for most sites where BTEX and, for some sites, where PCE were the chemicals of potential concern, the empirical alphas were of lower reliability, indicating background sources of these chemicals likely resulted in upwardly biased estimates of alpha.



## B6.0 EMPIRICAL ALPHA RESULTS

### B6.1 Groundwater Alpha

Empirical data on groundwater to indoor air alphas are available for 31 sites (27 residential and four commercial). The 27 residential sites are represented by 20 sites with chlorinated solvent data and seven sites with petroleum hydrocarbon data. All four commercial sites were tested for chlorinated solvents only. The total number of residential buildings at each site for which alphas are calculated (unfiltered) varies widely and is summarized as follows:

	Chlorinated Solvents	Petroleum Hydrocarbons
1 to 9 buildings	14 sites	7 sites
10 to 100 buildings	7 sites	No sites
>100 buildings	2 sites	No sites

#### B6.1.1 Chlorinated solvent residential alphas

##### B6.1.1.1 Data reliability assessment

The residential chlorinated solvent alphas according to the higher, moderate, and lower reliability designations are shown in Figures B9 and B10. The majority of the data points represent higher reliability data. The median higher reliability alpha ( $1.1 \times 10^{-4}$ ) is greater than the moderate ( $2.8 \times 10^{-5}$ ) and lower reliability alpha ( $8.8 \times 10^{-6}$ ). The chlorinated solvent alphas for individual sites are shown in Figure B11. Statistical parameters for individual sites are tabulated in Table B2.

Figure B9. Indoor Air Concentration Versus Vapour Concentration Providing Reliability Data for Chlorinated Solvent Sites (Filtered)

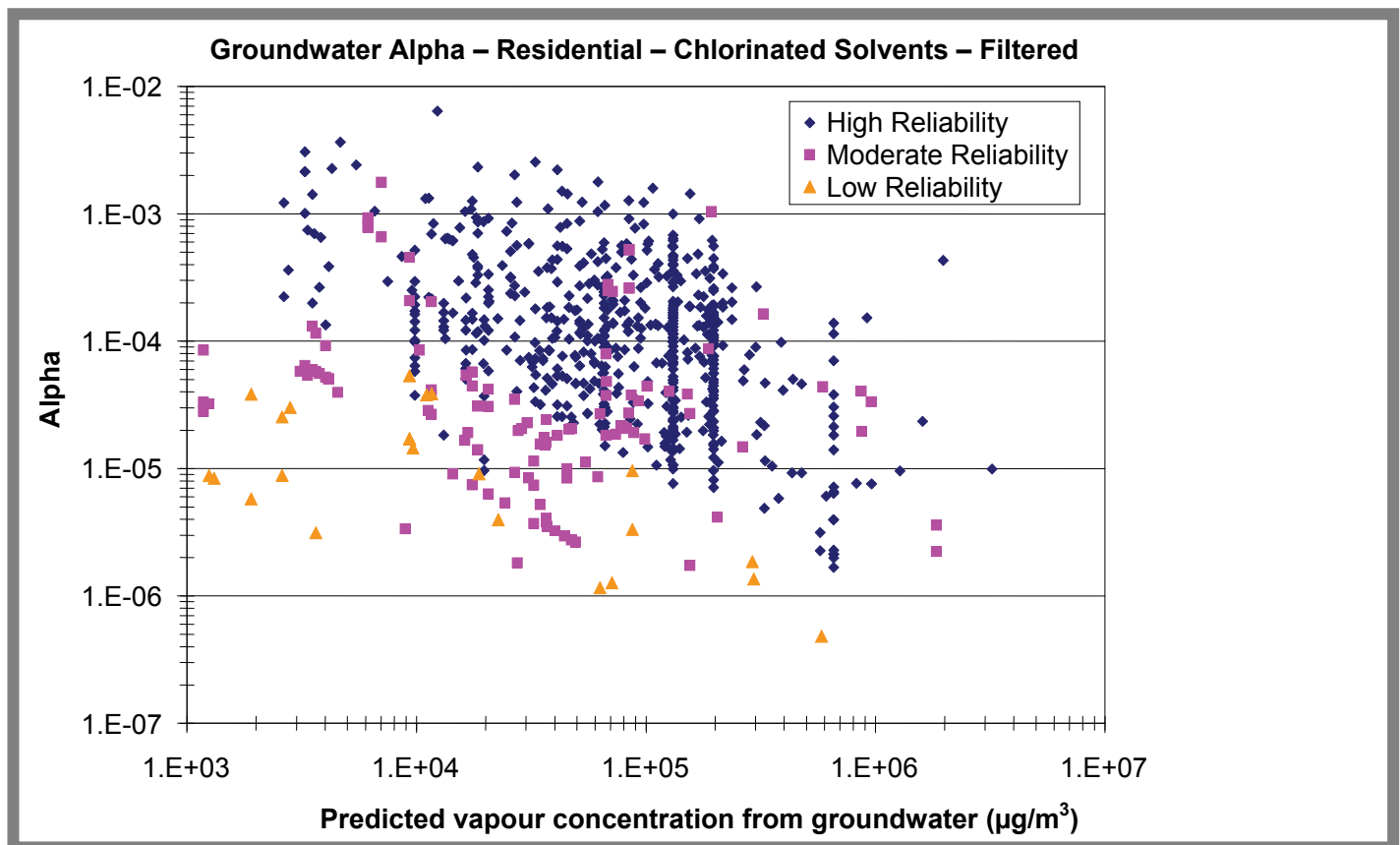


Figure B10. Groundwater Alphas Versus Vapour Concentration Providing Reliability Data for Chlorinated Solvent Sites (Filtered)

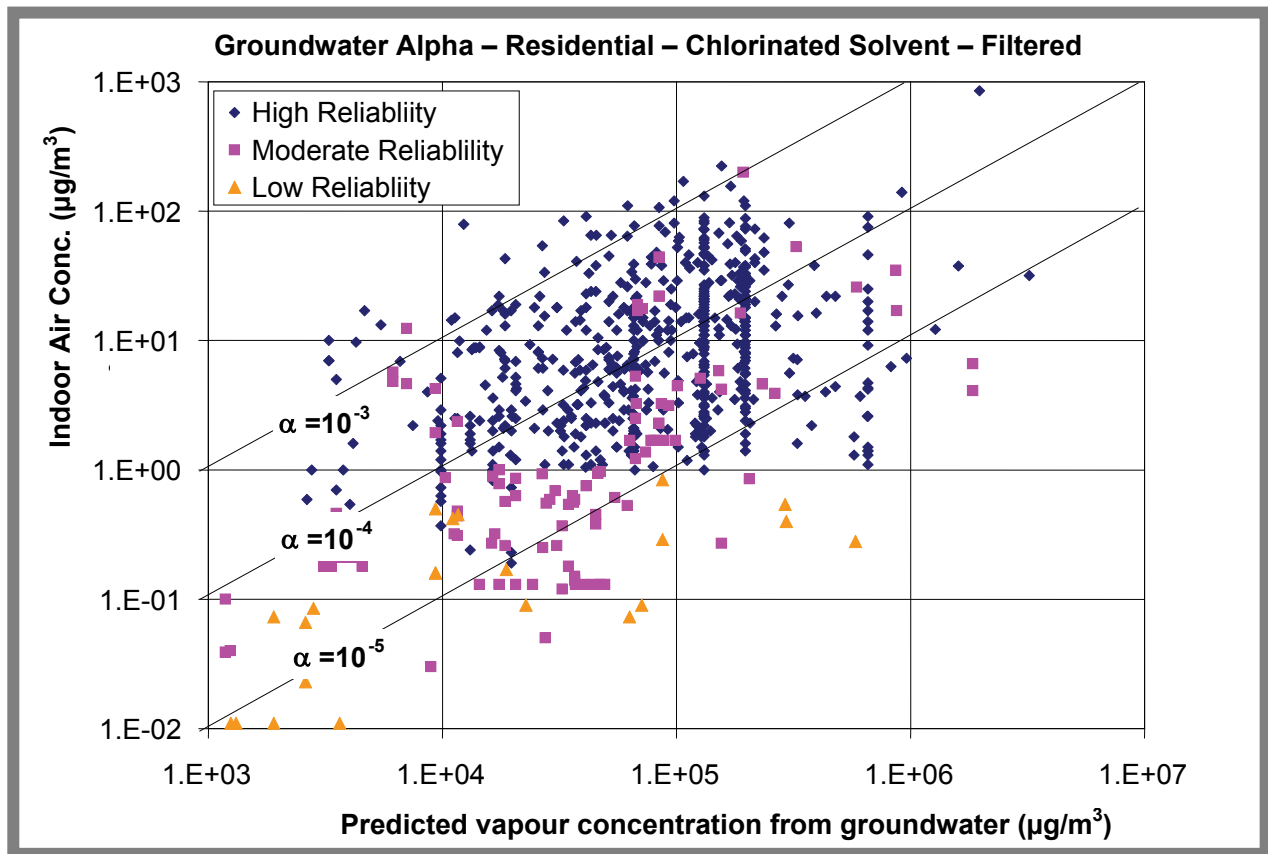
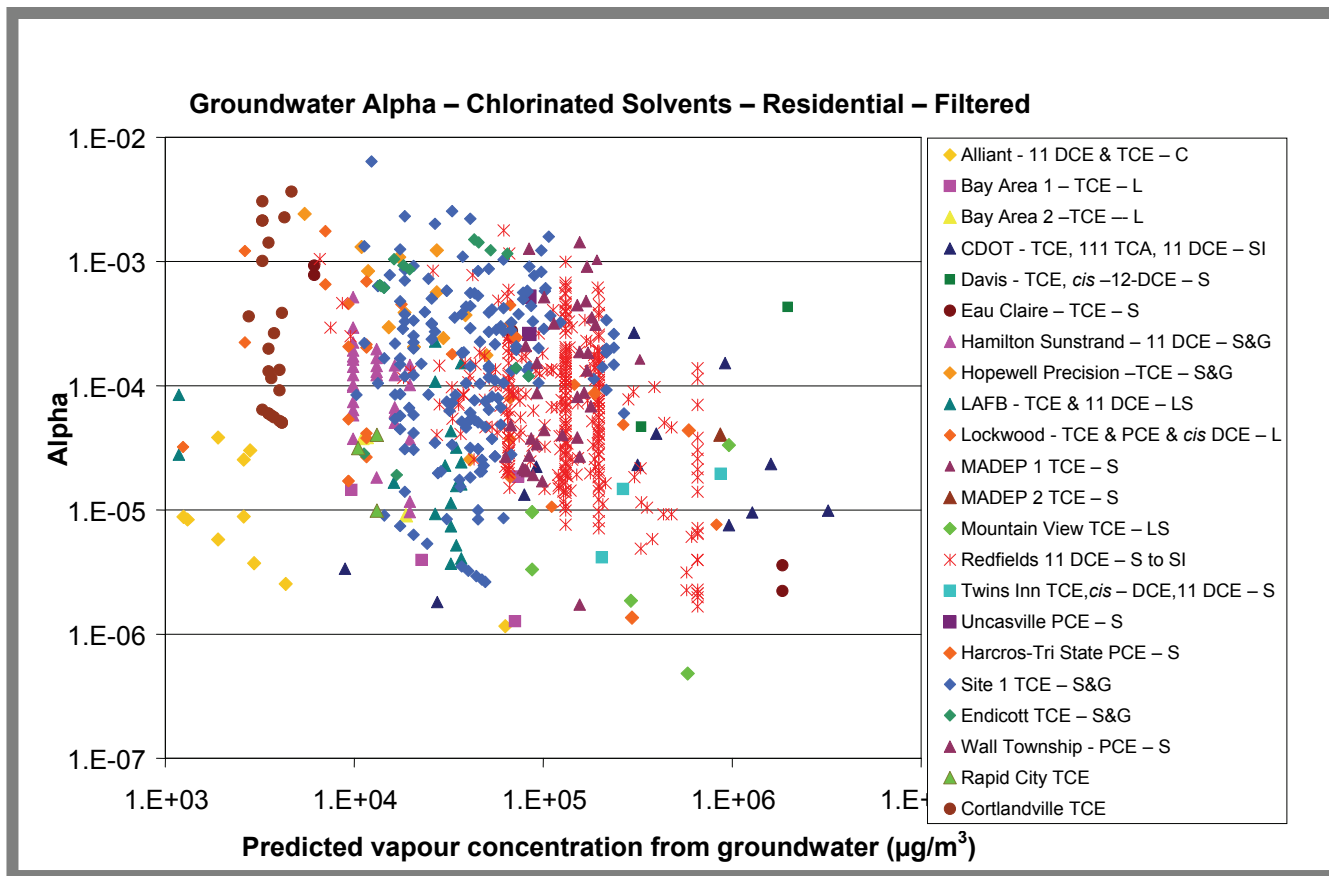


Figure B11. Groundwater Chlorinated Solvent Alphas for Sites (Filtered)

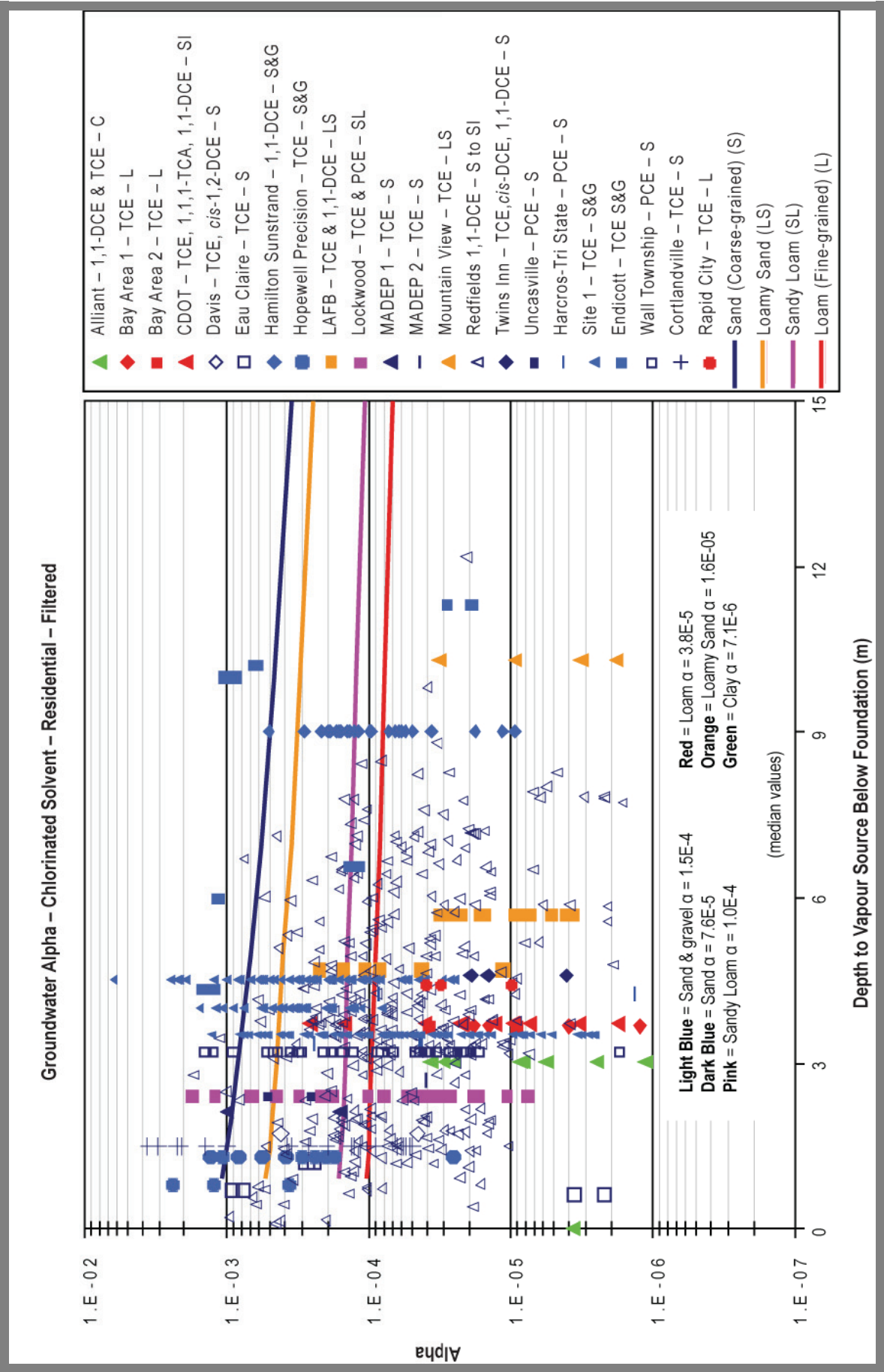


#### B6.1.1.2 Comparison with guidance alphas

The empirical alphas are compared with the guidance quantitative screening groundwater alphas in Figure B12. The sites are colour coded according to soil type. For most data points for both coarse-grained soils (loamy sand, sand, sand and gravel) and fine-grained soils (loam, claystone), the empirical alphas are less than the guidance alphas. There are five sites where the 90th percentile empirical alpha exceeds the guidance alpha (Table B2); however, the ratio of the 90th percentile to guidance alpha is relatively small for most sites (factor of two to three). The largest difference is the Lockwood site, where the guidance alpha was  $1.5 \times 10^{-4}$  compared with a measured 90th percentile alpha of  $6.7 \times 10^{-4}$ .

The median empirical alpha for all site data for each soil type is also presented in Figure B12. There is significant scatter in the data and the number of data points for each soil type varies. Therefore, it is not possible to attribute statistical trends to the data or draw strong conclusions about the data. Nevertheless, the trend of declining alpha with finer soil type supports guidance alphas that vary based on soil type.

Figure B12. Comparison of Empirical Groudwater Chlorinated Solvent Alphas to Guidance Alphas (Filtered)



### B6.1.1.3 Preliminary screening reliability evaluation

A preliminary evaluation of the reliability of the guidance alpha curves for screening purposes was conducted for TCE by comparing predicted indoor air concentrations, obtained from measured groundwater concentrations and guidance alpha values, to measured indoor air concentrations. The predicted and measured indoor air concentrations were normalized to the indoor air screening level (IASL) for TCE, which for the purposes of this assessment was taken to be 5 µg/m<sup>3</sup>. The analysis was performed as follows:

1. For each building, the U.S. SCS soil texture classification (Sand, Loamy Sand, Sandy Loam, and Loam) was determined (sand and gravel was taken to be sand, and clay was taken to be loam).
2. The guidance alpha value was calculated using the curves in Figure B12.
3. The predicted indoor air concentration was obtained using the assigned groundwater concentration for each building and alpha value.

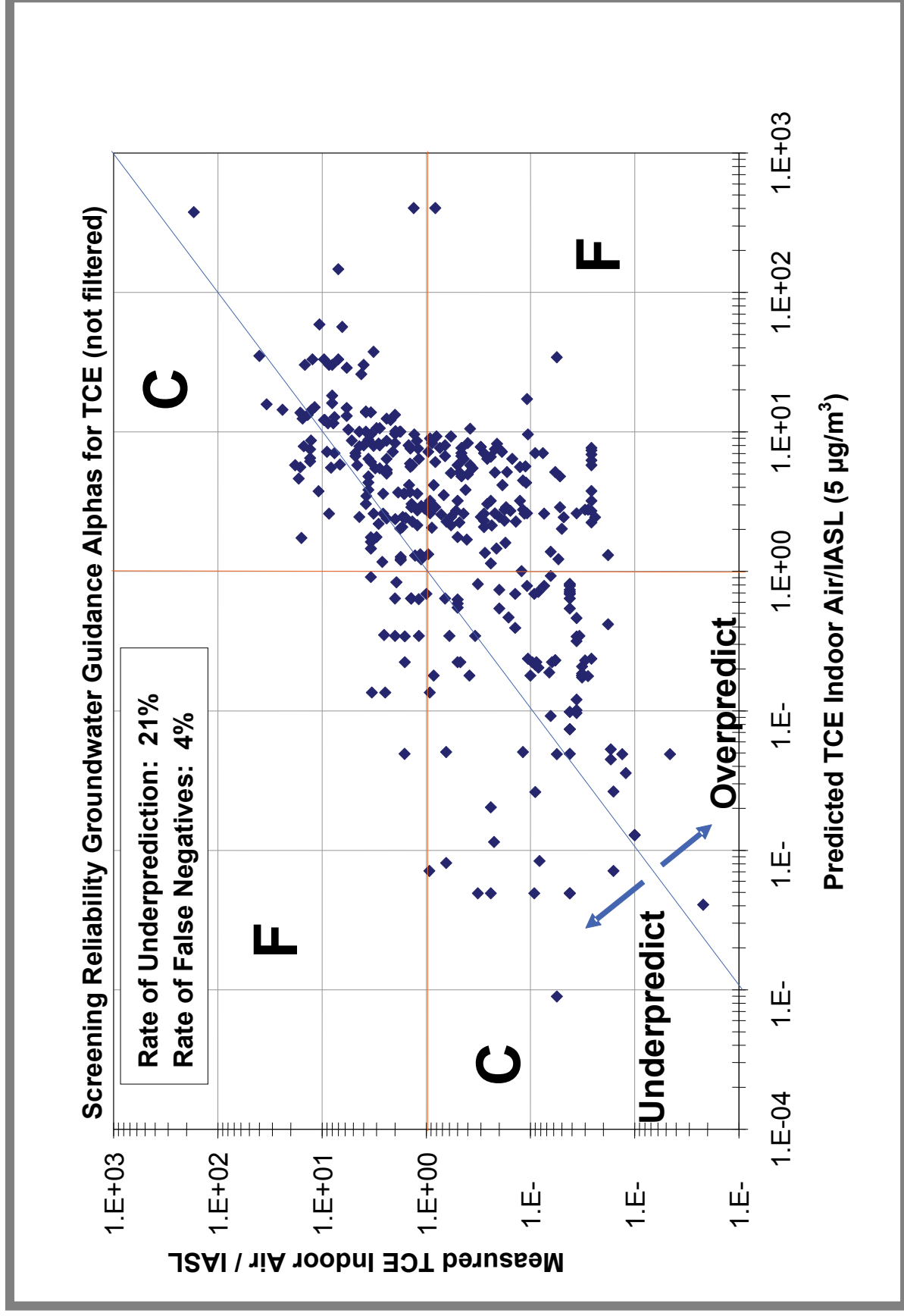
From the analysis, the following screening reliability matrix was developed:

False Negative	Predicted indoor air concentration < IASL Measured indoor air concentration > IASL Predicted indoor air < Measured indoor air
Correct Negative	Predicted indoor air concentration < IASL Measured indoor air concentration < IASL
False Positive	Predicted indoor air concentration > IASL Measured indoor air concentration < IASL Predicted indoor air concentration > Measured indoor air
Correct Positive	Predicted indoor air concentration > IASL Measured indoor air concentration > IASL

The results of the screening reliability evaluation conducted using all unfiltered data indicate that for TCE the rate of underprediction (predicted < measured) is 21% (348 measurements), whereas the rate of false negatives is 4% (Figure B13). There were three individual sites with false negatives (Hopewell, Lockwood, and Cortlandville). For each of these sites, there were buildings with indoor TCE concentrations above the screening level. Therefore, using a

site-wide screening process (i.e. any measurement above the IASL triggers further assessment), the correct decision would have been made. Incorrect decisions could have been made at these sites if the process were to focus strictly on individual screening of buildings using groundwater data. The preliminary screening reliability assessment suggests a relatively low rate of false negatives. A lower rate of false negatives would have been obtained had filtered data only been analyzed. It is also important to note that the screening reliability assessment depends on the IASL chosen.

Figure B13. Screening Reliability of Semi-Site Specific Guidance Groundwater Alphas for Trichloroethene (Not Filtered)



Note: TCE, trichloroethene; IASL, indoor air screening level; FN, false negative; CN, correct negative; FP, false positive; CP, correct positive.

#### B6.1.1.4 Influence of foundation on alpha

For foundation type, there are no clear trends (Figure B14), although at a fundamental level, the results demonstrate soil vapour intrusion occurs for several different types of residential foundations including basement, slab-on-grade, and crawlspace. The median alpha values for basements and crawlspace are not widely divergent ( $1.5 \times 10^{-4}$  versus

$1.6 \times 10^{-4}$  for Site 1 and  $7.6 \times 10^{-5}$  versus  $6.9 \times 10^{-5}$  for Redfields), suggesting that the difference in foundations for these scenarios may not be important. The alpha values for a limited number of earthen floor basements (Site 1) were elevated; however, there are insufficient data points to draw conclusions with respect to these data. The alpha data suggest that soil type and through inference the effective diffusivity may, in general, have a greater influence on vapour intrusion than foundation type for residential dwellings.

Figure B14a Site 1

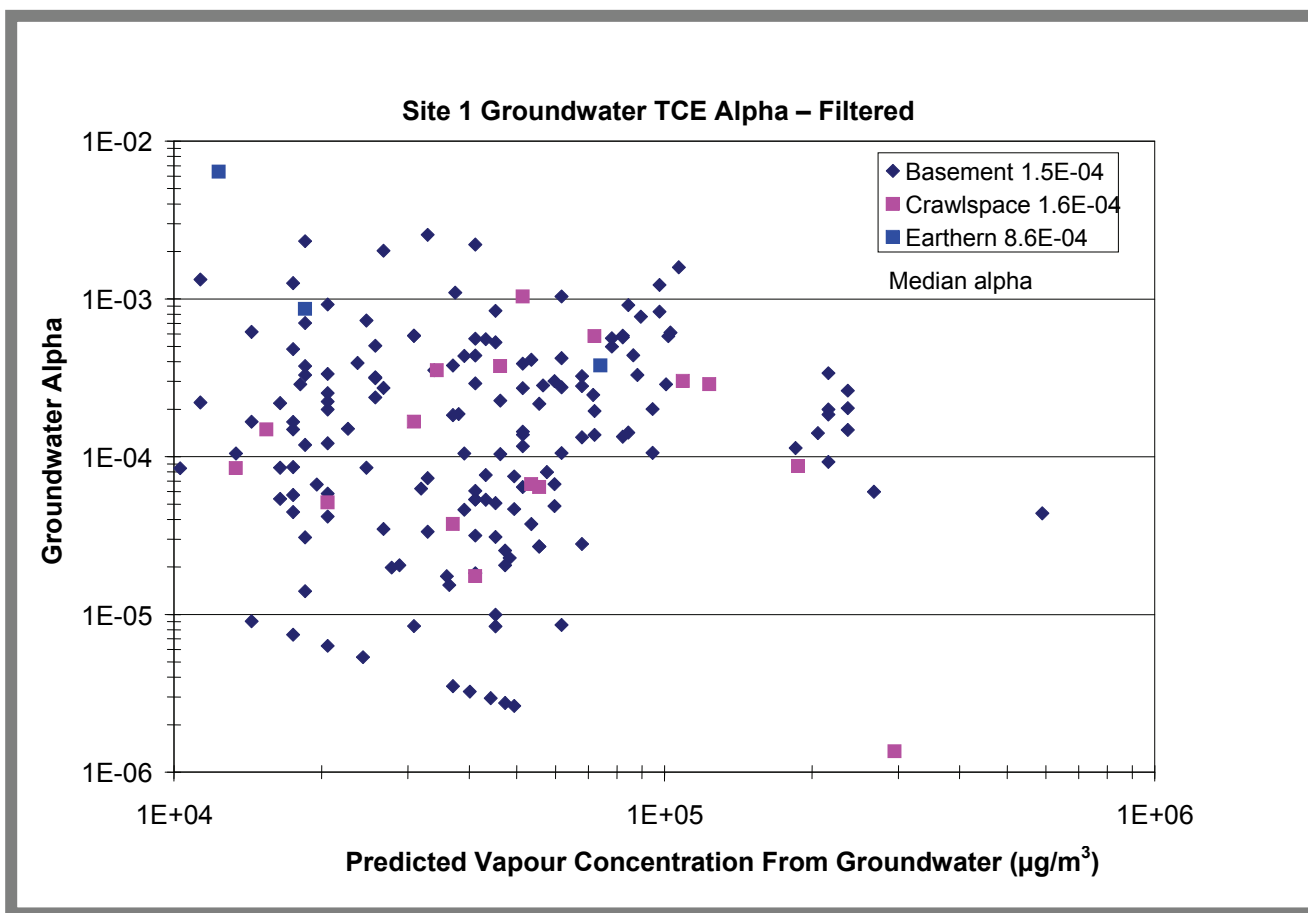


Figure B14b Redfields Site

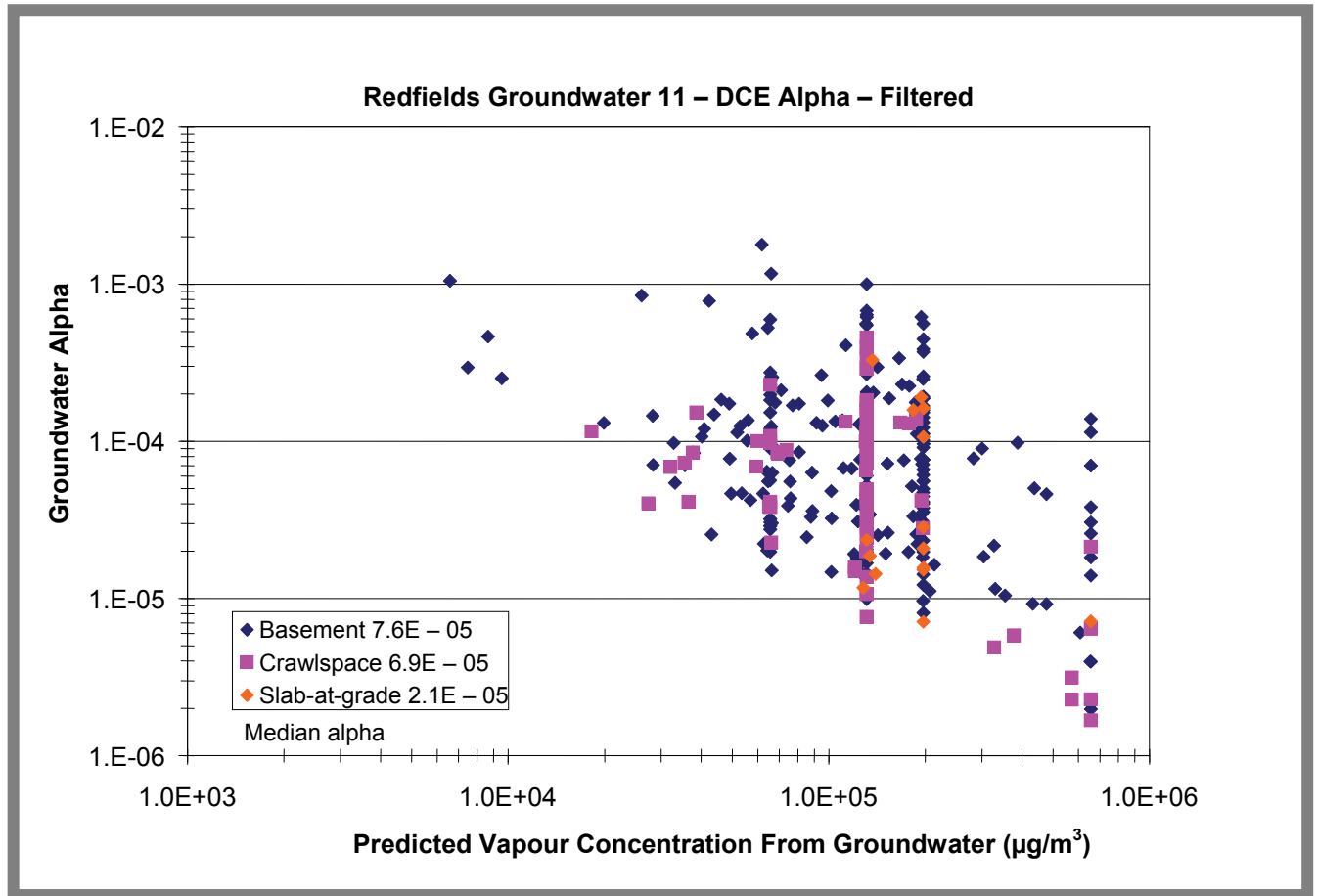
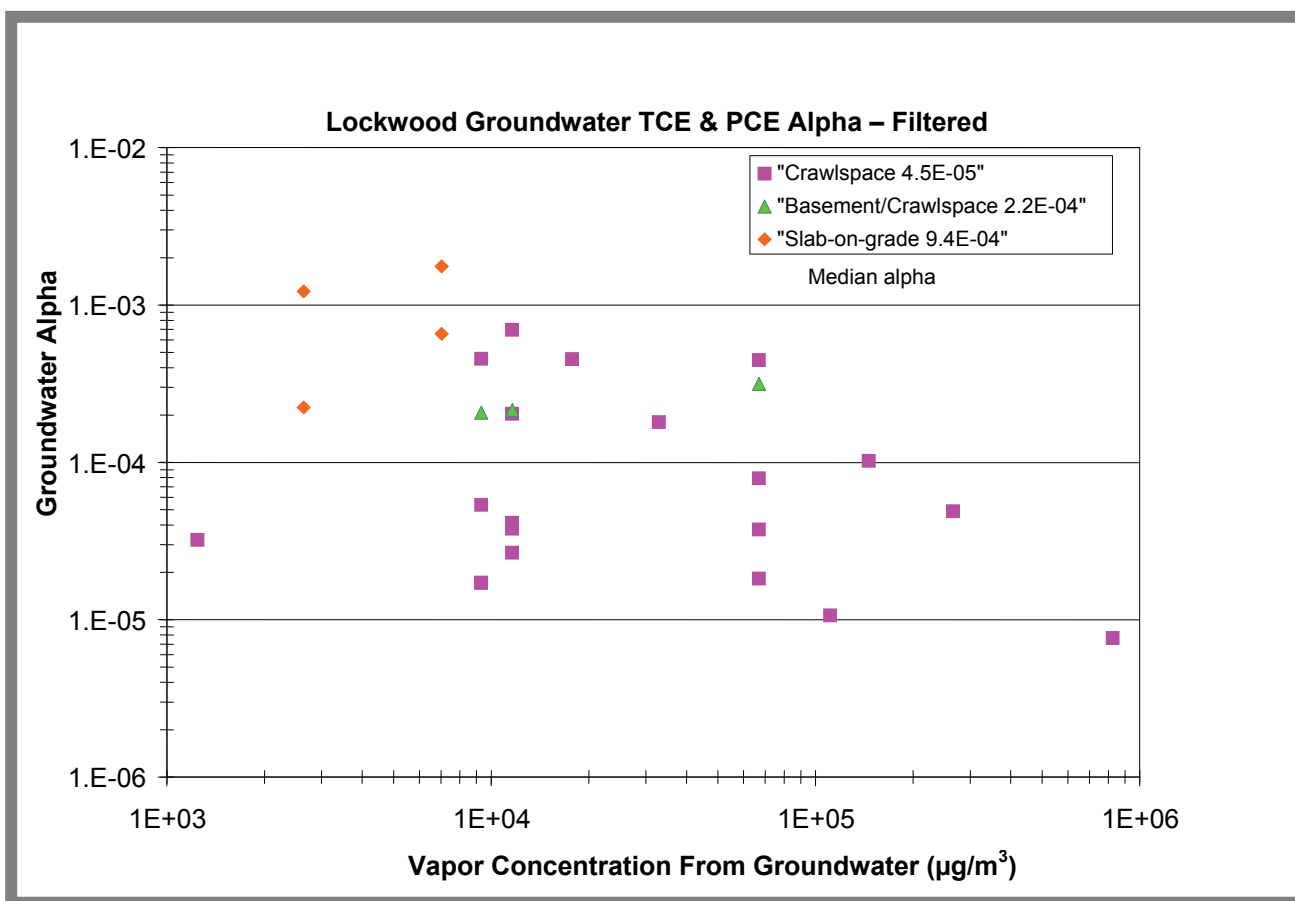




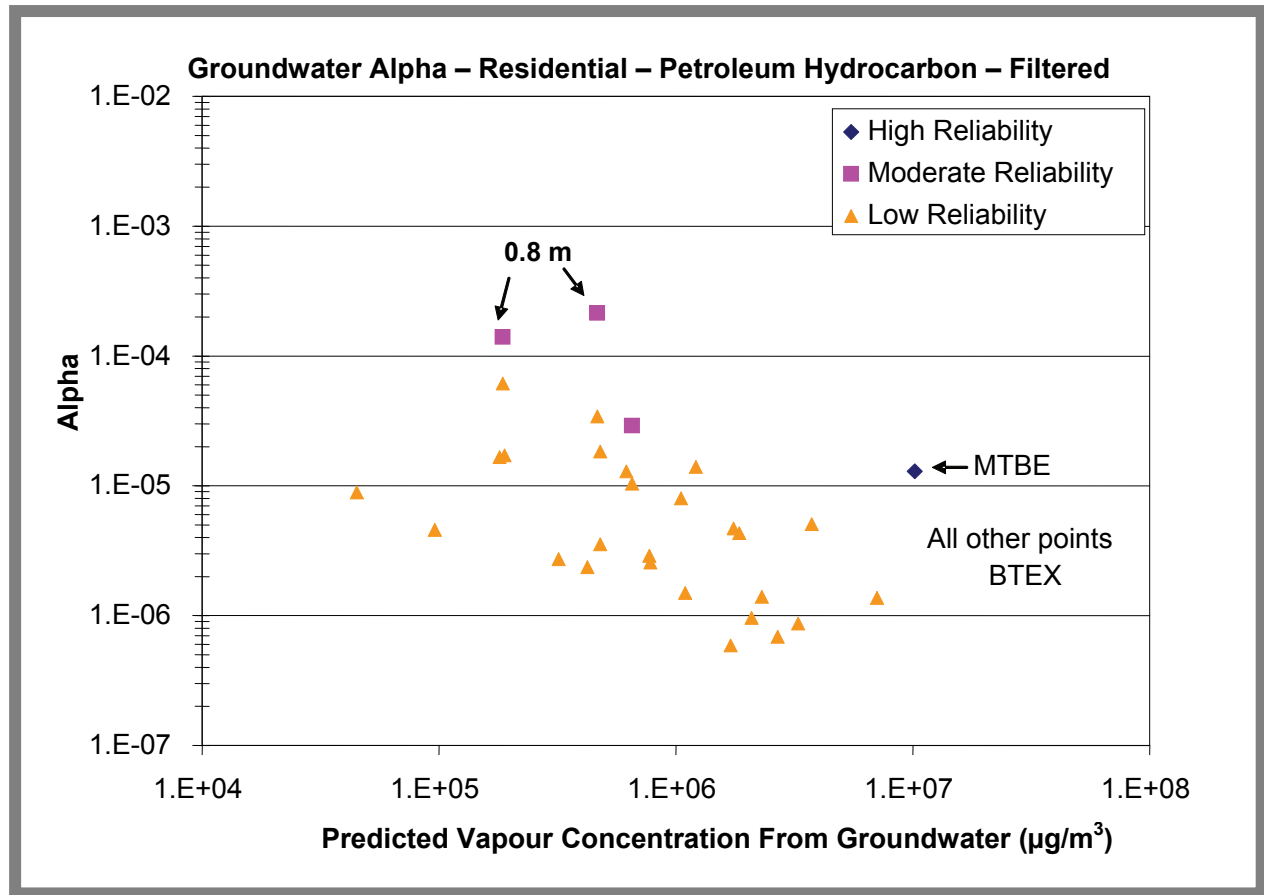
Figure B14c Lockwood Site



### B6.1.2 Petroleum hydrocarbon residential alphas

The residential petroleum hydrocarbon alphas plotted according to the reliability designations are shown in Figure B15. Alpha measurements where the depth to groundwater was less than 1 m are notated in Figure B15; this normally is a precluding factor for groundwater. With the exception of one data point (methyl *tert*-butyl ether [MTBE]), all the data points represent BTEX measurements. At two sites (BP and Stafford), the buildings overlie residual non-aqueous phase liquid (NAPL) present at the water table. At the Mount Holly site, residual NAPL was present below, but not at the water table. For the remaining MADEP sites (Massachusetts Department of Environmental Protection), information on NAPL was not available. The majority of the data points represent lower reliability data, indicating that the measured indoor air concentration was below the 90th percentile literature background concentration. Therefore, it is probable that the empirical alphas, to varying degrees, include a background component, and that the vapour-derived alphas are lower than those shown.

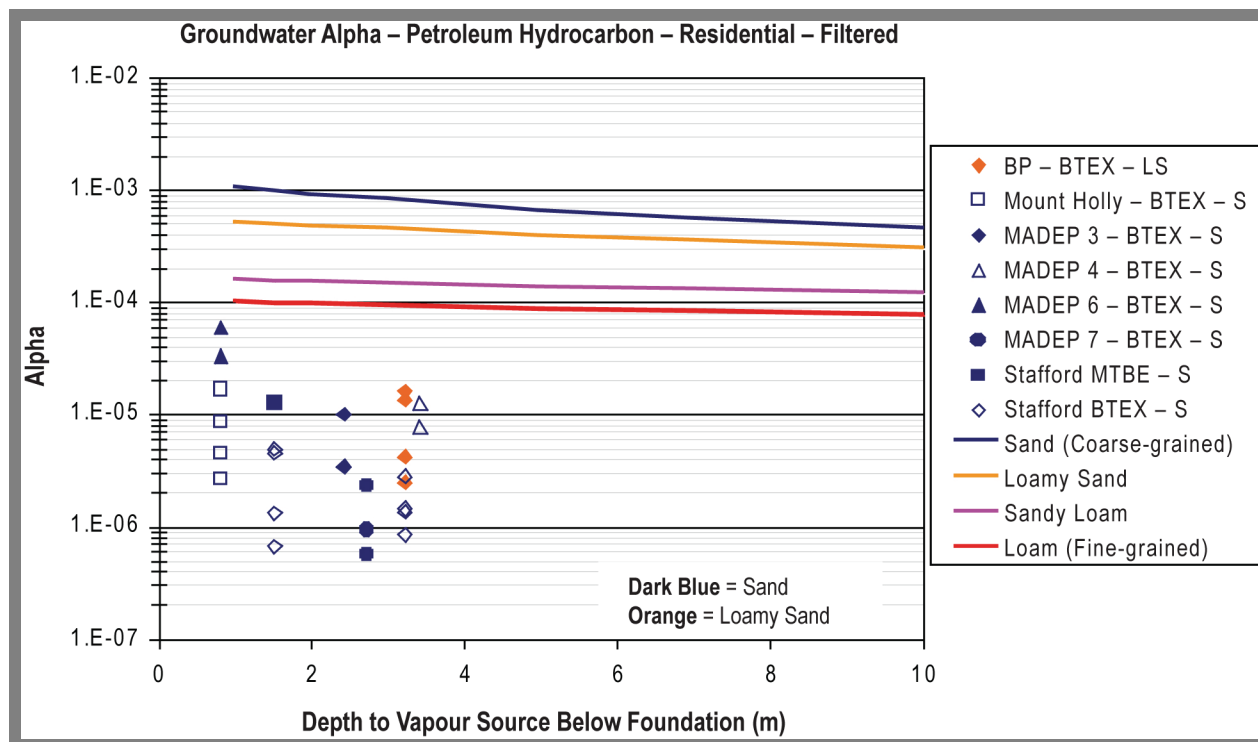
Figure B15. Groundwater Alphas Versus Vapour Concentration Providing Reliability Data for Petroleum Hydrocarbon Sites (Filtered)



Note: MTBE, methyl *tert*-butyl ether; BTEX, benzene, toluene, ethylbenzene, and xylenes

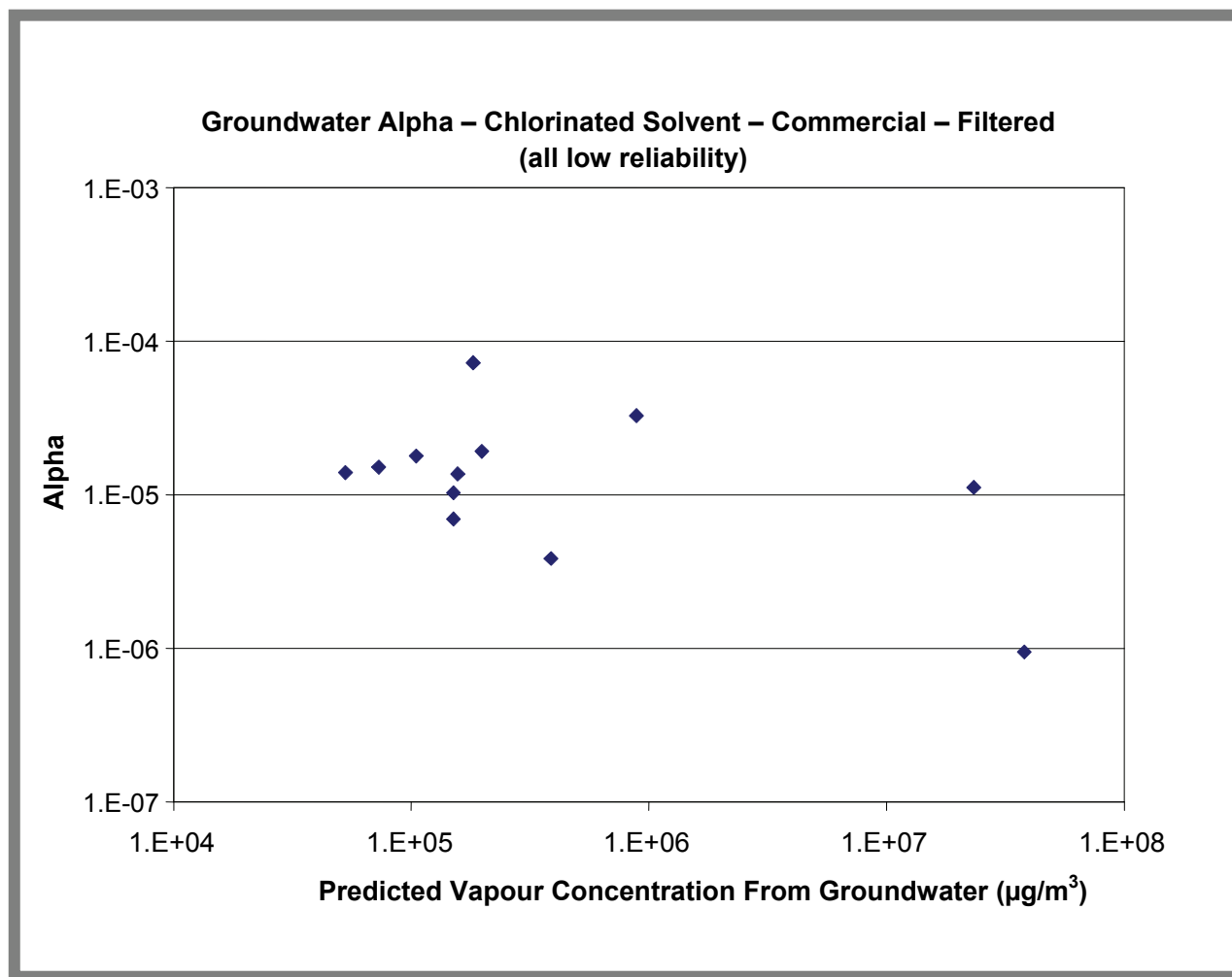
The groundwater empirical alphas for petroleum hydrocarbons are compared with the guidance quantitative screening alphas in Figure B16. The sites are colour coded according to soil

type and are all coarse-grained soils. The results indicate that the empirical alphas are over one order of magnitude less than the guidance alphas.

**Figure B16. Comparison of Empirical Groundwater Petroleum Hydrocarbon Alphas to Guidance Alphas (Filtered)****B6.1.3 Chlorinated Solvent Commercial Alphas**

Data available for commercial buildings (Figure B17) are limited. The documentation and description of the sampling programs conducted at commercial sites is also limited. All commercial data are considered to be of lower reliability.

Figure B17. Alpha Versus Vapour Concentration for Chlorinated Solvents and Commercial Sites (Filtered)



### B6.2 Soil Vapour Alpha

Empirical data on soil vapour-to-indoor air alphas are available for 17 sites (15 residential and two commercial). The 15 residential sites are represented by 11 sites with chlorinated solvent data and four sites with petroleum hydrocarbon data. The two commercial sites were tested for chlorinated solvents only. The total number of residential buildings at each site for which alphas are calculated is summarized as follows:

The soil-gas measurements were generally obtained from deep probes located close to the water table, although information for a few sites on soil-gas and groundwater depths was incomplete.

	Chlorinated Solvents	Petroleum Hydrocarbons
1 to 9 buildings	5 sites	4 sites
10 to 100 buildings	6 sites	No sites
>100 buildings	No sites	No sites

### B6.2.1 Chlorinated solvent residential alphas

The residential chlorinated solvent alphas according to the higher, moderate, and lower reliability designations are shown in Figure B18. Alpha values for individual sites are shown in Figure B19. The majority of the data points represent higher

and moderate reliability data, and 62% of the data points are for one site. The median alphas are  $7.0 \times 10^{-4}$  for higher reliability,  $2.6 \times 10^{-4}$  for moderate reliability, and  $1.0 \times 10^{-4}$  for lower reliability. Most empirical alphas for chlorinated solvent chemicals are in the range of alphas observed for subslab vapour (U.S. EPA, 2008). Statistical parameters for individual sites are tabulated in Table B3.

**Figure B18. Soil Vapour Alphas Versus Vapour Concentration Providing Reliability Data for Chlorinated Solvent Sites (Filtered)**

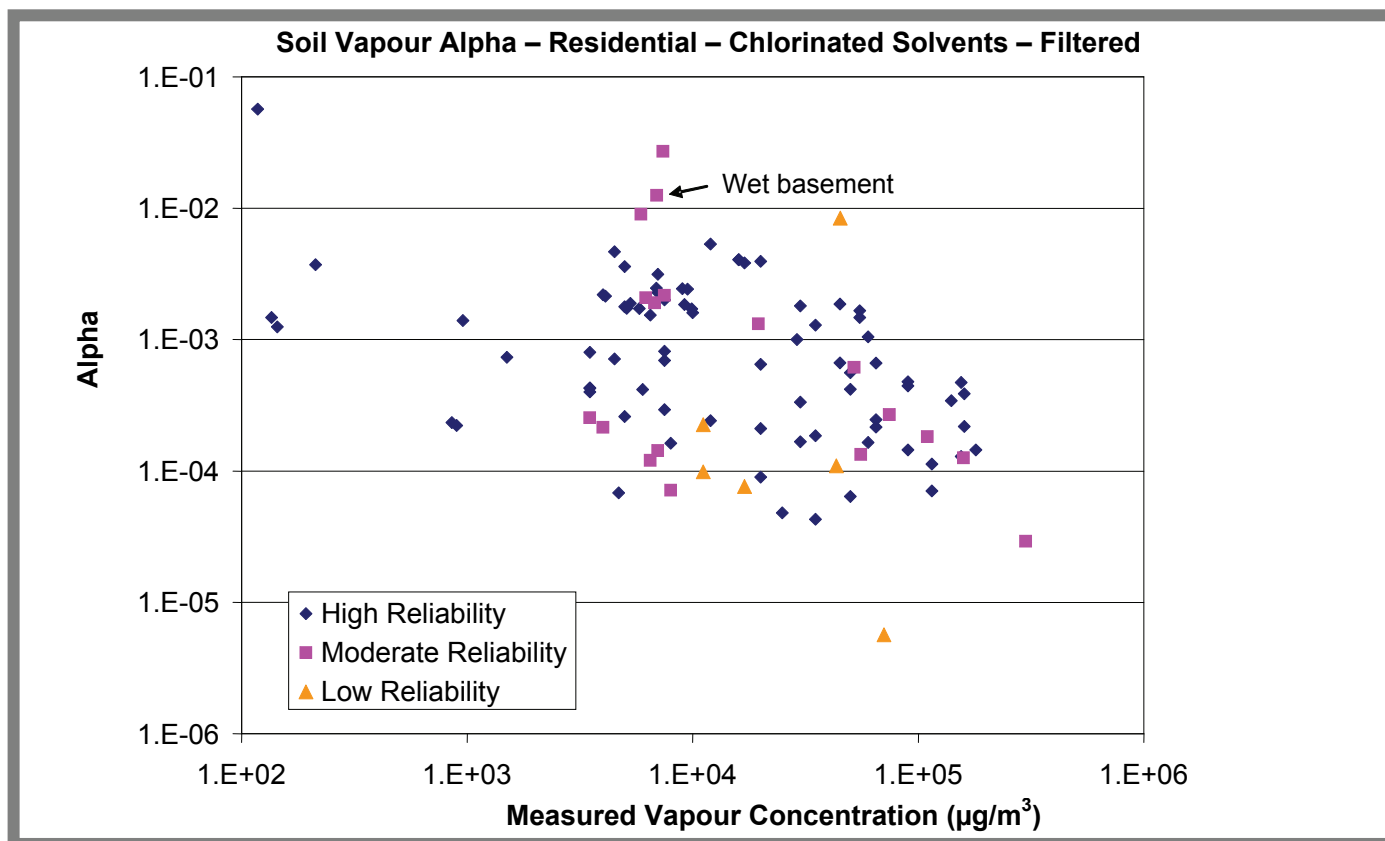
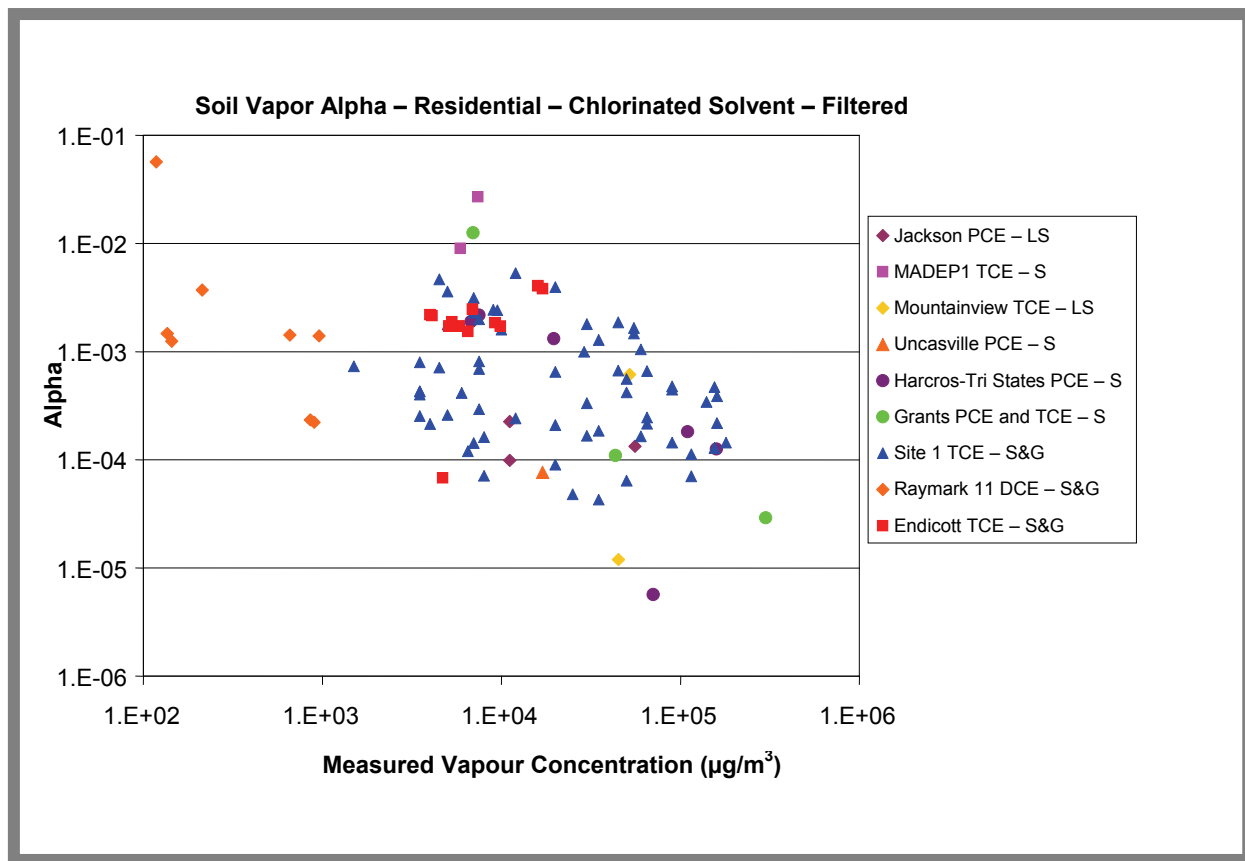


Figure B19. Soil Vapour Chlorinated Solvent Alphas for Sites (Filtered)



Note: LS, loamy sand; S, sand; S&G, sand and gravel.

Table B3. Soil Vapour Empirical Alphas

Reliability			Depth to Vapour Source	Groundwater Concentration (mg/m <sup>3</sup> )	Number	Minimum	25th	Median (50th)	75th	90th	95th	Maximum	Guidance SLRA (J&E Model) Alpha
<b>Chlorinated Solvents Sites</b>													
Low to moderate			N/A	11.1 – 55.8	3	9.9E-05	N/A	1.3E-04	N/A	N/A	N/A	2.3E-04	2.00E-03
Moderate			2.1	5.9 – 7.4	2	9.0E-03	N/A	1.8E-02	N/A	N/A	N/A	2.7E-02	2.10E-03
Low to moderate			1.5	45.1 – 52.1	2	1.2E-05	N/A	3.1E-04	N/A	N/A	N/A	6.1E-04	2.30E-03
Low			2.1	17	1	7.6E-05	N/A	7.6E-05	N/A	N/A	N/A	7.6E-05	2.30E-03
Moderate			-0.15 – 3.6	6.2 – 159	6	5.7E-06	N/A	7.5E-04	N/A	N/A	N/A	2.2E-03	1.3E-03 – 2.6E-03
High			4	3.5 – 180	63	4.3E-05	2.0E-04	4.3E-04	1.2E-03	2.4E-03	3.6E-03	5.3E-03	1.30E-03
Moderate to high			1.5 – 8.2	0.4 – 63	13	6.8E-05	1.7E-03	1.9E-03	2.5E-03	4.0E-03	4.1E-03	4.1E-03	7.2E-04 – 2.3E-03
Low to moderate			0.6 – 1.2	1.6 – 300	3	2.9E-05	N/A	1.1E-04	N/A	N/A	N/A	1.3E-02	2.70E-03
<b>All Sites</b>													
<b>Petroleum Hydrocarbon Sites</b>													
Moderate			0.7	28,000	1	1.3E-06	N/A	1.3E-06	N/A	N/A	N/A	1.3E-06	>3E-03
Low			3.2	228 – 1483	4	3.4E-06	N/A	9.3E-06	N/A	N/A	N/A	2.2E-05	1.50E-03
Low			5	1,600	1	2.4E-06	N/A	2.4E-06	N/A	N/A	N/A	2.4E-06	1.10E-03
High			1.2 – 2.9	445 – 5,930	2	6.4E-06	N/A	1.4E-05	N/A	N/A	N/A	2.2E-05	2.1E-03 – 2.7E-03
High			1.2 – 2.9	708 – 1,062	2	2.5E-06	N/A	6.1E-05	N/A	N/A	N/A	1.2E-04	2.1E-03 – 2.7E-03
High			1.2 – 2.9	1,920 – 2,400	2	1.0E-06	N/A	1.8E-04	N/A	N/A	N/A	3.6E-04	2.1E-03 – 2.7E-03
Low			1.2 – 2.9	98 – 1,123	4	5.9E-06	N/A	1.1E-05	N/A	N/A	N/A	3.0E-05	2.1E-03 – 2.7E-03
<b>All Sites</b>													
					16	1.0E-06	3.1E-06	7.5E-06	2.2E-05	7.5E-05	1.8E-04	3.6E-04	

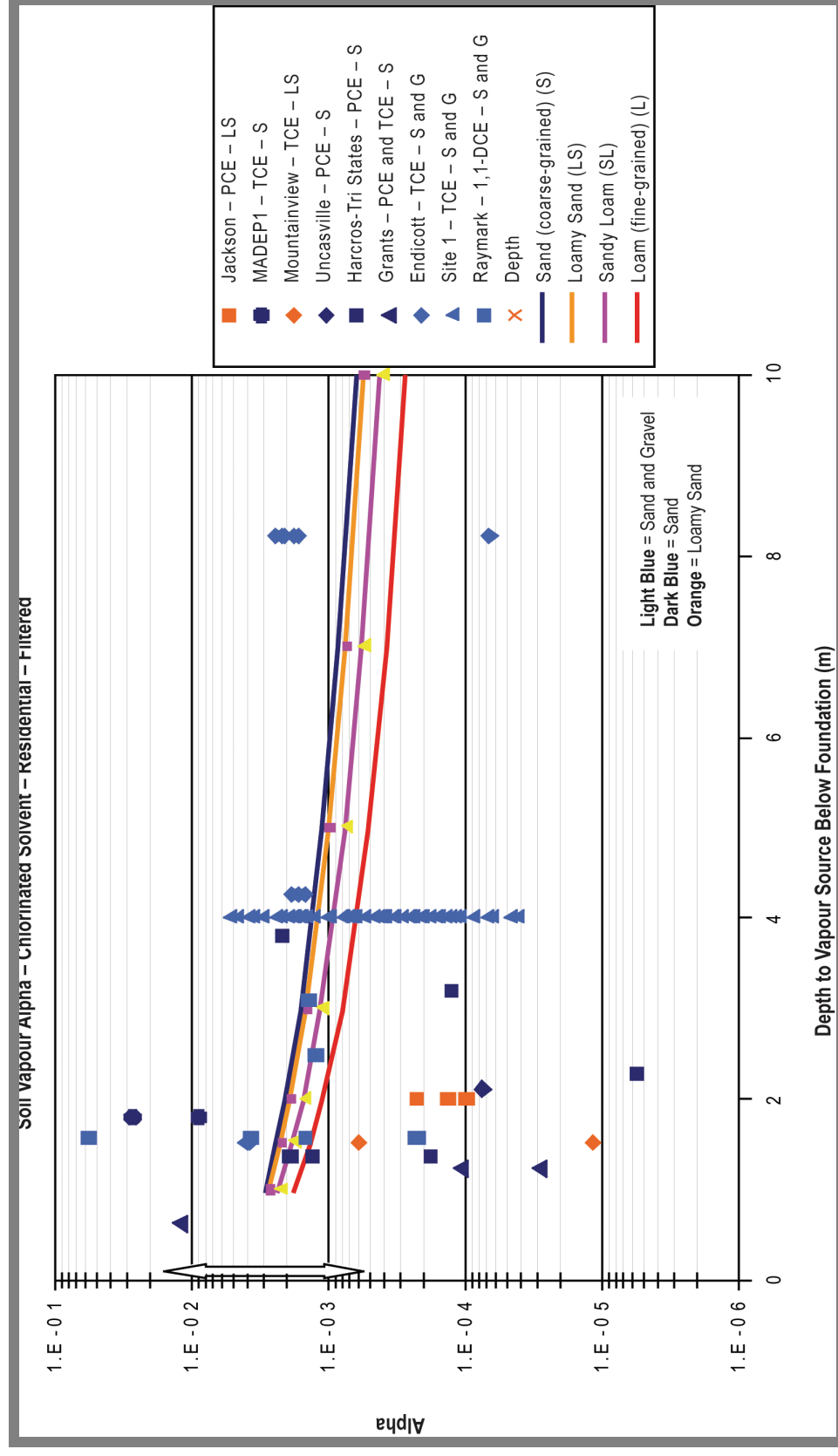
The empirical alphas are compared with the guidance quantitative screening groundwater alphas in Figure B20. The alphas for five sites (Endicott, Raymark, Site 1, MADEP 1, and Grants) exceed the guidance quantitative screening alphas, although the Grant data are for measurements that were from less than 1 m below the foundation (i.e. depth precluded). There is information on the soil-gas program for Endicott, Raymark, and Site 1, but none for MADEP 1. The soil-gas measurements for Endicott, Raymark, and Site 1 were relatively deep and close to the water table, with the possible exception of the Raymark site where most “deep” soil-gas measurements appear to be from about halfway between the foundation base and water table. For Endicott, the soil-gas measurements were for probes located up to 30 m from the building; in contrast, the measurements for Raymark were from a few metres from the building. For almost all buildings, the Endicott and Raymark data were limited to soil-gas measurements for one side of the building. For Site 1, the soil-gas measurements were interpolated concentrations below the building, based on probe spacing of about 20 m to 60 m. The data quality for the Endicott, Raymark, and Site 1 sites was considered acceptable. The relatively high alpha values for these three sites are primarily thought to be a result of the variability in soil-gas concentrations and presence of coarse-grained soils. Little vapour attenuation would be expected in coarse-grained soils, and therefore the soil vapour-to-indoor air alphas should be similar to the subslab alphas. Also shown on Figure B20 are the approximate range of subslab alphas that have been observed by U.S. EPA (2007).<sup>1</sup>

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<sup>1</sup> The 10th to 90th percentile of the subslab alphas using the filtering criteria previously described (100 times) are shown.



Figure B20. Comparison of Empirical Soil Vapour Chlorinated Solvent Alphas to Guidance Alphas (Filtered)



### B6.2.2 Petroleum hydrocarbon residential alphas

The residential petroleum hydrocarbon alphas graphed according to the reliability designations are shown in Figure B21. With the exception of four data points, all the data points represent BTEX measurements. At three sites (BP, Alameda, and Stafford), the buildings overlie residual NAPL present at the water table. For the remaining (MADEP) sites, information on NAPL was not available. All BTEX data points represent lower reliability data, indicating that the measured indoor air concentration was below the 90th percentile literature

background concentration. Therefore, it is probable that the empirical alphas, to varying degrees, include a background alpha, and that the vapour-derived alphas are lower than those shown.

The groundwater empirical alphas for petroleum hydrocarbons are compared with the guidance quantitative screening alphas in Figure B22. The maximum empirical alpha is about six times less than the guidance alpha, whereas the remaining empirical alphas are over one order of magnitude less than the empirical alphas.

**Figure B21. Soil Vapour Alphas Versus Vapour Concentration Providing Reliability Data for Petroleum Hydrocarbon Sites (Filtered)**

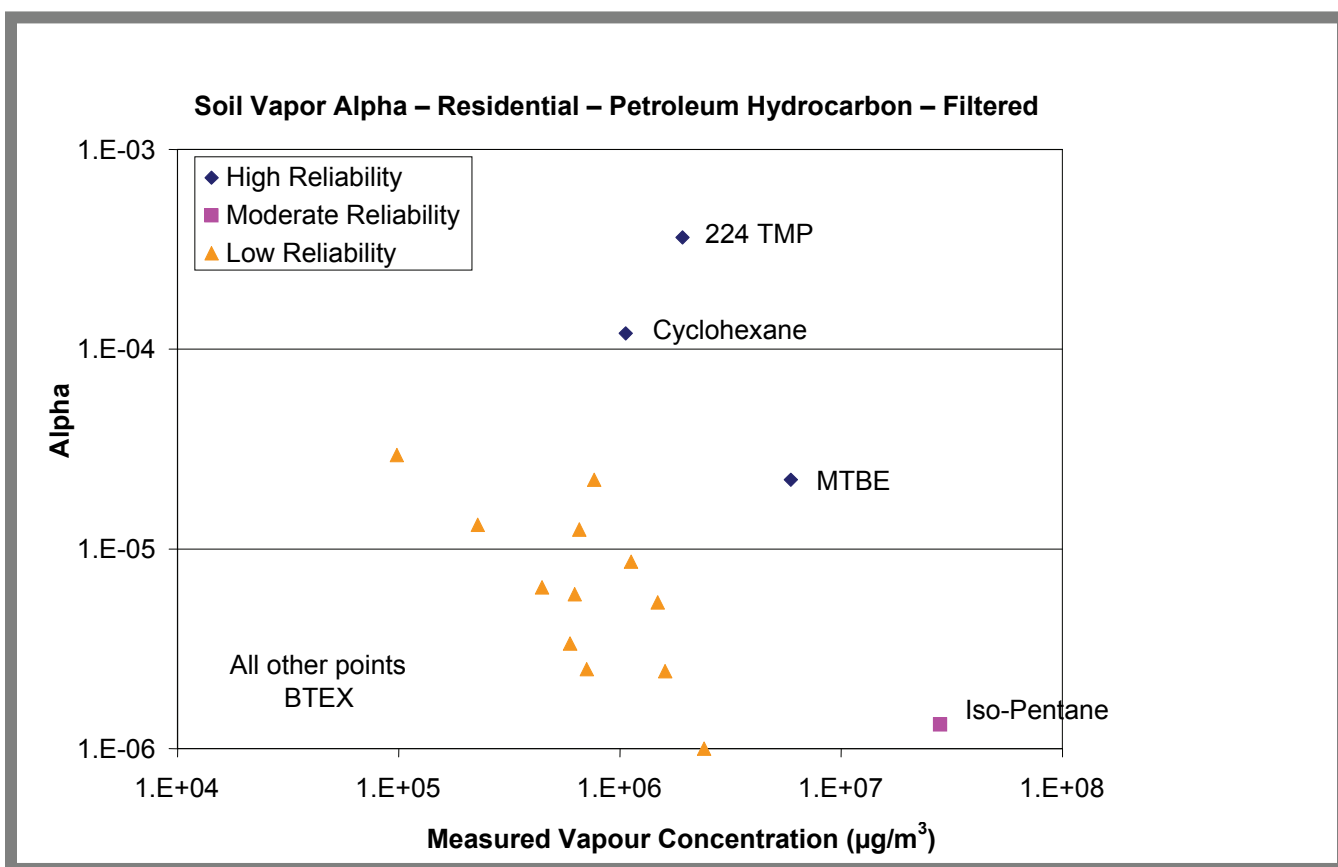
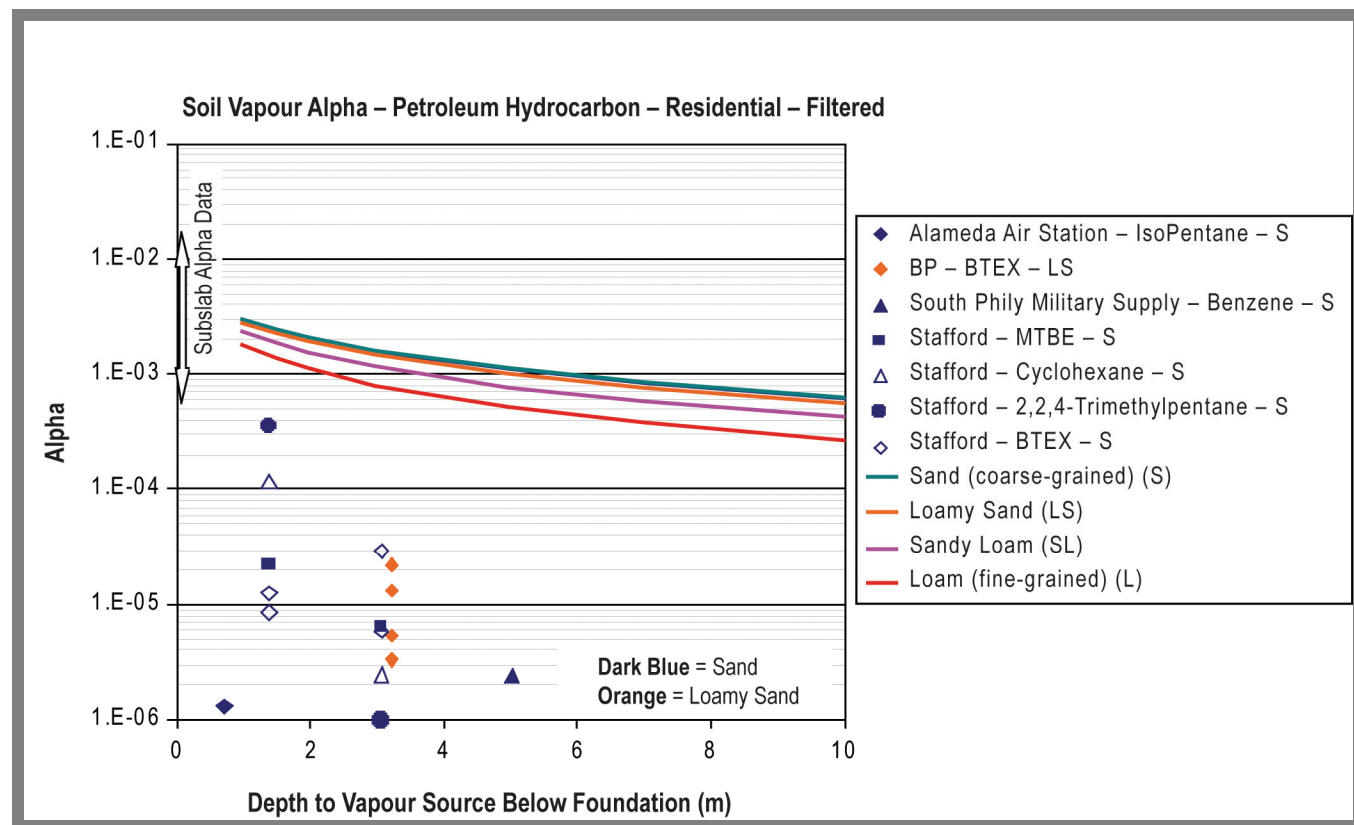


Figure B22. Comparison of Empirical Soil Vapour Petroleum Hydrocarbon Alphas to Guidance Alphas (Filtered)



## B6.3 Summary and Conclusions

### B6.3.1 Groundwater-to-indoor air pathway

The majority of the chlorinated solvent alpha values represent higher reliability data, whereas the petroleum hydrocarbon alpha values represent lower reliability data. For petroleum hydrocarbon sites, most of the empirical alphas likely include a background component.

Statistical parameters to characterize the combined set of empirical alphas for evaluated sites are discussed in the following text. It is recognized that the combination of data obscures the variability observed for individual sites (data for individual sites are provided in Table B2 and Table B3), and care must be taken when drawing inferences when there are different data populations. The combined data statistics, which are a useful way of summarizing data, are considered to provide approximate bounds to the range in alpha.

For chlorinated solvent sites, the majority of the alpha values (between 25th and 75th percentiles) fall between  $3.0 \times 10^{-5}$  and  $2.3 \times 10^{-4}$ . As a result of the uncertainty in empirical alphas and upward bias in the measurements (Section 3), maximum alphas should not be used for guidance purposes. The highest 90th to 95th percentile groundwater alphas for individual sites are approximately  $1 \times 10^{-3}$ . A generic groundwater alpha of  $1 \times 10^{-3}$  would result in a low probability of false negatives, based on the data in Table B2. The screening reliability assessment conducted for TCE also indicated a relatively low rate of false negatives in that there were only a very few cases where the predicted indoor air concentration was less than the measured indoor air concentration while also being greater than the indoor air screening level ( $5 \mu\text{g}/\text{m}^3$ ). A false negative is where vapour intrusion would be predicted to be of no concern when in fact it is.

For petroleum hydrocarbon sites, the majority of the alpha values (between 25th and 75th percentiles) fall between  $2.4 \times 10^{-6}$  and  $1.6 \times 10^{-5}$ . The 90th and 95th percentile groundwater alphas for all sites are  $3.7 \times 10^{-5}$  to  $1.0 \times 10^{-4}$ , respectively. Data to calculate percentiles for individual sites are insufficient. The petroleum hydrocarbon alphas are at least one order of magnitude lower than the chlorinated solvent alphas; however, caution should be used when comparing the data because the petroleum hydrocarbon data set is much smaller. For BTEX chemicals, it was not possible in almost all cases to distinguish the indoor air concentrations from background, meaning the empirical alphas are of low reliability and represent possible upper bound values.

The alpha values appear to be influenced by soil type with decreasing alpha as soil type becomes finer grained. There

are no significant apparent trends in alpha depending on the building foundation.

### B6.3.2 Soil vapour-to-indoor air pathway

The soil vapour alpha data set is much smaller than the groundwater alpha data set, and more of the site data are of low to moderate reliability. There is an unknown degree of uncertainty introduced by the significant spatial and temporal variability that can exist with respect to soil vapour concentrations and the potential for false negatives due to improper sampling of soil gas. Overall, the soil vapour alpha data set is considered less robust than the groundwater data set.

For chlorinated solvent sites, the majority of the alpha values (between 25th and 75th percentiles) fall between  $1.7 \times 10^{-4}$  and  $1.8 \times 10^{-3}$ . As a result of the uncertainty in empirical alphas and upward bias in the measurements, maximum alphas should not be used for guidance purposes. The 90th and 95th percentile soil vapour alphas for all site data are  $3.5 \times 10^{-3}$  and  $4.3 \times 10^{-3}$ , respectively.

For petroleum hydrocarbon sites, calculation of percentiles is not considered valid because of the small number of data points. Qualitatively, the petroleum hydrocarbon alphas are much lower (at least one order of magnitude) than the chlorinated solvent alphas; however, caution should be used when comparing the data because the data sets are small. At one site, there was less attenuation for cyclohexane and 2,2,4-trimethylpentane, compared with BTEX; this was inferred to be a result of greater bioattenuation for BTEX (Sanders and Hers, 2006). Cyclohexane and 2,2,4-trimethylpentane were also found to be effective tracers for quantifying vapour intrusion. For soil vapour empirical alphas, there are insufficient data to evaluate factors such as soil type and building properties.

In the absence of biodegradation, the alphas for chemicals such as benzene and trichloroethylene should be very similar because their chemical properties are similar. The differences in empirical alphas observed for chlorinated solvents and BTEX compounds suggest biodegradation is occurring at some sites. There are unfortunately only limited high-quality data sets that conclusively indicate biodegradation is causing attenuation of vapour concentrations below buildings.

In conclusion, the guidance attenuation factors are considered to be reasonably protective, in that the measured attenuation factors were, in almost all cases, less than those predicted using the J&E model, and incorporated in the guidance. The guidance alpha factors, when combined with appropriate guidance for site characterization and selection of input concentrations and protocol for collection of groundwater and soil vapour samples, will result in a screening process that will be reasonably conservative.

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## APPENDIX C

# NUMERICAL MODELLING OF BIOATTENUATION OF HYDROCARBON VAPOURS BELOW BUILDINGS

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## C1.0 INTRODUCTION

This appendix describes field studies that provide data on unsaturated soil biodegradation of hydrocarbon vapours and a numerical modelling study of hydrocarbon vapour bioattenuation below buildings. This information was used to develop the bioattenuation adjustment factors that are applied to the base vapour attenuation factors.

Biodegradation is a potentially significant mechanism for vadose-zone attenuation of petroleum hydrocarbon vapours (e.g. benzene, toluene, ethylbenzene, and xylenes [BTEX]). Field and modelling studies show that when there is sufficient oxygen for hydrocarbon biodegradation, vapour concentrations are often reduced to non-significant levels. There is also empirical evidence that vapour attenuation factors for BTEX

chemicals are lower than those measured for chemicals that are essentially non-degrading (e.g. chlorinated solvents). When evaluating the potential implications of biodegradation on BTEX vapour intrusion, the key requirement is the presence of oxygen below buildings. Mechanisms for oxygen transport include diffusion, advection of soil gas as a result of sustained building depressurization, variations in atmospheric pressure, and temperature gradients.

Because biodegradation research and empirical evidence supports a lower attenuation factor, this guidance includes an option to reduce the base attenuation factor by a factor of 10 times for BTEX and other readily degradable hydrocarbon compounds, when conditions warrant.

## C2.0 EVIDENCE FOR BIOATTENUATION BASED ON FIELD STUDIES

There are a limited number of field studies where vertical vapour profiling has enabled the evaluation of BTEX or hydrocarbon vapour attenuation below buildings. At the former Chatterton petrochemical plant site in Delta, British Columbia, there is extensive residual non-aqueous phase liquid (NAPL) contamination and sand soils. The benzene, toluene, and xylene (BTX) vapour concentrations decreased over three orders of magnitude over a small depth interval (about 0.3 m) for cases where there was no significant advective soil-gas transport. When an experimental building (small greenhouse) with a slab-at-grade foundation at the Chatterton site was depressurized to 10 Pa or greater, there was little BTX vapour attenuation because of increased BTX vapour flux from deeper soil and reduced biodegradation rates (Hers et al., 2000).

Fischer et al. (1996) reported that hydrocarbon vapour concentrations below an at-grade building decreased sharply over a small vertical interval (0.1 m to 0.7 m depth). The authors suggested that a partial physical barrier to vertical transport (i.e. high-moisture content zone) in combination with biodegradation accounted for the steep gradient. Contrasting results were presented by Laubacher et al. (1997) where vapour profiling was performed below and adjacent to a house with a basement. Testing directly below the basement floor slab indicated elevated BTEX vapour concentrations and low O<sub>2</sub> concentrations (<1%). In contrast, BTEX

vapour concentrations adjacent to the house (i.e. at the same depth) were two orders of magnitude lower, and O<sub>2</sub> levels were about 14%. The Laubacher et al. (1997) study is significant because it suggests that hydrocarbon vapours can accumulate below a building.

Several studies have involved monitoring at sites not covered by buildings. Ririe and Sweeney (1995) present data showing that BTEX vapour concentrations decreased sharply with decreasing depth. Complementary geochemical data were obtained to demonstrate biodegradation was occurring. Ostendorf and Kampbell (1991) present similar data for a site contaminated with aviation fuel, and derive kinetic biodegradation rate constants using a coupled diffusive hydrocarbon and O<sub>2</sub> transport model calibrated using field data.

Estimated first-order aerobic biodegradation rates for several case studies are presented in Table C1. The rates implicitly assume that oxygen- and hydrocarbon-degrading microbes are available in excess and only the hydrocarbon substrate is rate limiting. The estimated degradation rates are highly sensitive to the effective diffusivity and moisture content. Back-calculated biodegradation rates are overestimated when there are thin unquantified high-moisture content layers (i.e. that are not included in the analysis), because these layers represent a partial barrier to diffusive transport. At sites where there are unresolved moisture content effects, fitted biodegradation rates are, in effect, lumped parameters. Due to the various sources of uncertainty, the estimated biodegradation rates (kw1) should be considered order-of-magnitude estimates. The biodegradation rates in Table C1 are similar to rates given by DeVaul et al. (1997), which were for seven laboratory studies and one field study.

**Table C1. Measured Aerobic Biodegradation Rates from Field Studies**

Site	Chemical Class	Chemical	Biodegradation Layer Thickness (m)	First-Order Degradation Rate (water-phase) (hr <sup>-1</sup> )
Chatterton (Hers et al., 2000)	BTX	benzene	0.3	0.5–2.0 (1.2)
		toluene	0.3	0.3–1.5 (0.9)
		<i>m</i> - and <i>p</i> -xylenes	0.3	0.2–0.8 (0.5)
Alameda (Fischer et al., 1996)	gasoline	isopentane	0.2	~2
Traverse City (Ostendorf & Kampbell, 1991)	aviation fuel	total hydrocarbon	3	~0.01
California (Ririe and Sweeney, 1995)	gasoline	benzene	2	0.4

The vadose-zone first-order degradation rates are about two to four orders of magnitude higher than those obtained for dissolved BTEX plumes in groundwater (Wiedemeier et al., 1996). The likely reason for the much higher vadose-zone biodegradation rates is that the transfer of oxygen into groundwater is a much less efficient process than vadose-zone oxygen transport. Although the vadose-zone biodegradation rates are high compared with saturated zone rates, they are on the same order or lower than rates obtained for biofilters, suggesting that vadose-zone rates presented in Table C1 are reasonable. For example, Andreoni et al. (1997) report a toluene removal rate of 6 mg/L-hour for a biofilter constructed of wood bark, whereas Wu et al. (1999) report a toluene removal rate of 135 mg/L-hour for a biofilter constructed of peat beads.

## C3.0 MODELLING STUDY

### C3.1 Introduction

A two-dimensional finite difference numerical model was used to provide insight into the aerobic biodegradation of BTEX vapours below a building. The results of the modelling study were used to guide the selection of the depth cut-off criteria for applying the 10 times reduction factor for biodegradation in this guidance (e.g. greater than 3-m depth between foundation and contamination source). The modelling study scope was relatively limited and the results are preliminary. Further modelling studies are recommended to evaluate aerobic biodegradation of hydrocarbon vapours below buildings.

### C3.2 Description of Model and Input Parameters

A two-dimensional numerical model (VADBIO) for multispecies transport in the unsaturated zone was used to evaluate

hydrocarbon vapour biodegradation (Hers et al., 2000). The model simulates diffusion, gas-phase advection, absorption, and first- or zero-order reaction (biodecay), assuming equilibrium chemical partitioning between the vapour, aqueous, and sorbed phases, and linear isotherms for multiple chemical species. The model includes the capability to simultaneously solve the oxygen transport equation, and to link hydrocarbon vapour degradation to oxygen availability. This is done by estimating, for each simulation time step, the mass of hydrocarbon degraded and oxygen consumed using the stoichiometric relationship for complete mineralization of the hydrocarbon, and either a first- or zero-order biodecay process. The model currently allows for simultaneous transport of four chemicals (i.e. BTEX). The effect of other hydrocarbon compounds on biodegradation capacity is addressed through a scaling factor, as described in the following text. The input conditions and parameters are described below and summarized in Table C2.

**Table C2. Input Parameters for Biodegradation Modelling**

Parameter		Loam Below Building	Loam Adjacent Building	Sand Below Building	Sand Adjacent Building
Soil Properties	Water-filled porosity (dimensionless)	0.18	0.29	0.05	0.055
	Total porosity (dimensionless)	0.43	0.43	0.43	0.43
	Organic carbon content (dimensionless)	0.002	0.002	0.002	0.002
	Bulk density(g/cm <sup>3</sup> )	1.67	1.67	1.67	1.58
		Benzene	Toluene	<i>m</i> - and <i>p</i> -xylenes	Oxygen
Chemical	Henry's Law constant (dimensionless)	0.23	0.28	0.23	31.6
Properties	Diffusion coef in air (m <sup>2</sup> /sec)	8.44E-06	7.60E-06	7.00E-06	2.06E-05
	Diffusion coef in water (m <sup>2</sup> /sec)	1.00E-09	1.00E-09	1.00E-09	1.00E-09
	Partitioning coef (log K <sub>oc</sub> ) (cm <sup>3</sup> /g)	1.96	2.12	2.56	1
Concentrations	C <sub>g</sub> (x,y,t = 0) (mg/L)	0	0	0	279
	Conservative C <sub>g</sub> (x,y = 0,t) (mg/L)	2.8	8.7	2.7	Variable
	Best-estimate C <sub>g</sub> (x,y = 0,t) (mg/L)	0.6	1.5	0.8	Variable
	C <sub>g</sub> (x,y = ground surface,t) (mg/L)	0.000005	0.00001	0.000003	279
Biodegradation	Conservative first-order rates (kw <sup>1</sup> ) (hr <sup>-1</sup> )	0.05	0.05	0.05	N/A*
Rates	Conservative zero-order rates (kw <sup>0</sup> ) (mg/L-hr)	0.05	0.05	0.05	N/A
		0.5	0.5	0.5	N/A
	Best-estimate first-order rates (kw <sup>1</sup> ) (hr <sup>-1</sup> )	0.5	0.5	0.5	N/A
		3.1	3.1	3.1	N/A
	Best-estimate zero-order rates (kw <sup>0</sup> ) (mg/L-hr)				
	Average stoichiometric ratio				

\* Not applicable.

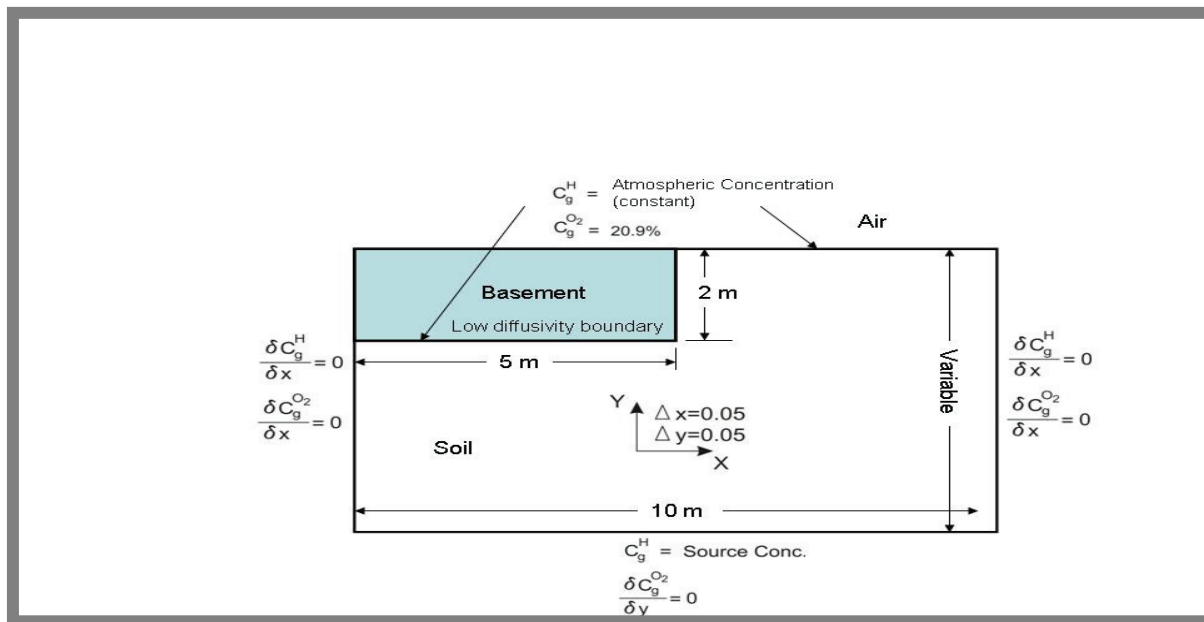
### C3.2.1 Boundary conditions

The model boundary conditions are shown in Figure C1.  
Boundary conditions for hydrocarbon transport are as follows:

**Bottom layer** – a constant vapour concentration (Dirichlet condition)

**Top layer** – constant concentration equal to atmospheric hydrocarbon concentration that assumes chemicals are subject to instantaneous mixing and dilution in the atmosphere

Figure C1. Model Domain



The boundary conditions for O<sub>2</sub> transport are as follows:

**Bottom layer** – constant flux set equal to zero (Neumann condition)

**Top layer** – constant atmospheric concentration with time (20.9%)

Conservative BTEX vapour concentrations at the contamination source were estimated assuming a constant non-depleting NAPL source of weathered gasoline, partitioning between the NAPL and vapour phases, and the mole fractions for gasoline vapour components in Johnson et al. (1990) (Table C3). The conservative benzene, toluene, and xylenes source concentrations are 2.8 mg/L, 8.7 mg/L, and 2.7 mg/L, respectively. Possible compositional changes in the NAPL source over time were not accounted for. A weathered gasoline source was used because source benzene concentrations are higher (conservative) for this case. The vapour concentrations were adjusted to 10°C using the Clausius-Clapeyron relationship (Schwarzenbach et al., 1993).

Table C3. Estimated Theoretical Vapour Concentrations Associated with a Gasoline Non-Aqueous Phase Liquid Source

No.	Component	Chemical Formula	Molecular Weight Mwl (g/mole)	Vapour Pressure Pv,l (atm, 20°C)	Boiling Temperature Tb (@ 1 atm, °C	Vapour Pressure Pv,l (atm, 10°C)	Fresh Gasoline Mole Fraction (–)	Weathered Gasoline Mole Fraction (–)	Fresh Vapour Concentration (µg/L, mg/m³)	Weathered Vapour Concentration (µg/L, mg/m³)
24	benzene	C6H6	78.1	0.1	80	0.06196	0.0093	0.0137	1938.1	2855.1
33	toluene	C7H8	92.1	0.029	111	0.017105	0.0568	0.1216	3853.6	8250.0
40	p-xylene	C8H10	106.2	0.0086	138	0.004789	0.0858	0.1247	1879.5	2731.6
41	m-xylene	C8H10	106.2	0.008	139	0.004432	0	0.0000	0.0	0.0
43	o-xylene	C8H10	106.2	0.0066	144	0.003634	0	0.0000	0.0	0.0
	<b>BTEX</b>						<b>0.1519</b>	<b>0.26</b>	<b>7671</b>	<b>13837</b>
1	propane	C3H8	44.1	8.5	-42	6.412941	0.0002	0.0000	2435.9	0.0
2	isobutane	C4H10	58.1	2.93	-12	2.14938	0.01999	0.0000	107507.1	0.0
3	n-butane	C4H10	68.1	2.11	-1	1.499217	0.1031	0.0000	453320.3	0.0
4	trans-2-butene	C4H8	56.1	1.97	1	1.394482	0.0012	0.0000	4042.9	0.0
5	cis-2-butene	C4H8	56.1	1.79	4	1.253633	0	0.0000	0.0	0.0
6	3-methyl-butene	C5H10	70.1	0.96	21	0.628192	0.0008	0.0000	1517.2	0.0
7	isopentane	CH12	72.2	0.78	28	0.560575	0.1384	0.0296	241236.0	51593.8
8	1-pentene	C5H10	70.1	0.7	30	0.477803	0	0.0000	0.0	0.0
9	2-methyl-1-butene	C5H10	70.1	0.67	31	0.453136	0	0.0000	0.0	0.0
10	2-methyl-1-butene	C5H8	68.1	0.65	34	0.465529	0	0.0000	0.0	0.0
11	n-pentane	C5H12	72.2	0.57	36	0.3884	0.0773	0.0169	93353.5	20409.8
12	trans-2-pentene	C5H10	70.1	0.53	36	0.34365	0	0.0000	0.0	0.0
13	2-methyl-2-butene	C5H10	70.1	0.51	38	0.338092	0.006	0.0000	6124.1	0.0
14	3-methyl-1,2-butadiene	C5H8	68.1	0.46	41	0.305193	0	0.0000	0.0	0.0
15	3,3-dimethyl-1-butene	C6H12	84.2	0.47	41	0.315391	0.0055	0.0000	6290.1	0.0
16	cyclopentane	C5H10	70.1	0.35	50	0.234752	0	0.0000	0.0	0.0
17	3-methyl-1-pentene	C6H12	84.2	0.29	54	0.190413	0	0.0000	0.0	0.0
18	2,3-dimethylbutane	C6H14	86.2	0.26	57	0.170059	0.0807	0.0744	50946.5	46969.3
19	2-methylpentane	C6H14	86.2	0.21	60	0.13269	0.0302	0.0000	14876.0	0.0
20	3-methylpentane	C6H14	86.2	0.2	64	0.129378	0	0.0000	0.0	0.0
21	n-hexane	C6H14	86.2	0.16	69	0.10182	0.0313	0.0459	11831.0	17349.5

No.	Component	Chemical Formula	Molecular Weight Mwl (g/mole)	Vapour Pressure Pv,l (atm, 20°C)	Boiling Temperature Tb (@ 1 atm, °C	Vapour Pressure Pv,l (atm, 10°C)	Fresh Gasoline Mole Fraction (–)	Weathered Gasoline Mole Fraction (–)	Fresh Vapour Concentration (µg/L, mg/m³)	Weathered Vapour Concentration (µg/L, mg/m³)
22	methylcyclopentane	C6H12	84.2	0.15	72	0.096147	0	0.0000	0.0	0.0
23	2,2–dimethylpentane	C7H16	100.2	0.11	79	0.069072	0.0093	0.0000	2772.0	0.0
25	cyclohexane	C6H12	84.2	0.1	81	0.062364	0	0.0000	0.0	0.0
26	2,3–dimethylpentane	C7H16	100.2	0.072	90	0.044458	0.0371	0.1088	7117.5	20872.8
27	3–methylhexane	C7H16	100.2	0.064	92	0.039114	0	0.0000	0.0	0.0
28	3–ethylpentane	C7H16	100.2	0.06	94	0.036646	0	0.0000	0.0	0.0
29	2,2,4–trimethylpentane	C8H18	114.2	0.051	99	0.031083	0.0101	0.0000	1544.0	0.0
30	n–heptane	C7H16	100.2	0.046	98	0.027416	0.006	0.0853	709.8	10091.6
31	methylcyclohexane	C7H14	98.2	0.048	101	0.029247	0	0.0000	0.0	0.0
32	2,2–dimethylhexane	C8H18	114.2	0.03	107	0.020862	0.0046	0.0000	472.0	0.0
34	2,3,4–trimethylpentane	C8H18	114.2	0.028	114	0.016644	0.0101	0.0000	826.8	0.0
35	2–methylheptane	C8H18	114.2	0.021	116	0.012078	0.0129	0.0468	766.3	2779.9
36	3–methylheptane	C8H18	114.2	0.02	115	0.011372	0	0.0000	0.0	0.0
37	n–octane	C8H18	114.2	0.014	126	0.007935	0.0011	0.0468	42.9	1826.4
38	2,4,4–trimethylhexane	C9H20	128.3	0.013	131	0.007437	0.0065	0.0000	267.1	0.0
39	2,2–dimethylheptane	C9H20	128.3	0.011	133	0.006205	0	0.0000	0.0	0.0
42	3,3,4–trimethylhexane	C9H20	128.3	0.0073	140	0.004013	0.0209	0.0208	463.4	461.2
44	2,2,4–trimethylheptane	C9H22	142.3	0.0053	149	0.002892	0.007	0.0000	124.1	0.0
45	3,3,5–trimethylheptane	C9H22	142.3	0.0037	156	0.001982	0	0.0188	0.0	228.4
46	n–propylbenzene	C9H12	120.2	0.0033	159	0.001762	0.0666	0.0737	607.4	672.2
47	2,3,4–trimethylheptane	C10H22	142.3	0.0031	160	0.001649	0	0.0000	0.0	0.0
48	1,3,5–trimethylbenzene	C9H12	120.2	0.0024	165	0.001261	0.0325	0.0222	212.1	144.9
49	1,2,4–trimethylbenzene	C9H12	120.2	0.0019	169	0.000985	0.0169	0.0222	86.2	113.2
50	methylpropylbenzene	C10H14	134.2	0.001	182	0.000504	0.0249	0.0297	72.5	86.5
51	Dimethylethylbenzene	C10H14	134.2	0.0007	190	0.000348	0.0218	0.0319	43.8	64.1
52	1,2,4,5–tetramethylbenzene	C10H14	134.2	0.00046	196	0.000223	0.0094	0.0319	12.1	41.1
53	1,2,3,4–tetramethylbenzene	C10H14	134.2	0.00033	205	0.000159	0.0091	0.0000	8.3	0.0
54	1,2,4–trimethyl–5–ethylbenzene	C11H16	148.2	0.00029	210	0.00014	0.026	0.0000	23.2	0.0

No.	Component	Chemical Formula	Molecular Weight Mwl (g/mole)	Vapour Pressure Pv,l (atm, 20°C)	Boiling Temperature Tb (@ 1 atm, °C	Vapour Pressure Pv,l (atm, 10°C)	Fresh Gasoline Mole Fraction (–)	Weathered Gasoline Mole Fraction (–)	Fresh Vapour Concentration (µg/L, mg/m³)	Weathered Vapour Concentration (µg/L, mg/m³)
55	n-dodecane	C12H26	170.3	0.0004	216	0.000201	0.0129	0.0181	19.0	26.6
56	naphthalene	C10H8	128.2	0.00014	218	6.43E-05	0.0033	0.0083	1.2	2.9
57	n-hexylbenzene	C12H20	162.3	0.0001	226	4.55E-05	0	0.0078	0.0	2.5
58	methyl/naphthalene	C11H10	142.2	0.000054	241	2.41E-05	0.0015	0.0000	0.2	0.0
	<b>Non-BTEX Components</b>									
	<b>Total Hydrocarbon (Sum BTEX and non-BTEX Components)</b>						<b>0.84519</b>	<b>0.7399</b>	<b>1009672</b>	<b>173737</b>
	<b>Ratio BTEX / Total Hydrocarbon Vapour Concentration</b>						<b>0.99709</b>	<b>0.9999</b>	<b>1017344</b>	<b>187573</b>
	<b>Approximate Ratio BTEX / Total Hydrocarbon Vapour Concentration</b>								<b>~0.01</b>	<b>~0.1</b>



The best-estimate BTEX vapour concentrations at the contamination source were obtained from several field studies where vapour concentrations were measured near to contamination sources (Hers et al., 2000). Soil vapour concentrations measured at source areas are less than predicted values based on equilibrium partitioning models. The best estimates of BTEX source concentrations are 0.6 mg/L, 1.5 mg/L, and 0.8 mg/L, respectively.

### ***C3.2.2 Scaling factor to account for other hydrocarbon vapours***

When modelling the transport of BTEX plumes in groundwater, electron acceptor use by hydrocarbon compounds other than BTEX is typically not a significant issue because BTEX represents over 70% of the soluble hydrocarbon components at gasoline and JP-4 sites (BIOSCREEN V 1.3 Manual). For vapour plumes, BTEX typically represents a small component of the total hydrocarbon vapour concentration. Therefore, a scaling factor to account for the oxygen demand presented by other hydrocarbon compounds is important. Two scaling factors were calculated and used in the model simulations: a conservative scaling factor and a best-estimate scaling factor.

The conservative scaling factor was estimated by the proportion of BTEX vapour mass to total hydrocarbon vapour mass for weathered gasoline, using properties given in Johnson et al. (1990). It is assumed that BTEX and hydrocarbon vapours, on average, have similar transport and biodegradation properties. The conservative scaling factor is 10%. To account for oxygen demand by other hydrocarbon compounds, the oxygen concentration for the top (ground surface) boundary was scaled to 10% of the atmospheric concentration (27.9 mg/L). The biodegradation function was turned off when oxygen concentrations reached 2.7 mg/L; this corresponds to 27 mg/L (2% by volume) scaled by 10%. The biodegradation function was turned off because biodegradation rates are significantly reduced at low concentrations (DeVaull et al., 1997).

There are little field data on relative oxygen consumption rates for BTEX and total hydrocarbon vapours. Therefore, the best-estimate scaling factor was obtained through consideration of relative vapour elimination rates for biofilters, and the proportion of BTEX to total hydrocarbon vapours measured in effluent of soil vapour extraction systems. Jutrus et al. (1997) report that the elimination rate for BTEX relative to total hydrocarbons for a biofilter was about 20% for gasoline vapours. Togna and Skladany (1994) report that the proportion of BTEX to total hydrocarbon vapours, on a mass basis, ranged from 10% to 30% for extracted gasoline vapours. A similar range has been found for projects conducted by the authors. The best-estimate scaling factor was taken to 20%. It is again assumed that BTEX and hydrocarbon vapours have similar transport and biodegradation properties.

### ***C3.2.3 Biodegradation rates***

The best-estimate first- and zero-order rates for individual BTEX components were taken to be 0.5/hour and 0.5 mg/L-hour, respectively. The best-estimate values are equal to the low end of the range of first-order rates measured for BTEX at the Chatterton site (Hers et al., 2000). The conservative first- and zero-order rates were one order of magnitude lower and equal to 0.05/hour and 0.05 mg/L-hour, respectively. When individual BTEX concentrations in pore-water concentration exceed 1 mg/L, a zero-order model was used. When concentrations are less than 1 mg/L, a first-order model was used. The rationale for this approach is described in Hers et al. (2000).

### ***C3.2.4 Soil properties***

Soil properties were estimated for sand and loam, as defined by the U.S. Soil Conservation Service (SCS) soil texture classifications. The total porosity and field capacity were estimated using the van Genuchten equation (van Genuchten, 1980) for the water-retention curve, and van Genuchten soil water-retention curve parameters for U.S. SCS soil textures computed by Carsel and Parrish (1988).

Below the building, the volumetric soil moisture content was assumed to lie halfway between the residual water content and field capacity (0.05 for sand and 0.18 for loam). Adjacent to the building, the volumetric moisture content was assumed to be equal to the field capacity (0.055 for sand and 0.29 for loam). The total porosity for both sand and loam was 0.43. The organic carbon fraction was assumed to be 0.002.

For the case of sand soil, it was assumed that the top 0.1 m of soil adjacent to the building consisted of loam. The use of loam is intended to simulate topsoil that would typically be present in vegetated areas.

### ***C3.2.5 Building properties***

The building modelled was a single-family residence with basement that was 10 m × 10 m in size and 2 m deep. The effective diffusion coefficient for a concrete foundation slab and walls was estimated using the method in Hers et al. (2000), and a crack ratio and crack tortuosity equal to 0.0005 and 0.2, respectively. The crack tortuosity used was for dry dust-filled cracks.

### ***C3.2.6 Model domain***

The model domain is shown in Figure C1. The model grid was set equal to  $\Delta X = 0.1$  m and  $\Delta Y = 0.2$  for computational efficiency. As shown in Hers et al. (2000), there is small degree of model error for a model grid size of  $\Delta Y = 0.1$  m; however, numerical model concentrations are biased high relative to the analytical solution and therefore are

conservative. There was no significant difference in results between a model grid size of  $\Delta X = 0.1$  m and  $\Delta X = 0.2$  m. The model domain was also adjusted to ensure that the width of the open ground surface adjacent to the building was sufficiently large such as not to affect the results.

### C3.3 Model Simulation Results

Model simulations for diffusion, biodegradation, and sorption were run for sand and loam soil, the conservative and best-estimate biodegradation values, and four depths to

contamination below the basement foundation (1.7 m, 3.6 m, 5.7 m, and 8 m). The results are expressed two ways:

1. predicted subslab vapour concentration for benzene below the centre of the building versus depth to vapour contamination source (Figures C2 and C3)
2. predicted subslab vapour concentration for benzene below the centre of the building versus depth to vapour contamination source divided by building width (D/W) (Figures C4 and C5)

**Figure C2. Model-Predicted Subslab Benzene Concentrations Directly Below Centre House**

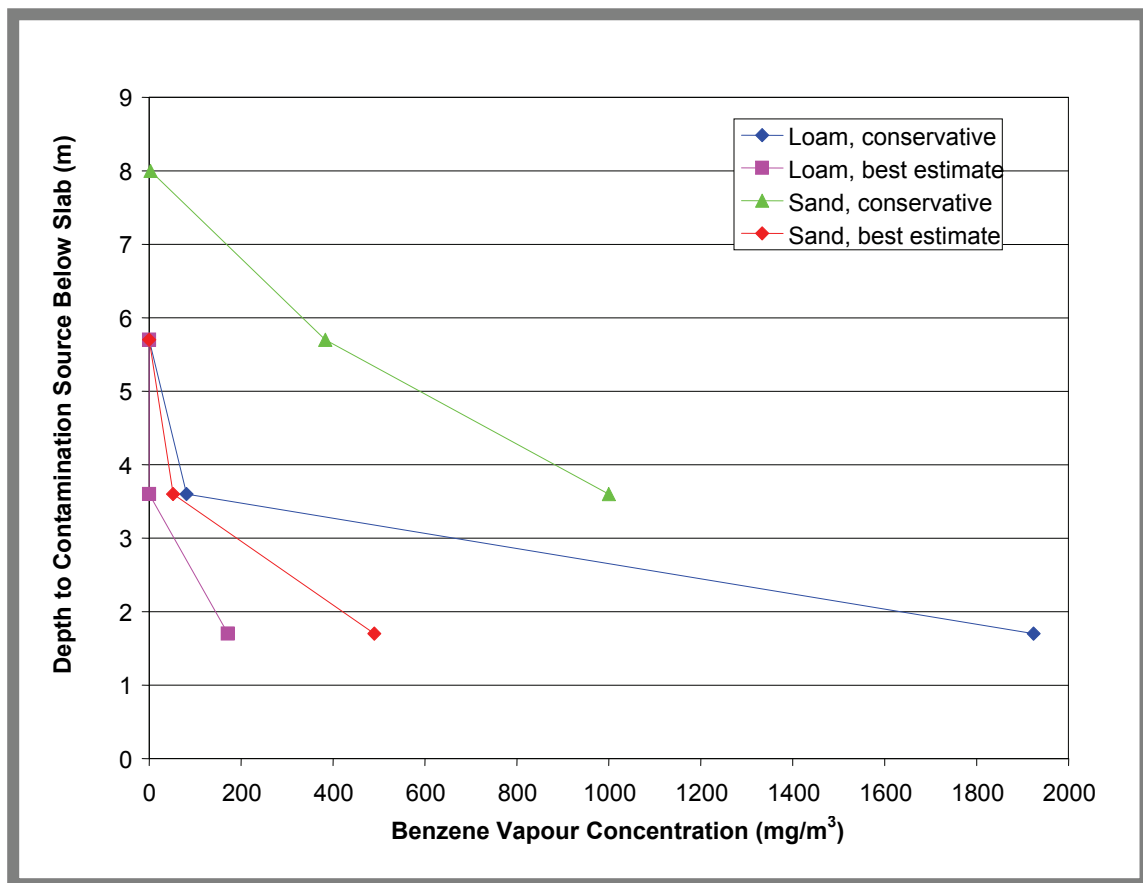


Figure C3. Model-Predicted Oxygen Concentrations Directly Below Centre House

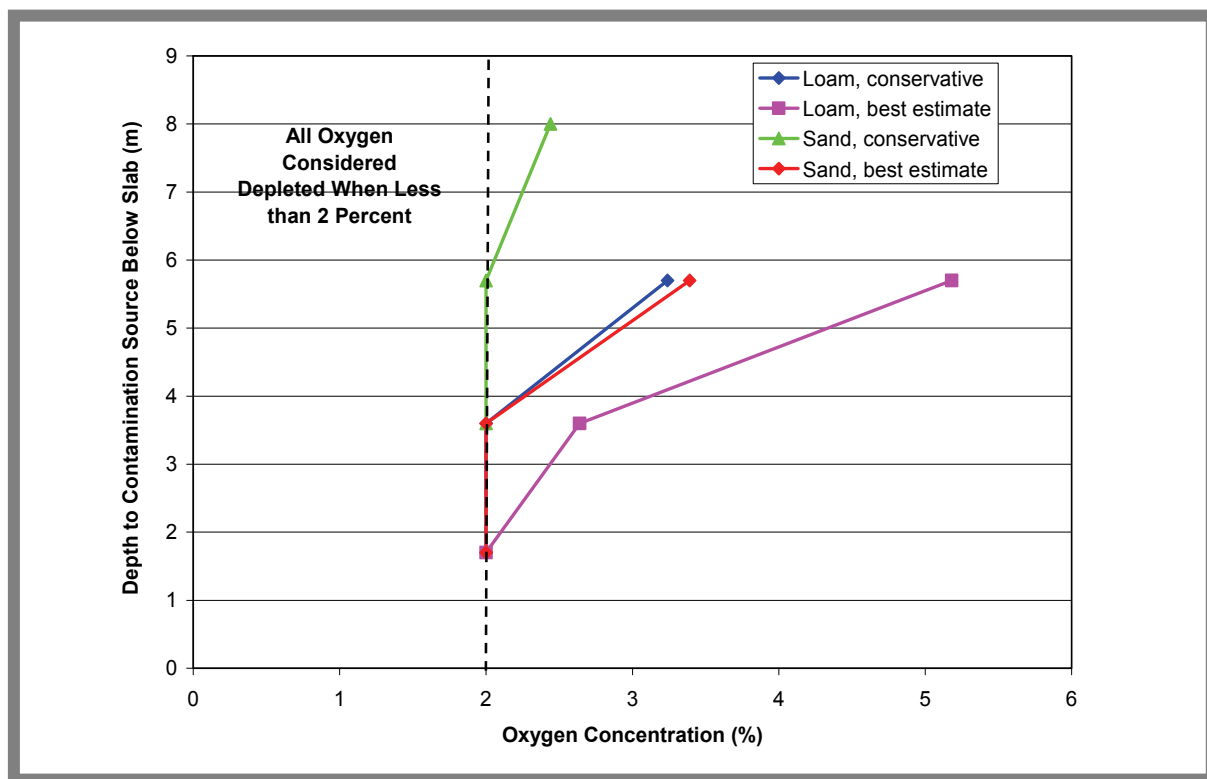


Figure C4. Model-Predicted Benzene Vapour Concentrations Directly Below Centre of House (Depth/Width)

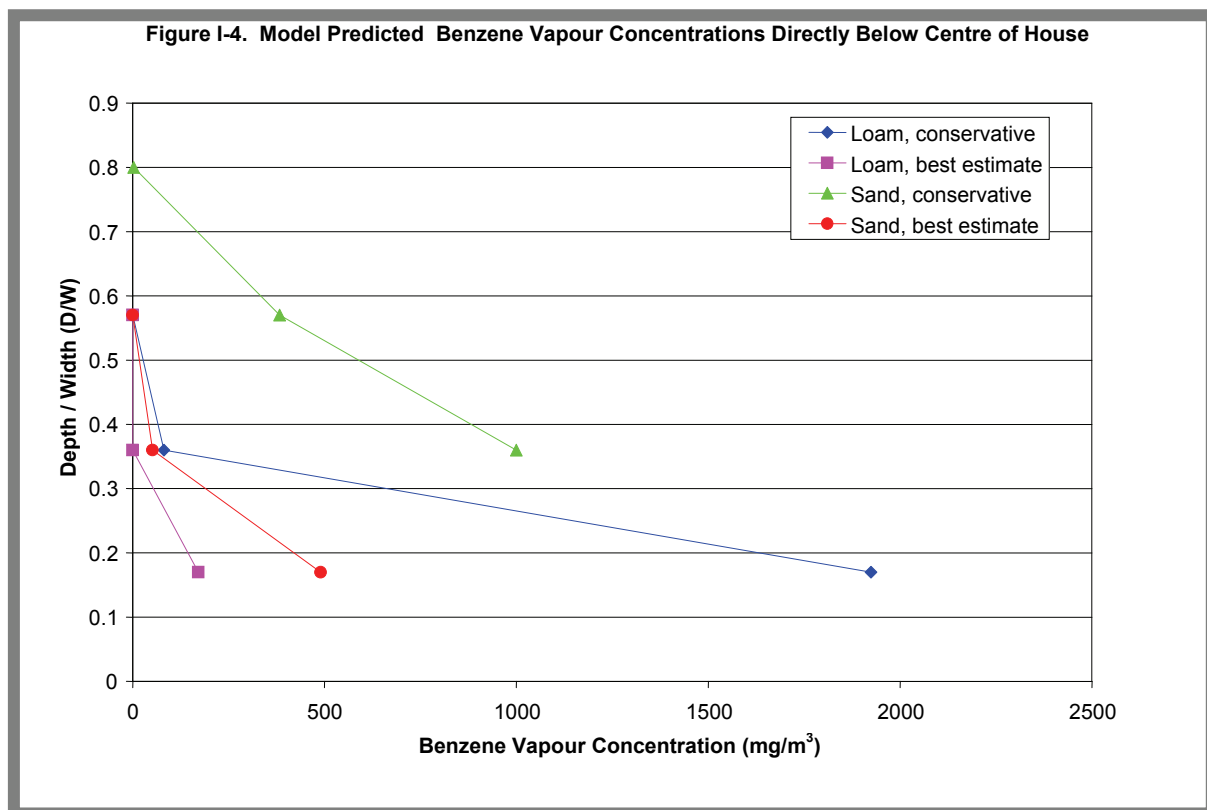
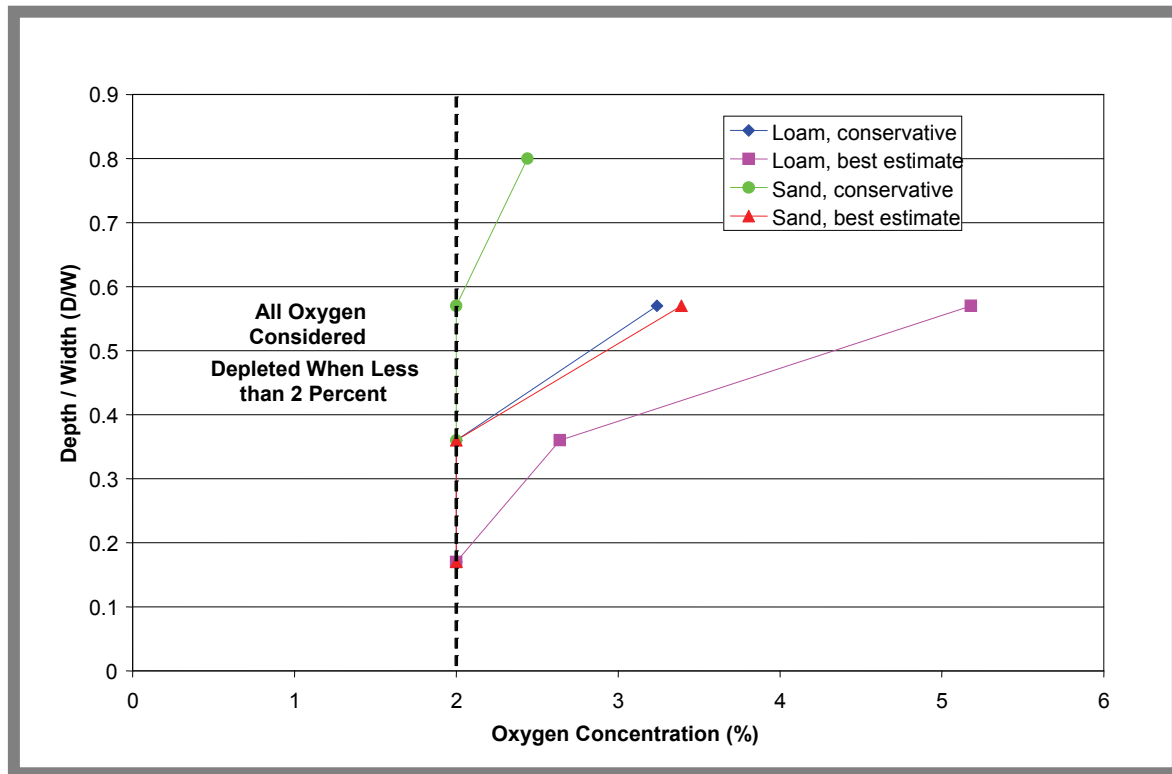


Figure C5. Model-Predicted Oxygen Concentrations Directly Below Centre House (Depth/Width)



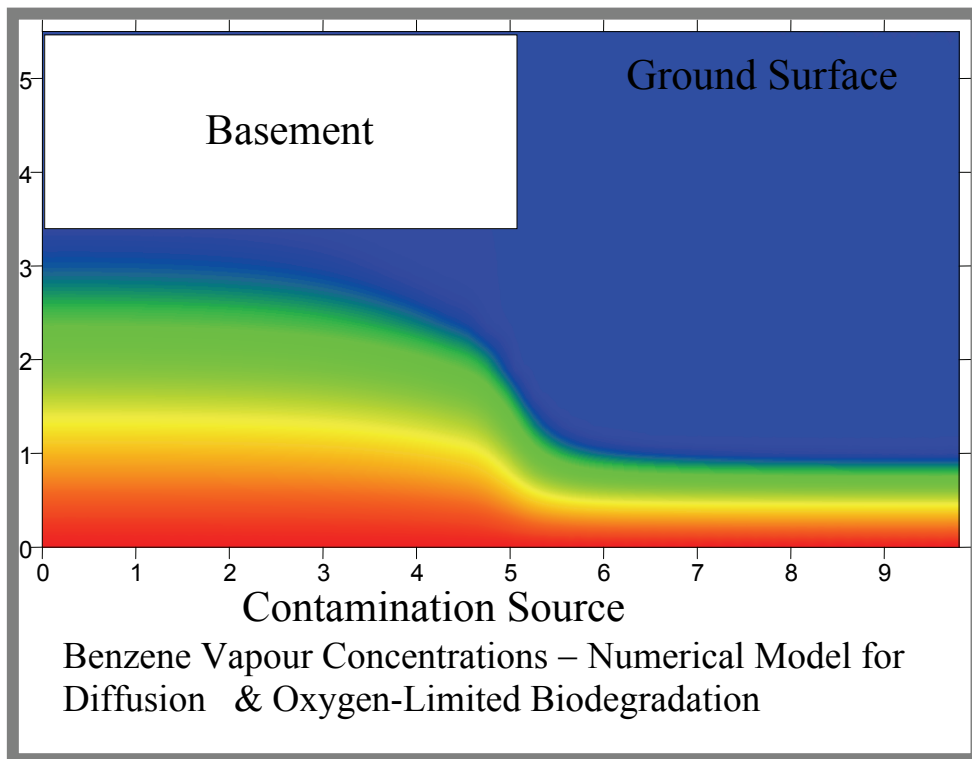
The benzene concentration 0.15 m below the underside of the slab, and corresponding to 3 months' simulation time is presented. After 3 months, approximate steady-state conditions had been reached.

For three of the four cases (loam conservative, loam best estimate, sand best estimate), the predicted subslab benzene vapour concentrations below the centre of the building had decreased to fairly low levels (less than about 100 mg/m<sup>3</sup>) for contamination depths greater than 3 m to 4 m (Figure C2). The predicted benzene concentrations near the edge of the building were less than those predicted below the centre of the building. The oxygen concentrations were depleted relative to atmospheric levels for all cases simulated, but were sufficiently high to enable biodegradation to occur for depths greater than about 3 m to 4 m for three of the four cases simulated. Excluding the sand- conservative case, the minimum D/W ratio that corresponds to a relatively low subslab benzene vapour concentrations below the centre of building was about 0.4.

For the sand-conservative case, the benzene concentrations do not decrease to low levels until the depth to contamination is at least 8 m below the basement. It is noted that for the sand scenario, a loam surface layer was simulated. This loam layer has a much lower effective diffusion coefficient than the sand; as a result, oxygen transport to below the building is significantly reduced. Because other mechanisms for oxygen transport are not included (e.g. barometric pumping, wind), the sand-conservative scenario is likely overly conservative. It does, however, illustrate the effect of a capping layer on diffusive transport.

The predicted benzene vapour concentrations were also contoured for the best-estimate loam case (Figure C6). The results show that there is a sharp increase in benzene vapour concentrations near the edge of the underside of the building. The reason for this increase is that oxygen diffusion rates through the concrete are much lower than through soil, and because the effective diffusion coefficient is higher below the building than adjacent to the building. This is due to the estimated moisture content being lower below the building.

**Figure C6. Vertical Cross-Section Showing Contoured Benzene Concentrations Below Building**



### ***C3.4 Implication for the Guidance***

The implication of the modelling results is that, when oxygen-controlled biodegradation is modelled, the building geometry, contrasts in effective diffusion coefficient, and depth to contamination all have a significant effect on BTEX vapour fate and transport below buildings. The results suggest that for a typical size single-family residence with a 2-m deep basement, the depth to contamination must be greater than roughly 3 m to 4 m below the basement (D/W ratio greater than 0.4) to enable aerobic biodegradation to occur for most cases evaluated. These values assume that there is no significant capping effect due to asphalt or other low-permeability surfaces adjacent to houses.

The modelling study here is preliminary in nature. Additional modelling studies are recommended to further evaluate hydrocarbon vapour biodegradation below buildings. The D/W ratio approach discussed previously requires further verification to determine its applicability for larger buildings.

## C4.0 DISCUSSION AND RECOMMENDATIONS

The research indicates the BTEX vapours are readily biodegraded in the presence of oxygen. Whether there is sufficient oxygen below the building for biodegradation will depend on a number of factors, including:

- source-vapour concentrations;
- depth of contamination source below building foundation (distance “D”);
- size or width of the building (distance “W”) (It is assumed that most atmospheric air migrates from adjacent to the building to below the building.);
- a capping effect that limits transport of atmospheric air from areas adjacent to building (e.g. low-permeability pavement surrounding building); and
- soil properties.

The potential for biodegradation of BTEX vapours will tend to be the greatest at sites with low source-vapour concentrations, a large depth to vapour contamination source compared with building size (large D/W ratio), permeable soils, and no capping effect that would limit transport of atmospheric air into subsoils.

The results of the empirical attenuation factor study indicated that the attenuation factors for BTEX sites were lower than those measured for chemicals that are essentially non-degrading (i.e. chlorinated solvents). In addition, the empirical attenuation factors observed for BTEX sites were, in most cases, at least an order of magnitude lower than the base

attenuation factor charts developed for this guidance. The modelling study indicates that when there is sufficient separation distance between the building and contamination source, there is significant bioattenuation of vapours below the building (for the modelling cases evaluated).

Because biodegradation research and empirical evidence supports a lower attenuation factor, it is proposed that this guidance include an option to reduce the base attenuation factor by a factor of 10 times for BTEX or other similar biodegrading chemicals, when conditions warrant. The two conditions that must be satisfied in order to make this reduction are:

1. sufficiently large depth to contamination below building foundation
2. no significant capping effect that would prevent oxygen transport into subsoils

There is no definitive basis for setting a depth criterion for this biodegradation adjustment. The results of the two-dimensional model simulations presented in this appendix suggest that a separation distance of 3 m to 4 m between the foundation and contamination source may be reasonable based on the cases evaluated (i.e. house with basement). The model processes and scenarios considered were relatively limited; therefore, the results are preliminary, but they provide a starting point for evaluation of conditions where biodegradation of BTEX vapours will reduce concentrations to non-significant levels.

The current framework for evaluating biodegradation is based on depth and capping effect. It is recommended that future versions of the guidance address the use of dimensionless ratios based on the ratio of contamination depth to building width, contamination source strength, and soil type. Additional modelling studies are recommended to further evaluate biodegradation of hydrocarbon vapours below buildings. Future published case studies may also be useful in this regard.

## C5.0 REFERENCES

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## APPENDIX D

### EXAMPLE CALCULATIONS SHOWING USE OF THE GUIDANCE

Appendix D presents example calculations illustrating the use of this guidance for four hypothetical site scenarios. The example calculations include the partitioning equations, the exposure calculations, and the subsequent risk calculations for both a residential and commercial setting.

#### Scenario 1

Scenario 1 illustrates a residential land-use setting with a dissolved phase plume in groundwater contaminated with trichloroethylene (TCE) and vinyl chloride (VC). The depth to water table (i.e. contamination) is estimated to be 4 m below the building foundation. The soil type is sand and gravel, and an adult receptor is assessed for exposure over a period of 30 years. The partitioning equations illustrate how to estimate the soil vapour concentration from the groundwater concentration using the Henry's Law constant. Using the representative attenuation factor, the indoor air concentration is calculated. Risk estimates are provided for an adult receptor. Both of these chemicals are considered to be carcinogenic or non-threshold-acting chemicals. Carcinogenic end points are considered protective of non-carcinogenic endpoints; therefore, non-carcinogenic risk does not need to be considered. For carcinogenic chemicals, assessment is of an adult.

The incremental lifetime cancer risk (ILCR) is estimated using both slope-factor and unit risk-factor approaches. For the slope-factor approach, the dose is amortized over life expectancy and can be adjusted for fraction of time exposed. For the unit risk-factor approach, there typically is no amortization as part of the risk calculations, although the risks could be adjusted by fraction of time exposed. Health Canada is currently reviewing the validity and acceptability of exposure amortization for carcinogenic substances in *Federal Contaminated Site Risk Assessment in Canada, Part I: Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA), Version 2.0* (2010). Until that review is complete, cancer risks estimated for a PQRA should assume life-long exposure.

#### Scenario 2

Scenario 2 illustrates a residential land-use setting with a weathered gasoline contamination. Non-aqueous phase liquid (NAPL) is present in soil above the water table in the unsaturated zone. The top of the NAPL zone is approximately 5 m below the building foundation. The contaminants of potential concern considered for this

scenario are benzene, toluene, xylenes, and hexane. Because NAPL is present, the two-phase partitioning model for NAPL to vapour partitioning is used. Because the mole fractions are available, Raoult's Law is used to estimate the vapour pressure (i.e. the pure-phase vapour pressure is multiplied by the mole fraction). Because the depth to contamination is greater than 5 m below the building and there is an open non-capped area surrounding the building, the vapour attenuation factors for benzene, toluene, and xylenes are decreased by a factor of 10 to account for biodegradation. The receptor exposure and risk estimates are presented for an adult receptor and a toddler (for non-carcinogens only). As shown in the example calculation, when a tolerable concentration (TC) is available for a chemical, it is directly used to estimate the hazard quotient (HQ) ( $HQ = C_{air}/TC$ ). When only a tolerable daily intake (TDI) is available, the HQ is estimated using the dose rate ( $HQ = \text{dose rate}/TDI$ ).

#### Scenario 3

Scenario 3 illustrates a commercial land use with a coal tar contamination in soil above the water in the unsaturated zone. The depth to the top of the contamination is 2 m below the building foundation. The soil type is sand. The contaminant of potential concern assessed is naphthalene, which is a relatively volatile polycyclic aromatic hydrocarbon. The measured naphthalene concentration in soil is 20 mg/kg. Because this concentration is less than the soil saturation concentration for naphthalene (373 mg/kg), the three-phase partitioning model is used to estimate the vapour concentration from a soil source. The commercial building is a warehouse with an indoor room height of 4 m. Because this is greater than the default height of 3 m and because mixing of vapours inside the entire building height is expected, the vapour attenuation factor is adjusted by multiplying the attenuation by 3 m/4 m (0.75). Risk estimates are provided based on exposure defaults for a commercial worker.

#### Scenario 4

Scenario 4 illustrates a residential land-use setting with weathered gasoline and diesel contamination. There is soil contamination and possibly NAPL above the water table. The contaminants of potential concern are total petroleum hydrocarbon (TPH) fractions and benzene, toluene, ethylbenzene, and xylenes (only calculations for TPH fractions are presented). Soil vapour samples are obtained above the soil contamination zone at 1.5 m depth below the building foundation. Soil vapour test results are available for the individual components of the Canadian Council of Ministers of the Environment F1 and F2 fractions. Hazard quotients are provided for each of the F1 and F2 components.



## Scenario 1

## 1. SITE DESCRIPTION

Scenario: Residential  
 Contamination type: Chlorinated solvent, dissolved plume  
 COPCs: Trichloroethylene (TCE), vinyl chloride (VC)  
 Soil type: Sand and gravel (coarse grained)  
 Depth to contamination below foundation: 4m

## 2. PARTITIONING

$$C_v = CF1 * C_w * H'$$

$$C_{air} = \alpha * C_v$$

COPC			TCE	VC	Source
Input Parameters					
Concentration in groundwater	C <sub>w</sub>	(mg/L)	0.09	0.004	Site data HC, 2010b
Dimensionless Henry's Law constant	H'	(unitless)	4.77E-01	3.24E+00	
Attenuation Factor	α		7.4E-04	7.4E-04	
Unit conversion factor	CF1	(L/m³)	1.0E+03	1.0E+03	
Partitioning					
Concentration in soil vapour	C <sub>v</sub>	(mg/m³)	4.29E+01	1.30E+01	
Concentration in indoor air	C <sub>air</sub>	(mg/m³)	3.16E-02	9.54E-03	

## 3. EXPOSURE TERM (ET)

$$ET = D1 * D2 * D3 * D4$$

D1; hours/day	24	HC, 2004
D2; days/week (/7days)	7	HC, 2004
D3; weeks/year (/52 weeks)	52	HC, 2004
D4; total years (carcinogen only)	60	HC 2008, policy

$$ET = 24/24 * 7/7 * 52/52 * 60/60 = 1$$

## 4. RISK ESTIMATES

$$ILCR = \text{Air Concentration} * ET * \text{Cancer Unit Risk}$$

ILCR = Incremental lifetime cancer risk

For TCE, use HC, 2004 inhalation unit risk = 6.1E-4 (mg/m<sup>3</sup>)<sup>-1</sup>For VC, there is no HC inhalation TRV; use USEPA inhalation unit risk for exposure from birth = 8.8E-03 (mg/m<sup>3</sup>)<sup>-1</sup>

Calculation of Risks for Exposures using Unit Risk Approach

COPC	Unit Risk (mg/m <sup>3</sup> ) <sup>-1</sup>	ILCR
Trichloroethylene	6.1E-04	1.9E-05
Vinyl chloride	8.8E-03	8.4E-05

## Scenario 2

## 1. SITE DESCRIPTION

Scenario:	Residential
Contamination type:	Weathered gasoline, NAPL present
COPCs:	Benzene, toluene, xylenes, hexane
Soil type:	Sandy silt (fine grained)
Depth to contamination below foundation:	5 m

## 2. PARTITIONING

$$C_v = 1E06 * X * P * MW / RT$$

$$C_{air} = \alpha * C_v$$

COPC			Benzene	Toluene	Xylene	Hexane	Source
<b>Input Parameters</b>							
Mole fraction	X	(unitless)	0.0137	0.1216	0.1247	0.0459	Johnson et al., 1990 HC, 2010b HC, 2010b
Vapour pressure	P	(atm)	1.25E-01	3.75E-02	1.05E-02	1.99E-01	
Molecular weight	MW	(g/mol)	78.11	92.14	106.17	86.18	
Gas constant	R	(L-atm/K-mol)	8.21E-02	8.21E-02	8.21E-02	8.21E-02	
Temperature	T	(K)	298	298	298	298	
Attenuation factor	$\alpha$		5.0E-04	5.0E-04	5.0E-04	5.0E-04	
Adjusted attenuation factor	$\alpha$		5.0E-05	5.0E-05	5.0E-05	5.0E-05	
<b>Estimated Concentrations in Soil Gas and Air</b>							
Concentration in soil vapour	$C_v$	(mg/m <sup>3</sup> )	5.47E+03	1.72E+04	5.69E+03	3.22E+04	
Concentration in air	$C_{air}$	(mg/m <sup>3</sup> )	2.74E-01	8.59E-01	2.84E-01	1.61E+00	

Note: 1. The attenuation factor was reduced by a factor of 10 for benzene, toluene, xylene, and hexane, as per the guidance.  
1 E 06 = conversion factor

## 3. EXPOSURE TERM (ET)

*Carcinogens*

$$ET = D1 * D2 * D3 * D4 = 1$$

*Non Carcinogens*

$$ET = D1 * D2 * D3 = 1$$

<b>Exposure Parameters:</b>	Toddler	Adult	Source
Exposure term:			
D1; hours/day	24	24	HC, 2004
D2; days/week (/7days)	7	7	HC, 2004
D3; weeks/year (/52 weeks)	52	52	HC, 2004
D4; total years (carcinogens only)	N/A	60	HC policy, 2008

Note: As per HC (2004), an adult is evaluated for carcinogens and a toddler is evaluated for non-carcinogens.

## 4. RISK ESTIMATES

$$ILCR = \text{Air Concentration} * ET * \text{Cancer Unit Risk}$$

$$HQ = C_{air} * ET / TC$$

Calculation of Risks

COPC	Toxicity Reference Value		Source	Risk Estimate	
	TC (mg/m <sup>3</sup> )	Unit Risk (mg/m <sup>3</sup> ) <sup>-1</sup>		HQ (child)	ILCR (adult)
Benzene	-	3.30E-03	HC, 2004	-	9.03E-04
Toluene	3.80E+00	-	HC, 2004	2.26E-01	-
Xylene	1.80E-01	-	HC, 2004	1.58E+00	-
Hexane	7.00E-01	-	USEPA IRIS <sup>1</sup>	2.30E+00	-
<b>Total ILCR</b>					9.0E-04

1. USEPA Integrated Risk Information System (IRIS) accessed November 2008. Health Canada is currently reviewing hexane toxicity reference value.

## Scenario 3

## 1. SITE DESCRIPTION

Scenario:	Light industrial warehouse
Contamination type:	Coal tar contamination in soil
COPCs:	Naphthalene
Soil type:	Sand (coarse grained)
Depth to contamination below building	2 m
Vapour mixing height in building	4 m

## 2. PARTITIONING

$$C_v = X * S / \rho_b * (K_{oc} * f_{oc} * \rho_b * B + \theta_w + H' * \theta_a)$$

If  $C_t < C_{sat}$ , then no NAPL present and the following applies:

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

$$C_{air} = \alpha * C_v$$

COPC			Naphthalene	Source
<b>Input Parameters</b>				
Concentration in soil	$C_{soil}$	(mg/kg)	20	
Water solubility	S	(mg/L)	3.10E+01	HC, 2010b
Soil dry bulk density	$\rho_b$	(kg-soil/L-total)	1.7	CCME, 2008
Organic carbon partition coefficient	$K_{oc}$	L/kg	1.12E+03	HC, 2010b
Fraction of organic carbon	$f_{oc}$		0.005	CCME, 2008
Water filled porosity	$\theta_w$	(L-water/L-total)	0.119	CCME, 2008
Henry's Law constant	H'	(unitless)	1.70E-02	HC, 2010b
Air-filled soil porosity	$\theta_a$	(L-air/L-total)	0.239	CCME, 2008
Attenuation factor (AF)	$\alpha$		0.000312	
Adjusted AF for mixing height	$\alpha$		0.000234	
<b>Estimated Concentration in various media</b>				<b>Notes</b>
Concentration in groundwater	$C_w$	(mg/L)	3.52E+00	
Soil saturation concentration	$C_{sat}$	(mg/kg)	1.76E+02	$C_t < C_{sat}$
Concentration in soil vapour	$C_v$	(mg/m <sup>3</sup> )	5.98E+01	
Concentration in air	$C_{air}$	(mg/m <sup>3</sup> )	1.40E-02	

## 3. EXPOSURE TERM (ET)

Non Carcinogens

$$ET = D1 * D2 * D3 = 8/24 * 5/7 * 48/52 = 0.22$$

Exposure Parameters:	Adult Worker	Source
Exposure term:		HC, 2004
D1; hours/day	8	HC, 2004
D2; days/week (/7days)	5	HC, 2004
D3; weeks/year (/52 weeks)	48	HC, 2004

## 4. RISK ESTIMATES

$$HQ = C_{air} * ET / TC$$

COPC	TC (mg/m <sup>3</sup> )	Source	HQ
Naphthalene	3.0E-03	HC, 2010b	1.03E+00

## Scenario 4

## 1. SITE DESCRIPTION

Scenario: Residential  
 Contamination type: Weathered gasoline and diesel  
 COPCs: TPH fractions, benzene, toluene, xylenes  
 (only calculations for TPH shown)  
 Soil type: Sand (coarse grained)  
 Media tested: Soil vapour  
 Depth to contamination below foundation: 1.5 m

## 2. PARTITIONING

COPC			F1			
			C7-C8 Aromatic	C8-10 Aromatic	C6-8 Aliphatic	C8-10 Aliphatic
<b>Input Parameters</b>						
Attenuation factor	$\alpha$		2.34E-03	2.34E-03	2.34E-03	2.34E-03
Concentration in soil gas	$C_v$	(mg/m <sup>3</sup> )	8.00E+02	1.00E+03	1.40E+03	1.20E+03
Concentration in air	$C_{air}$	(mg/m <sup>3</sup> )	1.87E+00	2.34E+00	3.28E+00	2.81E+00

COPC			F2			
			C10-12 Aromatic	C12-16 Aromatic	C10-12 Aliphatic	C12-16 Aliphatic
<b>Input Parameters</b>						
Attenuation factor	$\alpha$		2.34E-03	2.34E-03	2.34E-03	2.34E-03
Concentration in soil gas	$C_v$	(mg/m <sup>3</sup> )	1.00E+03	2.00E+02	8.00E+02	1.00E+02
Concentration in air	$C_{air}$	(mg/m <sup>3</sup> )	2.34E+00	4.68E-01	1.87E+00	2.34E-01

## 3. RISK ESTIMATES

$$HQ = C_{air} * ET / TC$$

$$ET = 1$$

COPC	TC (mg/m <sup>3</sup> )	HQ (-)	HI (-)
C7-C8 Aromatic	0.4	4.68	1.94E+01
C8-10 Aromatic	0.2	11.7	
C6-8 Aliphatic	18.4	0.1780435	
C8-10 Aliphatic	1	2.808	
C10-12 Aromatic	0.2	1.17E+01	1.61E+01
C12-16 Aromatic	0.2	2.34E+00	
C10-12 Aliphatic	1	1.87E+00	
C12-16 Aliphatic	1	2.34E-01	

## APPENDIX E

### EXHIBIT E1. BACK CALCULATION OF ACCEPTABLE RISK-BASED SOIL VAPOUR AND GROUNDWATER CRITERIA

#### 1. Calculation of Acceptable Dose

*Carcinogen*

$$DR_C^a = ILCRT / SF$$

Non-carcinogen with only  $R_fD$

$$DR_{NC}^a = HQ_T * R_fD$$

#### 2. Calculation of Acceptable Air Concentration

*Carcinogen with Slope Factor*

$$C_{AIR} = DR_C^a * BW * LE / (IR * AF * D_1 * D_2 * D_3 * D_4)$$

*Carcinogen with UR*

$$C_{AIR}^a = ILCRT / (T * UR)$$

*Non-carcinogen with  $R_fD$*

$$C_{AIR}^a = DR_{NC}^a * BW / (IR * AF * D_1 * D_2 * D_3)$$

*Non-carcinogen with  $TC_{air}$*

$$C_{AIR}^a = HQ_T * TC_{air} / T$$

#### 3. Calculation of Acceptable Soil Vapour Criteria

$$C_a^a = C_{AIR} / \alpha$$

#### 4. Calculation of Acceptable Groundwater Concentration

- i. Calculate maximum theoretical soil vapour concentration based on theoretical partitioning

$$C_a^{max} = \text{Max} [UCF_1 * X_i * MW_i * P_i / RT, UCF_2 * X_i * S_i * H]$$

- ii. Calculate acceptable groundwater criteria

if  $C_a^{max} < C_a^a$  then no criteria possible (exceeds solubility limit)

if  $C_a^{max} > C_a^a$  then  $C_w^a = C_a^a / (1000 * H')$

Groundwater mass flux check (optional, only valid if dissolved contamination source)

$$VR = ACH * A_b * H_b / UCF_4$$

$$Flux_p^a = C_{AIR}^a * VR$$

$$Flux_m^a = U^a * C_g^a * D_g * W_b * R_v * UCF_2 / UCF_3$$

$$\alpha' = Flux_m^a / Flux_p^a * \alpha, \text{ if } Flux_p^a > Flux_m^a$$

$$\alpha' = \alpha, \text{ if } Flux_p^a < Flux_m^a$$

$$C_a^{a'} = C_{AIR} / \alpha'$$

$$C_w^{a'} = C_a^{a'} / (1000 * H')$$

Parameter	Default
$DR_C^a$ = Acceptable dose carcinogen (mg/kg-day)	Calculated
$DR_{NC}^a$ = Acceptable dose non-carcinogen (mg/kg-day)	Calculated
$ILCR_T$ = Target incremental lifetime cancer risk	Regulatory
$HQ_T$ = Target hazard quotient	Regulatory
$C_{Air}^a$ = Acceptable air concentration (mg/m <sup>3</sup> )	Calculated
$C_{AIR}$ = Concentration of contaminant in air (mg/m <sup>3</sup> )	Calculated
$C_a^a$ = Acceptable soil vapour concentration (mg/m <sup>3</sup> )	Calculated
$C_a^{max}$ = Maximum theoretical soil vapour concentration (mg/m <sup>3</sup> )	Calculated
$Flux_p^a$ = Acceptable predicted flux into building (mg/min)	Calculated
$Flux_m^a$ = Available flux from groundwater (mg/min)	Calculated
$U^a$ = Upper bound estimate of Darcy velocity (specific discharge)	500 m/year, assumed based on judgment
$\alpha'$ = Adjusted vapour attenuation factor based on mass flux consideration	Calculated
$C_a^{a'}$ = Adjusted acceptable vapour concentration (mg/m <sup>3</sup> )	Calculated
$C_w^{a'}$ = Adjusted acceptable groundwater concentration (mg/L)	Calculated
$C_w^a$ = Acceptable groundwater concentration (mg/L)	Calculated
$X_i$ = Mole fraction (no units)	Estimated from chemical data
$S_i$ = Pure-chemical solubility (mg/L)	Chemical specific
$H'$ = Dimensionless Henry's Law constant	Chemical specific
$UCF_1$ = Unit conversion factor (mg/g)	1,000
$UCF_2$ = Unit conversion factor (L/m <sup>3</sup> )	1,000
$MW_i$ = Molecular weight (g/mole)	Chemical specific
$P$ = Pure-chemical vapour pressure (atm)	Chemical specific
$R$ = Gas constant (m <sup>3</sup> -atm/K-mole)	8.21E-05
$T$ = Absolute temperature (K, 273°C + T(°C))	Estimated, site specific
$VR$ = Building ventilation rate (m <sup>3</sup> /min)	Calculated
$ACH$ = Air exchange rate (1/hour)	0.35 residential 1.0 commercial
$A_b$ = Area building (m <sup>2</sup> )	100 residential
	300 commercial



$H_b$ = Mixing height (m)	3.6 residential
	3.0 commercial
$UCF_4$ = Unit conversion factor (min/hour)	60
$D_g$ = Mixing zone in groundwater for chemicals volatilizing (m)	1.0
$W_b$ = Width of building (m)	10 residential 15 commercial
$R_v$ = Volatilization ratio for fraction of chemical mass in groundwater flowing below the building that volatilizes and enters buildings	1.0
$UCF_2^g$ = Unit conversion factor ( $L/m^3$ )	1,000
$UCF_3^g$ = Unit conversion factor (min/year)	525,600
IR = Receptor air intake rate ( $m^3$ /hour)	Scenario specific <sup>†</sup>
AF = Inhalation absorption factor (dimensionless)	1
$D_1$ = Hours per day exposed (hour/day)	Scenario specific <sup>†</sup>
$D_2$ = Days per week exposed/7 days (dimensionless)	Scenario specific <sup>†</sup>
$D_3$ = Weeks per year exposed/52 weeks (dimensionless)	Scenario specific <sup>†</sup>
$D_4$ = Total years exposed to site (years, carcinogens only)	Scenario specific <sup>†</sup>
BW = Body weight (kg)	Scenario specific <sup>†</sup>
LE = Life expectancy (years, carcinogens only)	(see HC, 2010) <sup>‡</sup>
T = Fraction of time exposed (i.e. hours per day, days per year)	Scenario specific <sup>†</sup>
$TC_{AIR}$ = Tolerable air concentration ( $mg/m^3$ )	Chemical specific
TDI = Tolerable daily intake ( $mg/kg$ -day)	Chemical specific
SF = Slope factor ( $mg/kg$ /day) <sup>-1</sup>	Chemical specific
UR= Unit risk ( $mg/m^3$ ) <sup>-1</sup>	Chemical specific

<sup>†</sup> For default values, see the Health Canada *Federal Contaminated Site Risk Assessment in Canada, Part I: Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA), Version 2.0* (2010).

<sup>‡</sup> Health Canada is currently reviewing the validity and acceptability of exposure amortization for carcinogenic substances. The Health Canada *Federal Contaminated Site Risk Assessment in Canada, Part I: Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA), Version 2.0* (2010) should be consulted.