NICOLA

Vapour Intrusion:

Global State of Practice and Guidance for South Africa

November 2021

Network for Industrially Contaminated Land in Africa

admin@nicola-org.com www.nicola-org.com

Vapour Intrusion: Global State of Practice and Guidance for South Africa

Author
Steve Mc Keown

Technical Peer Review
Matthew Lahvis

Steering Committee Review
Marcus van Zutphen
Johan Kriek
Erasmus Chauke
Margaret Duddington

Vapour Intrusion: Global State of Practice and Guidance for South Africa

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDIX A: VAPOUR INTRUSION SCREENING LEVEL TABLES

1. INTRODUCTION

The Network for Industrially Contaminated Land in Africa (NICOLA) is mandated by its memorandum of incorporation to provide policy position papers and practical guidance on the management and remediation of contaminated soil and groundwater in a South African context.

This technical report is intended as a practical guide to the management of risks related to vapours emanating from soil and/or groundwater contamination. This guide has been prepared in accordance with current internationally accepted literature by industry experts and government agencies worldwide and is not intended to introduce scientific concepts or opinions that differ from the current understanding of vapour intrusion. Where possible, relevant data from contaminated sites in South Africa have been considered in the development of the guidance.

This technical guideline is aimed at environmental practitioners, owners and operators of contaminated sites, and regulators in South Africa.

It intends to inform the development of an industry standard for addressing the risks of vapour intrusion. The guide uses published scientific research and takes into account relevant South African environmental legislation and guidance for assessing contaminated land.

1.1 Overview of Vapour Intrusion

Vapour intrusion (VI) is the term given to the migration of hazardous chemical vapours from sub-surface contamination sources into overlying buildings or occupied spaces (US EPA, 2015a). Certain chemicals, typically referred to as volatile organic compounds (VOCs), that are released into the sub-surface may cause hazardous vapours that migrate or are transported through the vadose zone and can enter buildings through cracks or other openings in the floor slab, walls or foundations, as well as intentional conduits created for utilities such as water and electricity supply, drains, sewers, etc. (US EPA, 2015a; ITRC, 2014).

VI can occur over a broad range of land use settings (e.g. residential, commercial or industrial) and can affect buildings with virtually any foundation type, i.e. basements, slab on grade or crawl space (US EPA, 2015a). VI is widely recognised as a key pathway of human exposure to volatile hazardous chemicals in indoor spaces, and is often found to be the only valid exposure pathway at contaminated sites.

VOC vapours fall into two broad categories; 1) those that form toxic and/or carcinogenic threats to human health (chemicals typically associated with fuels and solvents); and 2) those that can pose an explosive or asphyxiation risk (e.g. methane, carbon monoxide and hydrogen sulphide). The intention of this guidance document is to provide guidance and Tier 1 screening criteria related to VOC vapours from toxic and/or carcinogenic chemical compounds and not to focus on vapours that may pose an explosive or asphyxiation risk.

1.2 South African Regulatory Framework

The principal regulator that governs the management of contaminated land in South Africa is the Department of Forestry, Fisheries and the Environment (DFFE) at a national level and various provincial departments of the DFFE at a provincial level. Where site contamination includes impacts to natural water resources, these are managed in conjunction with the Department of Water and Sanitation (DWS), as the relevant authority.

Legislation and regulations that are specifically applicable to soil and groundwater contamination in South Africa include the following:

- National Environmental Management Act (NEMA), Act No. 107 of 1998 (NEMA, 1998): The NEMA sets out a 'duty of care' provision on every person who causes, has caused, or may cause significant pollution or degradation of the environment, to take reasonable measures to prevent such pollution or degradation from occurring, continuing or reoccurring;

- National Environmental Management: Waste Act (NEMWA), Act No. 59 of 2008 (NEMWA, 2008): The NEMWA provides for the listing of waste management activities that have, or are likely to have a detrimental effect on the environment. Chapter 4: Part 8 of NEMWA specifically addresses management of contaminated land;

- National Water Act (NWA), Act No. 36 of 1998 (NWA, 1998): The NWA sets out a 'duty of care' provision whereby an owner of land, a person in control of land or a person who occupies or uses the land on which any activity or process is or was performed or undertaken, which causes, has caused or is likely to cause pollution of a water resource, must take all reasonable measures to prevent any such pollution from occurring, continuing or reoccurring;

- Department of Environmental Affairs (DEA) (currently DFFE), National Norms and Standards for the Remediation of Contaminated Land and Soil Quality in the Republic of South Africa, Government Notice (GN) R331, published 2 May 2014 (DEA, 2014): GN R331 provides norms and standards for the screening, identification and registration of contaminated sites, to provide a risk-based decision support protocol for assessing sites, and to offer a set of guidelines for the preparation and submission of site assessment reports; and

- DEA, Framework for the Management of Contaminated Land (FMCL), 2010 (DEA, 2010): The FMCL outlines a risk-based approach to the assessment and reporting of contaminated land, and includes screening values for a range of contaminant compounds in soil for different exposure scenarios (protection of water resources, residential and commercial/industrial).

At the time of drafting this guidance, South Africa did not have legislation or guidance for vapour intrusion or associated screening criteria.

A key consideration in the drafting of this vapour intrusion guidance document is that it aligns with local environmental legislation, as applicable, and is consistent with the risk-based methodology that is documented in the DEA (2010) FMCL.

1.3 Key International Guidance

It is recognised that while South Africa has broadly encompassing environmental legislation and guidance that incorporates both duty of care and a risk-based approach, there are key international organisations that have effectively led the state of science applicable to contaminated land investigation, in general, and to vapour intrusion in particular. Three prominent organisations that have conducted research and published guidance on VI include the United States Environmental Protection Agency (US EPA), the Interstate Technology & Regulatory Council (ITRC) and the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE). The content of this guidance document draws on the research conducted by these organisations and incorporates local guidance and data, where available.

A complete list of references utilised in compiling this guidance document is provided in Section 9. The intention of this guidance document is to summarise the key topics and parameters that relate to vapour intrusion and not to provide detail into assessment methods or the background to the derivation of parameters. References are provided to key concepts and data presented in the text, and as such, the reader is encouraged to access these publications for further detailed information on the relevant topic.

1.4 Exclusions

This document is intended to focus on vapours that have accumulated in buildings as a result of VI only (i.e. vapours that were derived from sub-surface sources). It is not intended to address indoor vapours that have been derived from other sources, such as indoor use and storage of products or substances that contain VOCs, or vapours that are present in ambient air that migrate into indoor air spaces. Such vapours will contribute to the overall indoor air risk but are unrelated to VI and are difficult to quantify in an accurate and consistent manner, and these sources are therefore excluded from consideration in this document. However, the vapour intrusion screening levels take into account the total exposure to specific VOCs in indoor air.

The methodologies and screening levels presented in this document generally relate to chronic exposure to vapours under defined conditions rather than acute exposure (i.e., strong petroleum odours, combustible, explosive, or oxygen-deficient conditions), which would be treated as an emergency response issue and addressed prior to consulting this document. First responders should be contacted immediately if acute conditions are encountered.

This document does not address other routes of human exposure to soil and groundwater contaminants including ingestion, dermal contact, inhalation of particulates, inhalation of outdoor vapours, or inhalation while showering or washing with contaminated water.

2. CONCEPTUAL SITE MODEL

2.1 Overview of the Conceptual Site Model

The conceptual site model (CSM) for VI assessment follows the same source-pathway-receptor (S-P-R) approach as for other contaminated site assessments. Vapour intrusion is a potential human health pathway where people may come into contact with hazardous vapours while performing routine indoor activities. The human population of interest includes individuals living in, working in, or otherwise occupying buildings subject to VI. The VI pathway is considered "complete" for a specific building when the following five conditions are met:

1. A sub-surface source of hazardous vapour-forming chemicals (i.e. VOCs) is present underneath the building;
2. The vapours have a route along which to migrate;
3. Openings exist for the vapours to enter the building and "driving forces" exist to draw the vapours through the openings;
4. One or more of the hazardous vapours derived from the sub-surface source(s) is present in the indoor air; and
5. The building is occupied when the vapours are present in the indoor air.

If one or more of these conditions is absent or reasonably expected to be absent in future, the VI pathway is considered "incomplete" (US EPA, 2015a).

Key elements of the CSM for VI are illustrated in Figure 1.

2.2 Sub-Surface Vapour Sources

Primary sub-surface sources of contamination may include leaking infrastructure (tanks, vessels, pipelines, etc.), drains or septic tanks, and landfills or other forms of land disposal. Contaminants generally migrate downwards through the vadose zone to regional groundwater, creating a source zone in soil and groundwater. Contaminants that reach groundwater will then migrate in the general direction of groundwater flow creating a secondary source of contamination. Some up-gradient and/or cross-gradient migration of contamination is also possible in source zones, where substantial volumes of light non-aqueous phase liquids (LNAPL) have impacted the groundwater, initially spreading in multiple directions before stabilising and following the general groundwater flow gradient. These contaminants can become sources of VI if they are likely to volatilise under normal temperature and pressure conditions (US EPA, 2015a). Contaminants can also reside above the water table along low-permeability soil layers or in perched groundwater.

Contaminants that are more dense than water (e.g. chlorinated solvents and coal tars) are referred to as dense non-aqueous phases liquids (DNAPL) and can migrate below the groundwater table terminating on low permeability strata. In some cases, where DNAPLs are present, VI can be precluded by uncontaminated groundwater that occurs above the DNAPL source.

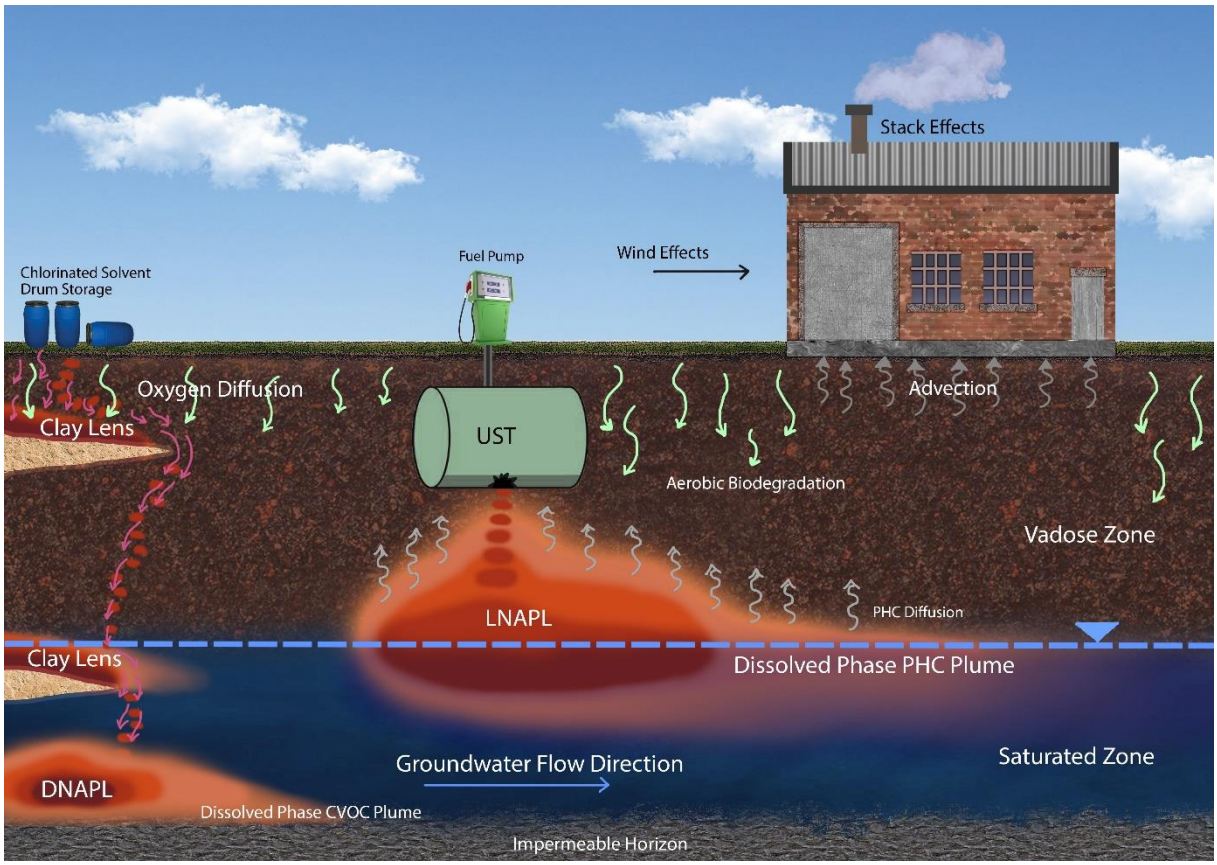


Figure 1 Key Elements of the Conceptual Site Model for Vapour Intrusion

Typical LNAPLs include petroleum products (e.g. petrol and diesel), lead scavengers (e.g. 1,2-dichloroethane – DCA, ethylene dibromide – EDB and ethylene dichloride – EDC) and ether oxygenates (e.g. methyl tertiary butyl ether – MTBE, ethyl tertiary butyl ether - ETBE, tertiary amyl methyl ether – TAME and di-isopropyl ether - DIPE), while typical DNAPLs include chlorinated organic solvents (e.g. tetrachloroethylene – PCE and trichloroethylene – TCE), coal tars, creosote and polychlorinated biphenyls (PCBs). Both LNAPL and DNAPL products contain VOCs that can result in VI. Common VOCs present in petroleum products, particularly petrol, include benzene, toluene, ethyl benzene, and xylenes (i.e. BTEX). VOCs typically associated with chlorinated solvents (i.e. chlorinated VOCs or CVOCs) include tetrachloroethylene (PCE) and trichloroethylene (TCE), which are largely used as degreasers. These chlorinated solvent compounds can also break down in the environment to form other VOCs that can also be a VI concern, such as dichloroethylene (DCE) (various isomers) and vinyl chloride (VC).

2.3 Sub-Surface Vapour Migration

VOCs present in soil gas emanating from a sub-surface source generally attenuate as the VOCs move from the source through the soil into the indoor air. The thickness and composition of the vadose zone has a substantial influence on the significance of the vapours migrating upwards. Diffusion is the typical process governing the movement of soil vapours away from the source, where the net direction of diffusive transport is from higher to lower concentrations.

The process of advection occurs in the vadose zone, generally in the vicinity of building foundations, where differences in temperature between the building interior and the sub-surface environment can create pressure differentials. The direction of advective transport is always towards the direction of lower air pressure. It is noted that advection of soil gas can also occur:

- near the ground surface due to fluctuations in atmospheric pressure, which can either release soil gas into the atmosphere or introduce ambient air into the subsurface environment (a process that can be important in oxygenating surface soil horizons); and
- wherever methane generation from anaerobic degradation is sufficiently high (e.g., near locations with degrading fuels); however, this effect is generally quite localised around the source (Molins, *et al.*, 2012).

Vapours can also migrate along subsurface preferential pathways, such as utility corridors or more porous zones of soil or rock, or beneath surface barriers that limit the direction(s) of vapour migration, such as hardstanding surfaces (e.g. asphalt, concrete).

Vapour migration in the vadose zone can be impeded by high soil moisture (reducing diffusion), low-permeability soils (preventing or impeding upward migration), adsorption to soil particles and organic matter, chemical degradation and biodegradation (microbial break-down of VOCs) (US EPA, 2015a).

2.4 Preferential Pathways

A preferential migration route or pathway is a naturally occurring subsurface feature or an anthropogenic subsurface conduit that is likely to exhibit little resistance to vapour flow in the vadose zone (i.e., exhibits a relatively high gas permeability) or groundwater flow in the saturated zone (i.e., exhibits a relatively high hydraulic conductivity), thereby facilitating the migration of VOCs in the subsurface and/or into buildings. Preferential subsurface pathways may include: utility corridors, manholes and vaults; more porous zones of soil or rock (i.e. permeable soil horizons or bedrock fractures); or migration along surface barriers such as paved surfaces that limit the direction of vapour migration (US EPA, 2015a). It is important to note that the mere presence of a utility corridor does not make it a preferential pathway, unless it connects the contaminant source to the building.

Soil gas VOCs emanating from subsurface sources generally attenuate, as the vapours move vertically upwards from the source through the vadose zone and into indoor air. If vapour monitoring data are not consistent with this trend, it is possible that a preferential pathway may be affecting vapour migration. Preferential migration pathways can facilitate vapour migration to greater distances and at higher concentrations than otherwise expected (i.e. a preferential pathway may result in lower concentrations being observed closer to the source and higher concentrations being present further away from the source). It is therefore important that these potential pathways are addressed in the CSM.

A preferential migration pathway can be a significant influence on vapour intrusion when it is of sufficient volume and proximity to a building that it may be reasonably anticipated to influence vapour migration towards or vapour intrusion into the building. Significant vertical routes of preferential migration may result in higher than anticipated concentrations in the overlying near-surface soils, whereas significant horizontal routes of preferential migration may result in elevated concentrations in areas on the periphery of subsurface contamination, where VOCs are not expected. It is important that the CSM identifies known or suspected preferential migration pathways that could facilitate vapour migration to greater distances and at higher concentrations than otherwise expected.

2.5 Limiting Conditions to Conventional Vapour Intrusion

The presence of certain subsurface conditions may prevent vapour migration and/or significantly reduce the potential for VI such that, at some sites, the subsurface source zone may contain high concentrations of VOCs while the indoor air concentrations in overlying buildings are relatively low (McHugh, *et al*, 2017; Ma, *et al*, 2020). Conditions that generally limit VI include:

- *Rapid biodegradation of VOCs in the vadose zone:* Aerobic degradation of petroleum hydrocarbons (PHCs) and certain CVOCs (e.g. vinyl chloride) can rapidly degrade these vapours (refer to Section 3.1).
- *Fresh water lenses:* VOC diffusion through water is orders of magnitude slower than through soil gas. As a result, layers of water between a VOC source and a building, generally associated with perched groundwater that builds up on low-permeability soil layers, which themselves, limit VI, can serve as effective barriers that prevent VI.
- *Fine-grained geological layers:* Fine-grained soil layers (i.e. silts and clays) with a high moisture content reduce vapour diffusion rates in the vadose zone, as diffusion rates are lower in water-connected soils.
- *Building designs:* Certain building designs may prevent the migration of VOCs into buildings. VOC migration into buildings can be prevented by passive or mechanical ventilation below the building foundation, or creating ventilated underground structures, such as parking garages (with the absence of elevator shafts), which can act as conduits for vapours. It is noted that parking garages are generally designed to have separate elevator shafts to limit exchange with indoor air.
- *Positive indoor air pressure:* In buildings with consistently positive indoor air – sub-slab gas pressure differences, the pressure gradient prevents ingress from sub-slab vapours (refer to Section 6.3.2).

2.6 Air Exchange and Mixing

Air exchange is the flow of air into and out of a building, which is generally in balance, and involves the following processes:

- *Infiltration:* Air leakage through unintentional openings such as cracks, seams, gaps or interstices;
- *Natural ventilation:* Airflow through open windows, doors and other intentional openings that are part of the building design; and
- *Mechanical ventilation:* Air movement driven by fans (US EPA, 2015a).

Air exchange from any of the above processes will tend to mitigate the effects of VI (i.e. reduce indoor air concentrations) via dilution, provided that the ambient (outdoor) air does not contain background concentrations of VOCs at similar or higher concentrations as those measured in the indoor air (refer to Section 2.7 below).

The air exchange rate is defined as the ratio of the airflow rate (e.g. cubic metres per hour) to the building volume (e.g. cubic metres) and is normally expressed as exchanges per hour. Values for residential air exchange rates range from about 0.2 to 1.3 air changes per hour (h^{-1}), and for non-residential buildings, which are highly dependent on building use, from 0.3 to 4.1 h^{-1} (US EPA, 2011; US EPA, 2015a; US EPA, 2018). Australian data indicate air exchange rates in residential buildings from 0.3 – 0.9 h^{-1}, and in commercial/industrial buildings from 0.6 – 2.0 h^{-1} (CRC CARE, 2011). These ranges are variable due to the nature and age of buildings, mechanical ventilation, etc. CRC CARE recommends default air exchange rates of 0.6 h^{-1} and 0.83 h^{-1} for residential and commercial buildings, respectively. These values are considered to be reasonably conservative but do not represent the worst case (CRC CARE, 2011). The BioVapor model uses default air exchange rates of 0.25 h^{-1} and 0.5 h^{-1} for residential and commercial buildings, respectively (ITRC, 2014).

Based on available information, building ventilation is likely to vary widely, and it is preferred to calculate a site-specific value, where possible, rather than adopting a default value.

In the USA, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has set minimum outdoor air ventilation rates for buildings under American National Standards Institute (ASNI)/ASHRAE guidelines. These standards specify how much outdoor air should be brought into a room every hour and are based on occupancy and room size. Recommended ASHRAE air exchanges per hour for common building types are summarised in Table 1.

Table 1 ASHRAE Recommended Air Ventilation Rates for Common Types of Buildings

Building Type	Air Exchange Rate (h^{-1})
Homes	0.35 – 1
Hotel rooms	1 – 2
Offices	2 – 3
Retail shops	2 – 3
Schools	5 – 6
Sports facilities	4 – 8
Restaurants	6 – 8

2.7 Background Air Quality

The indoor air quality in many buildings will contain detectable levels of VOCs regardless of whether a sub-surface source of vapours exists, as indoor air quality can be affected by a number of unrelated sources. Indoor air sources of VOCs include consumer products (e.g. aerosols, cleaners), combustion processes (e.g. smoking, cooking, heating), occupant activities (e.g. use of solvents, adhesives, oils and fuels for hobbies, home improvements or auto repairs), and releases from building materials (e.g. carpets, paints, insulation). Examples of outdoor sources of VOCs include vehicle exhaust emissions, industrial facilities, fuel storage tanks, and dispensing of fuel at service stations (US EPA, 2015a).

The contribution of these unrelated sources of VOCs to indoor air is referred to as “background.”

3. BIODEGRADATION AND VI SCREENING

3.1 Introduction

The concept of biodegradation in the context of VI is particularly important for petroleum hydrocarbons, which are known to degrade in the subsurface environment in the presence of oxygen, which diffuses into the soil from the atmosphere (CRC CARE, 2013; ITRC, 2014, US EPA, 2015b). An understanding of the rates at which this degradation occurs and the dynamics of the processes can allow for subsurface separation criteria to be established where the risk of VI from petroleum hydrocarbon compounds becomes negligible. These separation criteria include vertical separation distances and lateral inclusion zones, which can be established to allow assessments to be focussed on areas of potential contamination while excluding those where contamination is unlikely (i.e. biodegradation is likely to preclude the possibility of VI).

3.2 Biodegradation in the Vadose Zone

Biodegradation refers to the breakdown of organic compounds by microorganisms. Microorganisms capable of biodegrading petroleum hydrocarbon compounds (PHCs) are ubiquitous in most soil environments. Although PHCs can degrade in the absence of oxygen, they are more rapidly degraded under aerobic conditions. The shallow vadose zone above PHC source zones is often rich in oxygen, which is replenished from the atmosphere. In the presence of oxygen, the rate of degradation of petroleum vapours in the vadose zone is generally faster than the rate of upward diffusion of the PHCs, resulting in complete attenuation of the vapours before reaching building structures (ITRC, 2014).

The key difference with other non-petroleum VOCs is that they typically degrade under anaerobic conditions and are thus not attenuated in the same way as PHCs. Petroleum VI (PVI) is most likely when dissolved phase PHCs or LNAPL are in direct or close contact with building structures (e.g. sumps, basements).

A notable feature of PHC degradation is the short acclimation time for the degradation process (i.e. the time required for the microbial community to start consuming PHCs after the initial release), which can be of the order of hours or days (ITRC, 2014).

It has been shown that aerobic degradation can occur at oxygen concentrations of as low as 2%. Factors that inhibit the supply of oxygen to the subsurface include soils with high moisture or organic content, low-permeability soils, large building foundations and very high PHC concentrations, such as near LNAPL sources.

In the absence of oxygen, anaerobic bacteria can use other electron acceptors, such as nitrate, manganese, iron, sulphate or carbonate, to biodegrade PHCs, although this process is slower than aerobic degradation.

3.3 Lateral Inclusion Zones

Depending on the extent of characterization, there may be uncertainty in defining the exact edge of a vapour source in soil or groundwater and the extent of lateral vapour migration. To account for this uncertainty, ITRC (2014) recommends that a lateral inclusion zone (or buffer distance) be established beyond the edge of a vapour source in soil or groundwater such that any building located outside this zone generally may be excluded from further assessment for vapour intrusion. For PVI sites, a lateral inclusion zone of 30 feet (ft) has been recommended from the edge of the source and for CVI sites, a lateral inclusion zone of 100 ft has been recommended (ITRC, 2014; US EPA, 2015a). The inclusion distance applies to any building located within 30 feet (ft) of an LNAPL source in soil or a dissolved-phase source in groundwater. The lateral inclusion zone distances have been conservatively set, and for the purpose of this guidance document, it is recommended to use an approximate metric equivalent,[1] which is either equally or no less conservative than the ITRC and US EPA recommendations, as follows:

- PVI sites: 10 m from edge of source; and
- CVI sites: 30 m from edge of source.

If a building is located within the lateral inclusion zone, then vertical screening distances can be applied, as described in section 3.4. Buildings that are located outside of the lateral inclusion zone require no further VI evaluation (ITRC, 2014).

For PVI sites, it is noted that if the building is located within 10 m of a soil (LNAPL) source, then the LNAPL screening distance would apply, whereas if the building is located within 10 m of a dissolved groundwater source, then the dissolved phase screening distance would apply. Therefore, both potential scenarios need to be considered for most PVI sites.

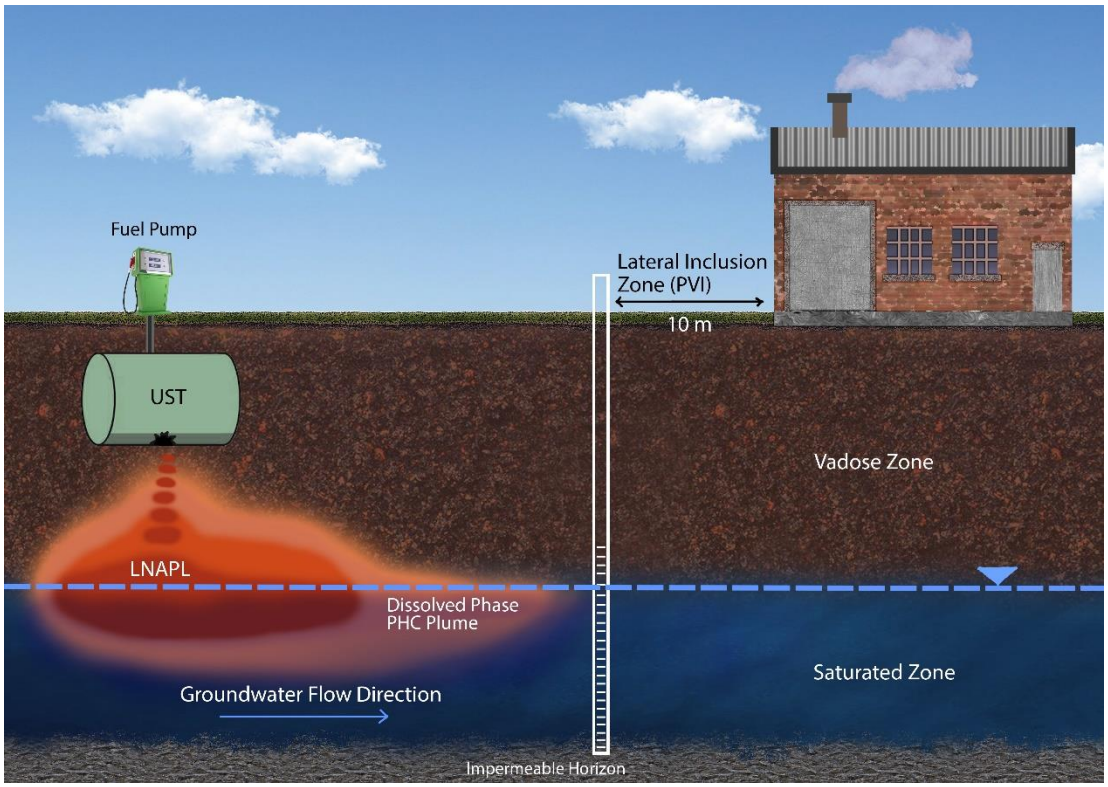
The extent of the lateral inclusion zone is typically site-specific, and can only be defined when the CSM is well understood. If contaminated groundwater is the source of the vapours, migration of the contaminant plume (both vertically and laterally) is an important consideration, as it may change the lateral inclusion zone over time. Confidently defining a lateral inclusion zone is an important screening tool for determining which sites require further VI assessment and which sites can be excluded (US EPA, 2015b).

Lateral inclusion zones are schematically depicted in Figure 2, for PVI and CVI sites, respectively.

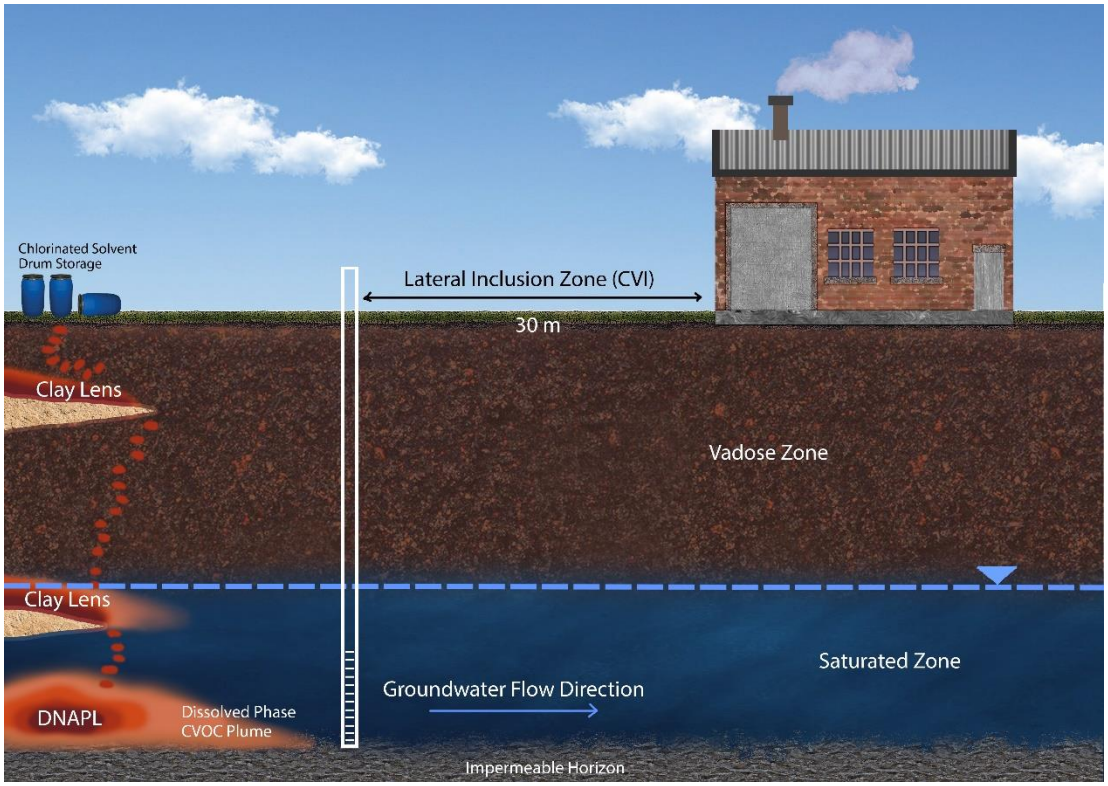
It is important to note that further assessment outside the lateral inclusion zone may be necessary under the following conditions:

- Where preferential pathways are present that connect vapour sources to receptors (e.g. utility conduits);
- Where an impermeable surface cover (e.g. concrete slab, large building foundation) has the potential to enhance lateral transport or limit oxygen availability for biodegradation (refer to Section 3.5 below); and
- Where soil conditions are too dry to support biodegradation (e.g. soils with less than 2% moisture content) (US EPA, 2015b).

[1] For this guidance document, it was considered more practical to use a metric equivalent to be consistent with the recognised SI system of units adopted in South Africa.



2a. Lateral Inclusion Zone for PVI Sites (10 m)



2b. Lateral Inclusion Zone for CVI Sites (30 m)

Figure 2 Lateral Inclusion Zones between Source of Contamination and a Potential Receptor (i.e. Occupied Building)

3.4 Vertical Separation Distances

The vertical separation distance is the distance between the top of a vapour source (or shallowest vertical extent of contamination) in soil or groundwater and the lowest depth of an overlying building (refer to Figure 3 for LNAPL and dissolved phase sources). If the thickness of biologically active soil is sufficient and oxygen and soil moisture are present, aerobic degradation will typically degrade vapour-phase PHCs before they can intrude into buildings (US EPA, 2015b). The US EPA summarised soil gas data from the work of various authors at a large number of sites in different hydrogeological settings where petroleum was released from underground storage tanks (USTs), and there was a high degree of consistency between the datasets.

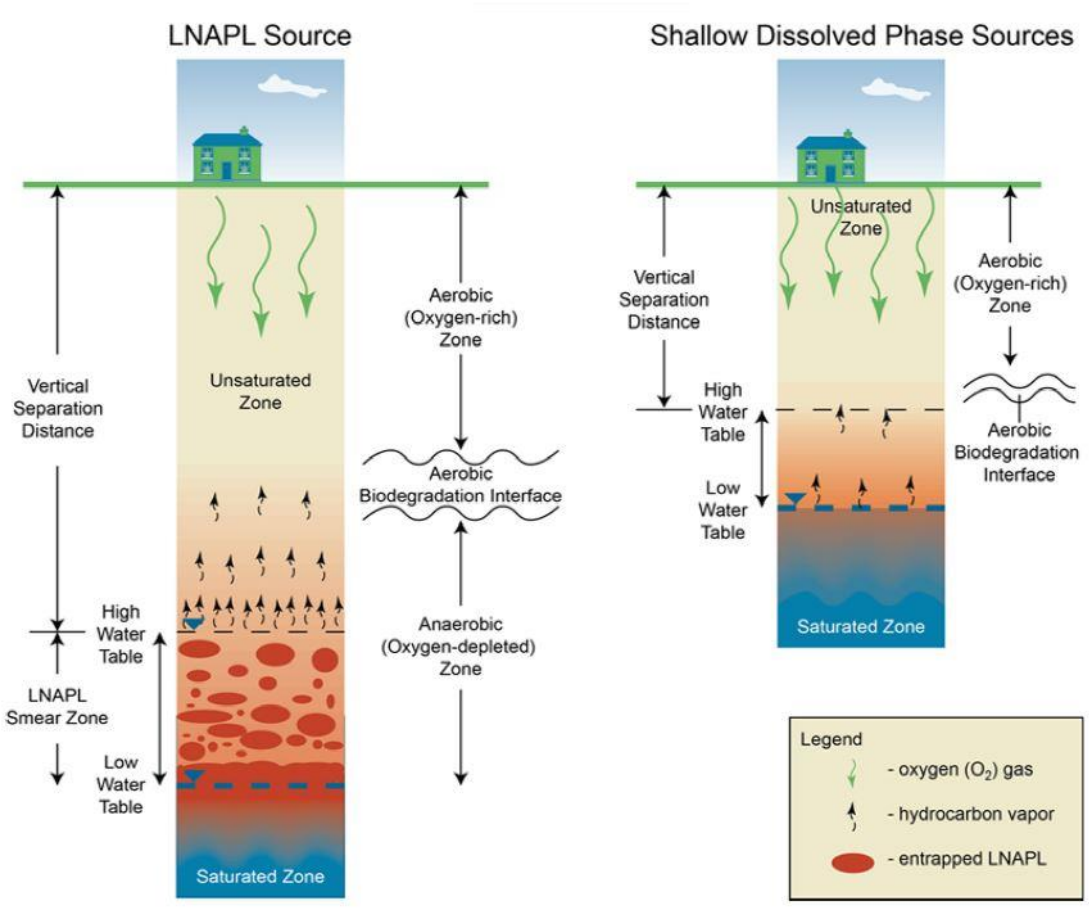


Figure 3 Vertical Separation Distance between Source of PHC Contamination and a Hypothetical Receptor (i.e. Occupied Building) (after ITRC, 2014)

In the local context, 91 pairs of benzene groundwater and soil vapour concentration data were collected from 34 South African sites, and these were used to determine an applicable vertical separation distance (Mohr and McKeown, 2014). The results of this study are illustrated in Figure 4, which plots soil vapour concentration as a function of vertical separation distance and groundwater dissolved phase concentration. Selected monitoring wells which had measurable thicknesses of LNAPL present were assigned a dissolved benzene concentration of 30,000 µg/L (assumed to be the approximate benzene solubility limit in groundwater sourced from a typical petrol product). Benzene vapour concentration data were grouped into three (3) primary categories: <30 µg/m^3, 30-3,000 µg/m^3 and >3,000 µg/m^3. Vapour data within the >3,000 µg/m^3 category where LNAPL was present on groundwater were subdivided into a separate category. The <30 µg/m^3 category corresponds to a residential benzene indoor air target value of 3 µg/m^3 (assuming a conservative cross-slab attenuation factor of 10 and a 10^{-5} target cancer risk).

The data presented in Figure 4 indicate that potential cases of PHC VI from a groundwater source are only likely where vapour source strengths are high and vertical separation distances are small. In this local study, the benzene vapour threshold was only exceeded where benzene dissolved phase groundwater concentrations exceeded 1,000 µg/L or vertical separation distances were less than 4m (Mohr and McKeown, 2014).

These data are broadly consistent with vertical separation distance evaluations previously published (Davis 2009, McHugh *et al*, 2010, Peargin and Kolhatkar 2011, and Lahvis *et al*, 2013), which indicate that VI assessments are not necessary where relevant separation distance threshold criteria are met.

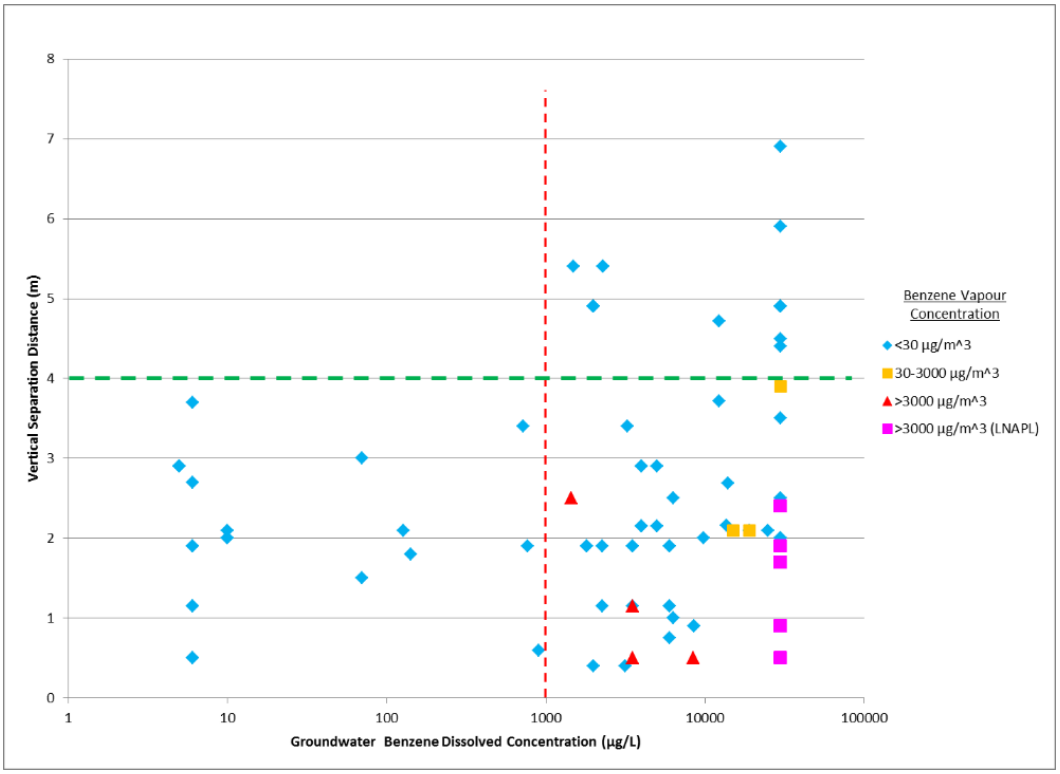


Figure 4 Benzene soil vapour concentrations as a function of groundwater dissolved benzene concentrations and vertical separation distance (after Mohr and McKeown, 2014)

To adopt a suitably conservative approach that is aligned with both internationally accepted and South African data, recommended vertical separation distances are provided in Table 2.

Table 2 Recommended Vertical Separation Distances between Sub-surface Contamination and Receptors (i.e. Building Basement or Foundation Slabs, Crawl Space, etc.) (adapted from USEPA, 2015b)

Media	Benzene	TPH	Vertical Separation Distance (m)
Soil (mg/kg)	<10	<100 (unweathered petrol) <250 (weathered petrol, diesel)	2
	>10 (LNAPL)	>100 (unweathered petrol) >250 (weathered petrol, diesel)	5
Groundwater (mg/L)	<5	<30	2
	>5 (LNAPL)	>30 (LNAPL)	5

3.5 Attenuation Beneath Building Slabs

Oxygen ingress from the atmosphere to the subsurface soil environment can occur via: a) open ground surrounding buildings followed by lateral penetration beneath the building slab, b) cracks in a building foundation (same as those involving transport of PHC vapours from the subsurface to indoor air), and c) diffusion directly through the building foundation (Patterson and Davis, 2009), as illustrated in Figure 5.

In certain cases, extensive building foundation dimensions can restrict the transport of oxygen beneath a building. For sufficient oxygen to penetrate beneath a building where a PHC source is present, the minimum distance from the centre of the building to the edge of the building slab has been estimated to be 7.5 m (i.e. the shortest dimension of a square or rectangular building should be no more than 15 m) and the PHC source zone should occur at a depth greater than 2 m below the building foundation slab (CRC CARE, 2009; Patterson and Davis, 2009).

In a study conducted by the US EPA (2013a), oxygen availability below most buildings was found to be greater than for paved surfaces, and this may relate to convective flow beneath buildings caused by the presence of the building itself. Data from large building foundations is more limited and is generally derived from modelling, which underestimates the convective flow beneath buildings, predicting longer screening distances than those mentioned above (US EPA, 2013b). However, with insufficient empirical data on oxygen availability beneath large buildings, it is considered prudent to adopt the precluding factors for site screening proposed by Patterson and Davis (2009) above.

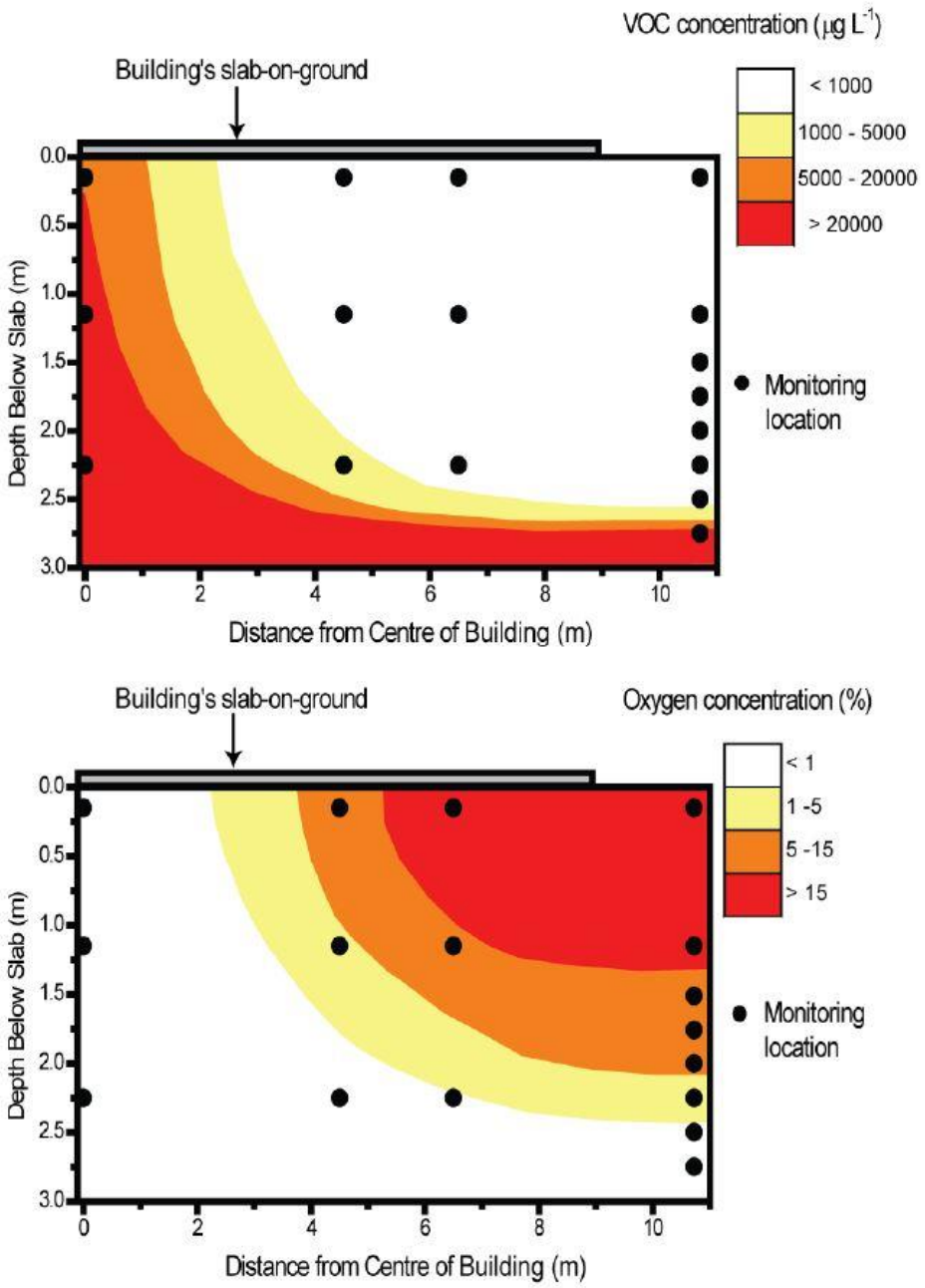


Figure 5 Contour Plots showing Vadose Zone Soil Gas PHC Concentrations and Oxygen Ingress (after Patterson and Davis, 2009)

3.6 Attenuation Across Building Slabs

The degree to which vapour migrates from the subsurface across the building slab and into a building is determined by the VI attenuation factor (AF). The AF, designated alpha (α), is defined as the concentration in indoor air divided by the vapour concentration in the vadose zone. Large values of α (i.e., values approaching one) indicate that little attenuation is taking place, whereas small values of α (i.e., values much smaller than one) indicate that significant attenuation is taking place (US EPA, 2015b).

As part of a risk evaluation, the concentrations of chemicals in indoor air can actually be measured, or they can be predicted. A generic AF can be used as part of a risk evaluation to predict or estimate the concentration of a chemical in indoor air from the concentration measured in soil gas below or near a building (US EPA, 2015b). To predict the indoor air concentration, the measured concentration in soil gas is multiplied by a suitable AF for the particular building, or by using a suitably conservative default value. Based on an understanding of the constituent-specific risk-based screening levels in indoor air, the generic AF can be used to derive constituent-specific risk-based screening levels for vapour sources in groundwater or in the vadose zone (soil gas or sub-slab).

When evaluating the vapour source and attenuation of VOC vapours, paired vapour samples are required to measure the actual attenuation that occurs across the slab. Where contamination is not in direct contact with an overlying building, the following two options can be applied: (1) collect near-slab (exterior) shallow soil gas samples paired with deep (source) soil gas samples, or (2) collect indoor air samples paired with sub-slab soil gas samples. Note that subsurface vapour concentration measurements may not be necessary if vapour concentrations in indoor air do not exceed associated risk-based screening levels. If contamination is in direct contact with a building basement, foundation, or slab, it is necessary to collect indoor air samples, as it will not be feasible to collect sub-slab vapour samples (US EPA, 2015b). If both the generic AF and the measured concentration of a VOC in shallow soil gas predict an acceptable concentration in indoor air, that prediction may be adequate to support a screening decision without the need for indoor air sampling. However, generic AFs may not be appropriately representative of conditions at a particular site, and can often be overly conservative where building slabs are intact and in good condition. The US EPA (2015b) has recommended a generic AF of 0.03 for residential and non-residential buildings, which is currently the subject of significant debate and is discussed in more detail below.

The US EPA Vapor Intrusion Database contains data to support site-specific estimates of vapour attenuation, or the reduction in vapour concentrations as vapour-forming chemicals move from soil and groundwater into indoor air. The US EPA data captured in the database was last updated in 2012 and is depicted in Figure 6 together with VI data collected from a number of South African sites (McKeown and Naude, 2019).

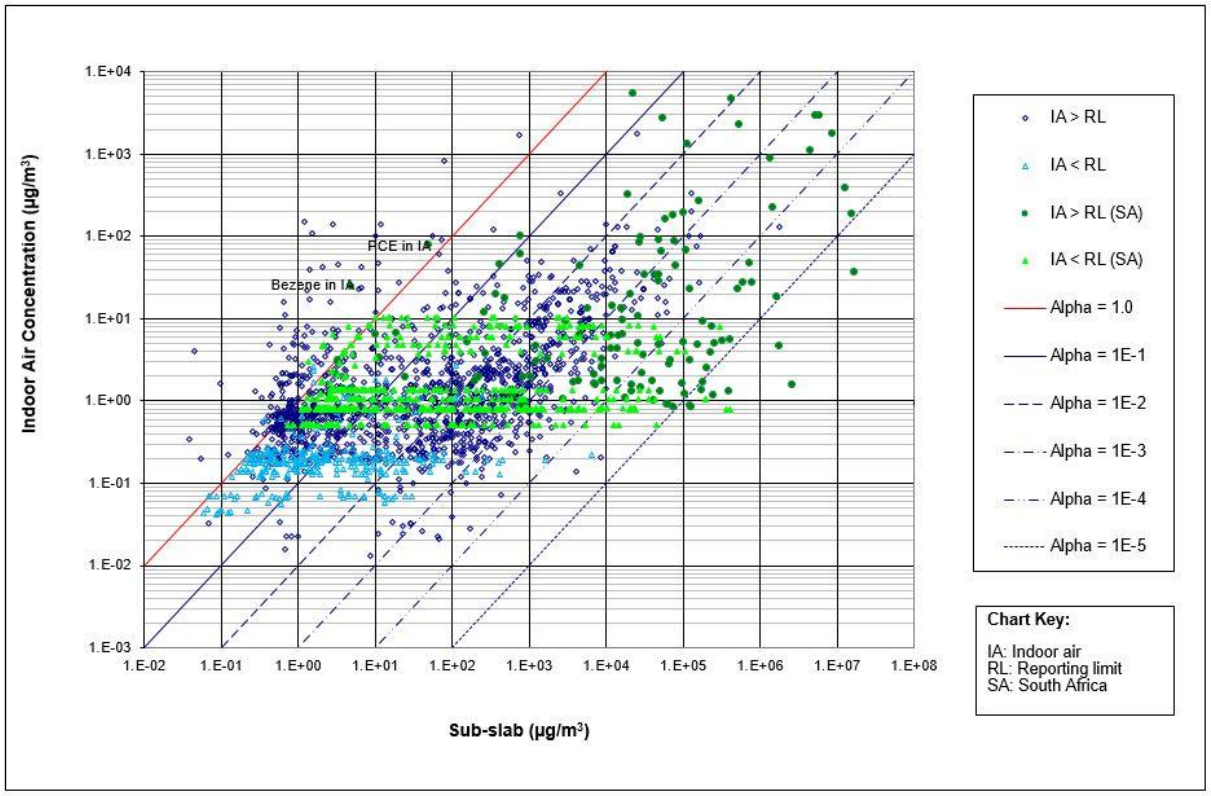


Figure 6 Paired Indoor Air and Sub-slab VOC Data from the US EPA Vapor Intrusion Database and a Selection of South African Sites (adapted from McKeown and Naude, 2019)

The data in Figure 6 show broad consistency between the US EPA and South African sites, which indicates similar trends in AFs. In the South African database, only two paired samples indicated indoor air concentrations greater than the respective sub-slab concentrations. In both these instances, unrelated indoor air sources of the contaminants (i.e. benzene and PCE) were found in the buildings, as shown in Figure 6. The South African data indicate an overall α of 0.0088. It is noted that the South African data were exclusively collected from buildings with slab on grade foundations, which are typical to South African building construction. Where sub-slab VOCs were detected, more than 70% of the co-located indoor air results were below the detection limit, indicating remarkable overall attenuation in general.

A large variation in AFs was observed in both US EPA VI Database and the data from South African sites, with the higher attenuation factors typically associated with lower sub-slab vapour concentrations. This may indicate that the indoor concentrations may be more susceptible to background sources. As sub-slab vapour concentrations increase, the AFs tend to decrease, likely providing a more accurate attenuation scenario. It is noted that the data within the US EPA Database and from the South African sites has not been filtered to exclude data that may be of poor quality or where background concentrations may be creating significant biases in the interpretation of cross-slab attenuation.

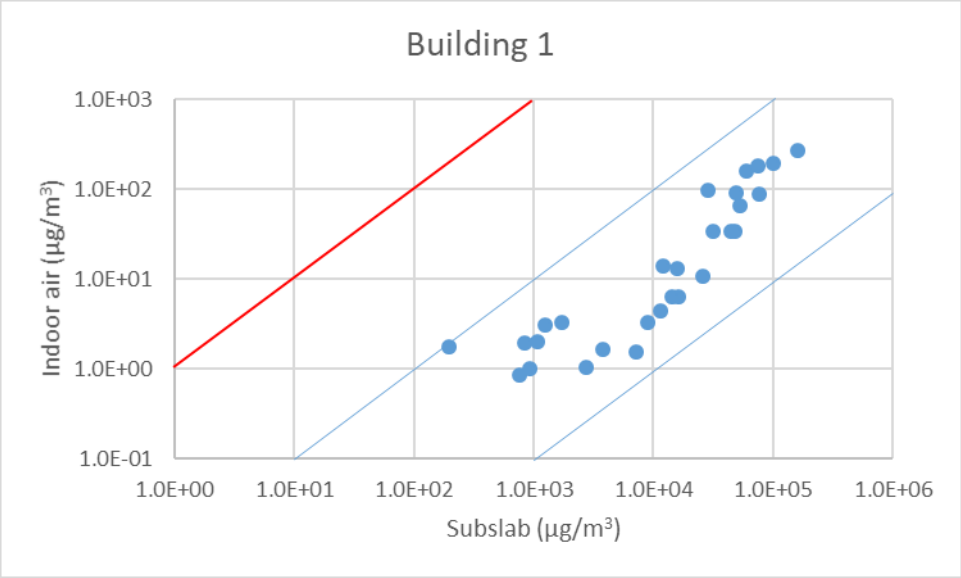
There is considerable ambiguity in the US EPA, South African and other empirical AF studies. Attenuation factors derived using alternative methods; e.g., reliability analysis instead 95th percentiles, or values based on mass flux principles, such as the AF of 0.003 used in the Johnson and Ettinger (1991) model, are arguably more technically defensible than the US EPA proposed AF value of 0.03, which is likely to be overly conservative by at least one order of magnitude.

In an analysis of the data within the US EPA VI Database, Yao, *et al.* (2013) found that the data were poorly correlated in general. There appeared to be an inverse relationship between the indoor air concentration AFs and the subsurface source vapour concentrations, which is inconsistent with the understanding of current vapour intrusion models. The attenuation of VOCs occurs during two processes; the first is the transport of the contaminants through the soil and, the second is its entry into the building space. These steps are different, and relatively independent of each other in most cases. While the US EPA VI database is valuable for understanding some aspects of the VI process, it is not useful for validation of modelled predictions of indoor air contaminant concentrations. Observed indoor air concentrations appear to be governed by factors that are not yet fully understood (Yao, *et al*., 2013). Attenuation into buildings and measured VOC concentrations within buildings can be affected by a number of building factors, including type of foundation (e.g. slab on grade, crawl space, basement), multiple buildings, indoor pressurisation, air exchange, impermeable surface cover, and indoor pressure distribution (wind load).

A recent study was conducted by Lahvis and Ettinger (2021) using data from 485 buildings at 36 sites in California to evaluate AFs. Filtering was applied to remove data of dubious quality that may have been affected by background (non-VI) sources. The results of the study indicated an AF of 0.0008 using only TCE data (paired indoor air and sub-slab samples), with a reliable accuracy of 95%.

With sufficient data, building-specific AFs can be derived. However, in collecting data, seasonal effects and potential influences from other sources of VOCs must be considered. In particular, the background levels within a building can be affected by household products, such as aerosols, solvents, paints, adhesives, oils, and fuels, but indoor air can also be affected by outdoor sources, such as vehicle emissions, which are common contributors of PHC contaminants in urban environments. In the calculation of building-specific AFs, it is therefore often more appropriate to use CVOC data, where non-VI related indoor sources are more predictable (or absent) and where attenuation in the sub-surface is limited.

Analysis of the VI AF data for specific buildings in South African has indicated consistently high attenuation, which could lead to the development of building-specific AFs. Two such examples are shown in Figure 7, where the data were filtered to exclude any data that may be affected by non-VI sources. The data were collected over different seasons and years to account for potential fluctuations in attenuation that might occur. The data indicate an α of 0.003 for Building 1 and 0.0003 for Building 2 at the 95th percentile level.



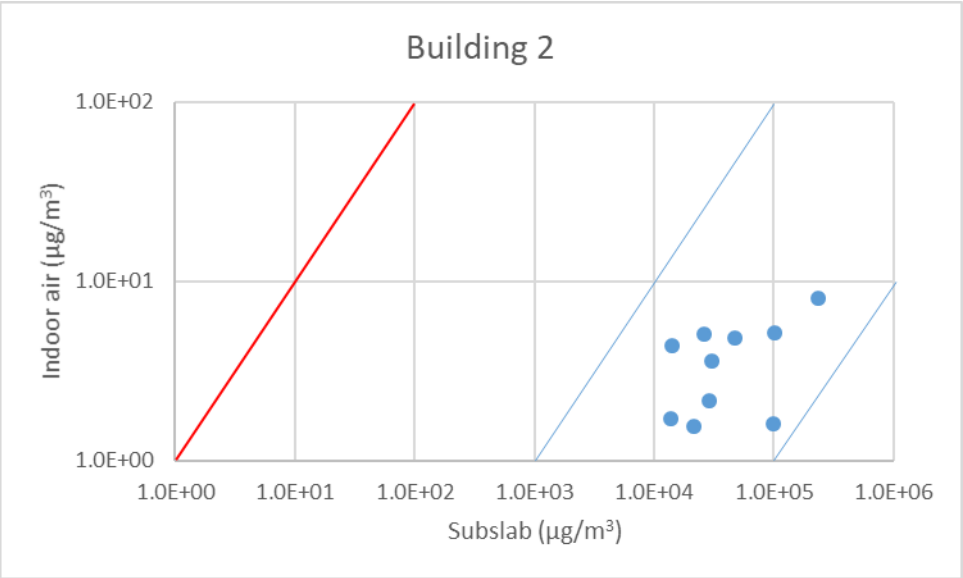


Figure 7 Paired Indoor Air and Sub-slab VOC Data from Buildings in South Africa (after McKeown and Naude, 2019)

A range of AFs from different sources is presented in Table 3 showing a relatively wide variation. The generally poor correlation of the data within the US EPA VI Database has led to the development of an AF of 0.03, which is considered to be overly conservative and is likely to result in the "screening in" of numerous buildings where the risks of VI are acceptably low. This is also observed in the empirical study using South African data. An improved understanding of VI attenuation processes has led to the development of more reliable AFs that are lower (by orders of magnitude) than the US EPA recommended value. It is therefore recommended to adopt an adequately protective approach that takes into account recent research and also considers local data.

A generic AF value of 0.003 is proposed, which is broadly consistent with both international research and local data. This AF should only be applied to buildings with slab on grade foundations and where no building-specific AF can be derived. However, it is encouraged to develop building-specific AFs where possible and where sufficiently reliable seasonal and temporal data are available. To develop building-specific AFs, multiple data points over different seasons should be collected, and data should be filtered to exclude background non-VI sources, as per the examples illustrated in Figure 7. In urban environments and industrial facilities, it may not be suitable to use petroleum VOC data due to background effects that are difficult to quantify accurately.

Table 3 Vapour Intrusion Attenuation Factors from Local and International Sources

Data Source	Attenuation Factor (α)	Notes
US EPA VI database	0.03	Based on empirical unfiltered data
South African database	0.0088	Based on empirical unfiltered data
South Africa (building-specific)	0.003 – 0.0003	Based on empirical filtered data
Lahvis and Ettinger (2021)	0.0008	Based on filtered TCE data
Johnson and Ettinger (1991)	0.003	Based on mass flux principles
Recommended AF:	**0.003**	**Applicable to slab on grade buildings**

4. MODELLING

4.1 Vapour Intrusion Modelling

A number of VI models have been developed for the transport of VOCs from sub-surface soil and groundwater to indoor air. The appropriate role of a model is to explain observed behaviour. The one-dimensional (1-D) models most frequently used for simulation of VI include the Johnson & Ettinger (J&E) and BioVapor models. Both these models are based on one-dimensional contaminant mass conservation among upward diffusive flux at the foundation bottom, the entry rate through a perimeter crack, and the exchange rate from indoor air to outdoor air. The key difference between these models is that the BioVapor model accounts for aerobic biodegradation whereas the J&E model does not, making the J&E model overly conservative. A further VI model, PVIScreen, also accounts for variability and uncertainty in input parameter values. In addition to these 1-D models, Yao, *et al*. (2016a) has more recently developed a two-dimensional (2-D) PVI model (i.e. PVI2D), which also accounts for the lateral migration of oxygen beneath buildings, unlike the 1-D models. Yao, et al. (2016b) has also developed a 2-D CVI model, which accounts for vertically heterogeneous soils overlying a homogenous vapour source.

In the context of PVI, models that include oxygen limited biodegradation support the development of petroleum-specific exclusion distance criteria (refer to Sections 3.3 and 3.4), and are consistent with empirical data collected from various PVI field investigations.

Prior to conducting modelling, the purpose and objectives should be defined. The modelling objectives and purpose can influence the selection of parameter values and can help to determine the level of detail and accuracy required in the model simulations. Examples of VI modelling applications and typical objectives are provided as follows:

- *Site-specific predictive modelling to assess current or future conditions:* This modelling would typically be conducted in conjunction with a risk assessment. Input parameter values are selected to represent site conditions, but tend to be conservative to adequately address all potential risk scenarios. In some instances, such as where buildings do not currently exist but are planned for the future, modelling can predict vapour migration and attenuation for the future conditions anticipated at the site.
- *Site-specific modelling to support and steer CSM development:* VI models can be used to identify key variables affecting vapour transport and to steer the CSM by identifying key data collection needs. At petroleum release sites, a biodegradation model, such as BioVapor, may be used to match measured oxygen and PHC profiles in soil gas. In addition, VI models can be used to evaluate the possible contribution of background sources to indoor air relative to the contribution from subsurface vapour sources.
- *Inverse modelling to develop site-specific clean-up goals:* For inverse modelling, acceptable concentrations of contaminants in indoor air are first identified, and then a site-specific model is used to back-calculate the predicted concentrations needed in soil gas, soil, or groundwater to attain the acceptable contaminant concentrations in indoor air.
- *Remedial design and selection:* A VI model can be used to assess the oxygen flux to the subsurface that is required to achieve clean-up goals as part of a soil gas mitigation evaluation and technology selection process.
- *Modelling to support the development of PVI screening criteria and distances:* This type of modelling may be used to define site-specific PVI screening criteria (i.e. separation distances) where conditions or assumptions differ from those presented in Section 3. An example is a petroleum vapour source composition that differs significantly from petrol. The screening criteria may include site-specific vertical screening distances or modified source-to-indoor air ratios, which apply when specific conditions are met (ITRC, 2014).

Brief summaries of the key features of the VI models mentioned above are provided below.

4.1.1 Johnson & Ettinger Model

One of the first VI models developed was the J&E model (Johnson and Ettinger, 1991), which includes the following features:

- A steady or transient source of sub-surface vapours from groundwater or residual contaminants in soil;
- Diffusive vapour flow through vadose zone soil;
- Vapour transport through a building floor slab; and
- Building air exchange.

The J&E model assumes that concrete foundation slabs are impermeable and that vapour movement is through cracks and other openings; however, evidence shows that hydrocarbons and other gases can effectively diffuse through concrete over a range of rates.

For sites where aerobic biodegradation of PHCs occurs in the vadose zone, comparisons to the J&E model consistently show the model to over-predict indoor air concentrations by several orders of magnitude, particularly where sub-surface concentrations of PHCs are low (US EPA, 2015b).

4.1.2 BioVapor Model

The BioVapor model (DeVaull 2007a; API 2010) is a one-dimensional model based on a CSM similar to the J&E model, but it includes aerobic biodegradation. The BioVapor model includes the following features:

- A steady sub-surface vapour source;
- Diffusive vapour flow through vadose zone soil;
- Vapour transport through a building floor slab; and
- Building air exchange.

In contrast to the J&E model, BioVapor accounts for oxygen-limited, aerobic degradation. Oxygen availability is mainly driven by vertical diffusion into the soil and lateral transport beneath building slabs (refer to Section 3.5). Key inputs to the BioVapor model are chemical-specific aerobic degradation rates and estimates of these have been provided by DeVaull (2011) for a range of chemicals (US EPA, 2015b).

The BioVapor model has been reviewed and accepted by US EPA and forms the basis of the US EPA PVIScreen model, which is described below.

4.1.3 PVIScreen Model

The PVIScreen model was introduced in 2013 and is based on the equations used in the BioVapor model (Weaver, 2013; US EPA, 2016). However, while most computer models need to be run multiple times by varying input parameters to account for uncertainty within the data, the PVIScreen model has built in algorithms, which treat input parameters as ranges and then conduct a Monte Carlo analysis of the data. The results of the model provide a probability that the indoor air concentrations are less than a risk-based value (US EPA, 2015b).

4.1.4 PVI2D Model

The PVI2D model was developed by Yao, *et al.* (2016a) and presents a 2-D PVI analytical solution, which incorporates steady-state diffusion-dominated vapour transport in a homogeneous soil and stepwise first-order aerobic biodegradation limited by oxygen availability. The model can generate 2-D soil gas concentration profiles for both hydrocarbons and oxygen, and estimate hydrocarbon indoor air concentrations as a function of site-specific conditions such as source strength and depth, reaction rate constant, soil characteristics and building features (Yao, *et al*., 2016a). In contrast to the 1-D J&E, BioVapor and PVIScreen models, PVI2D is a 2-D model, allowing for lateral migration of oxygen, which is known to be the most sensitive parameter to PHC transport.

In addition, PVI2D was developed to achieve most of the functions of the more widely used Abreu and Johnson model (AJM) (Abreu and Johnson, 2005), which is a more complex 3-D model, requiring expertise with advanced numerical techniques and computational effort, thus limiting its access and application as a PVI risk-screening tool for common investigators (Yao, *et al*., 2016b). PVI2D can provide similar soil gas concentration profiles and source-to-indoor air attenuation factors (within one order of magnitude difference) as those by the AJM. The overall results of the comparison between the PVI2D model and the 3-D AJM show that for cases involving a homogenous source and soil profile, PVI2D can represent a valid alternative to more rigorous three-dimensional numerical models (Yao, *et al*., 2016b).

4.1.5 2-D Chlorinated Vapour Intrusion Model

An analytical CVI model was developed by Yao, *et al.* (2017), which can estimate source-to-indoor air concentration attenuation by simulating 2-D vapour concentration profiles in vertically heterogeneous soils overlying homogenous vapour sources. Field validation sampling from a building overlying a layered soil profile showed that the model provided results (particularly indoor emission rates) similar to the measured data. Further studies found that the 2-D CVI model closely replicated the results of 3-D numerical models at steady state in scenarios involving layered soils overlying homogenous groundwater sources. The model is capable of simulating lateral variation of subsurface soil gas concentrations in layered soils with homogenous sources, which cannot be achieved using 1-D models (Yao, *et al*., 2017).

4.2 VI Modelling Input Parameters

Key parameters that are important to VI modelling are summarised in Table 4.

Table 4 PVI Modelling Input Parameters (adapted from ITRC, 2014)

Parameter	Unit	Normal Range
Indoor mixing height (L_{mix})	cm	Site value
Air exchange rate (ER)	1/hour	(refer to Section 2.6)
Foundation thickness ($_{crack}$)	cm	Site value
Foundation area (A_b)	cm^2	Site value
Foundation crack fraction (η)	cm^2-cracks/cm^2-total	0 – 1
Total porosity (soil-filled cracks) ($\Theta_{T\ crack}$)	cm^3-void/cm^3-soil	0 – 1
Water filled porosity (soil-filled cracks) ($\Theta_{W\ crack}$)	cm^3-void/cm^3-soil	0 – 1
Air flow through foundation (Q_s)	cm^3-air/sec	0 (minimum)
Airflow underneath foundation (Q_f)	cm^3-air/sec	$\geq Q_s$
Soil porosity (Θ_T)	cm^3-void/cm^3-soil	0.1 – 0.5
Soil water content (Θ_w)	cm^3-water/cm^3-soil	0.0 – 0.5
Soil organic carbon fraction (f_{oc})	cm^3/cm^3-soil	0.0001 – 0.1
Soil bulk density (ρ_s)	g-soil/cm^3-soil	1.5 – 2.0
Oxygen concentration below building at soil surface (O_2)	%	0 – 21
Aerobic depth (L_a)	cm	0 - L_T
Minimum oxygen concentration for aerobic biodegradation ($O_{2\text{-}min}$)	%	0 – 1
Annual median soil temperature (T)	(°C)	0 – 30
Baseline soil oxygen respiration rate (Λ_{base})	mg-O_2/g-soil-sec	0 (minimum)
Depth to source from bottom of foundation (L_T)	cm	Site value
First order aerobic biodegradation rates (k_w)	1/sec	Chemical specific
Chemical-specific source vapour concentration	mg/m^3	0 – 100,000
Total source vapour concentration	mg/m^3	0 – 100,000

Where possible, site-specific values should be used for modelling. However, in some cases, default values will be required where site measurements are not possible or where changes to parameter values are less sensitive to the modelled results. In the PVIScreen model, uncertainty analysis is used to account for the ranges in parameter values. Default values for the parameters in Table 4 can be found in the ITRC PVI guidance document (ITRC, 2014).

4.3 Vapour Intrusion Model Limitations

When selecting appropriate computer models, the mathematical formulations need to be consistent with site conditions and the CSM. Modelling input parameters should be representative of the actual physical, chemical and biological properties of a site. Typically, all factors influencing VI are not included in currently available models, or conditions are variable and therefore difficult to simulate using mathematical algorithms. Factors that influence model accuracy include geological heterogeneity, variation in building operation or construction, sub-surface moisture content, meteorological factors, and biodegradation rates/oxygen availability (in the case of PVI).

A limitation to most VI models is that field measurement of input parameters (e.g. biodegradation rates, soil moisture content, air exchange rates) are typically not available and those parameters that are available (e.g. source concentrations) may be spatially or temporally variable. Literature values are typically substituted for parameters that are not available, which leads to uncertainty, and this must be accounted for through an uncertainty analysis. This provides error bounds on predictions of the computer model.

For PVI assessments, models that consider aerobic degradation are recommended. Models can be used to improve a site-specific sampling strategy, validating or refuting the CSM or estimating the effects of changed site conditions (e.g. construction of a new building). Models can be used as one line of evidence that buildings are not impacted by vapours, but should typically be accompanied by other lines of evidence (i.e. by adopting a weight of evidence approach).

5. VAPOUR SAMPLING METHODS

5.1 Overview of Vapour Intrusion Investigations

Due to the large number of variables that can affect the concentrations of vapour compounds detected in air, a multiple-line-of-evidence approach for evaluating the vapour intrusion pathway is recommended. Using this approach, all available results are evaluated to determine whether the pathway is likely to be complete or not. Although a wide variety of investigation methods may be applied in the multiple-line-of-evidence approach, VOC concentrations in groundwater, soil gas, and indoor air typically constitute the primary lines of evidence. When VOCs are detected in one or more of these media at concentrations exceeding relevant screening levels, further assessment is required. The key challenges to evaluating the VI pathway include: spatial and temporal variability in VOC concentrations, and other unrelated sources of VOCs (i.e., indoor and ambient sources) (McHugh, et al., 2017).

The general approach taken to characterize the VI pathway also differs for PVI versus CVI because of differences in key factors affecting VI. For CVOCs, the sensitivity to VI lies with the attenuation that takes place near to or inside the building. For PHCs, most of the attenuation takes place in the vadose zone between the source and the building, and the source type (i.e. LNAPL or dissolved phase) is a key factor. In addition, there are often many indoor air sources of PHCs that make interpretation of indoor air results difficult; hence, for PVI assessments, a bottom up approach (source to pathway to indoor air) is recommended. For CVOCs, most of the sensitivity to VI occurs in and around the building; hence, a receptor (building) focused VI assessment is generally recommended.

5.2 General Sampling Principles

Sampling of indoor air, outdoor air, soil gas, and groundwater for analysis of VOCs is considered to be an important part of vapour intrusion investigations. The location of vapour source, characteristics of the subsurface material, expected vapour migration routes and potential receptors of concern should be considered in selection of sampling locations and depth. Soil sampling and analysis is not recommended for estimating VI risks, because of the following:

- The potential for vapour loss due to volatilization during soil sampling;
- Difficulties with preservation; and
- The potential to encounter spatially variable soil concentrations and the inherent inconsistencies with the chemical analysis (i.e. only a small aliquot of the overall sample is selected for the analysis, potentially biasing the result).

To ensure that the sampling data will meet the site-specific data quality objectives, it is important that the analytical methods are able to achieve detection limits that are lower than the relevant risk-based screening levels (e.g., vapour intrusion screening levels – VISLs). It is also important to select appropriate sampling locations and durations and to address spatial and temporal variability to fulfil the specific objectives of the investigation. The sampling duration depends on the type of medium being sampled and the temporal variability can be addressed by conducting sampling on a distinct seasonal basis. Multiple rounds of sampling are generally recommended to develop an understanding of temporal variability to ensure that risk management decisions are based on consideration of reasonable maximum exposure conditions (US EPA, 2015a).

5.3 Active and Passive Sampling

In general, vapour sampling can be divided into passive and active techniques. Passive techniques generally involve the collection of samples using adsorbent samplers that are allowed to be exposed to vapours over a prolonged period of time (typically 7-14 days) and are then collected for laboratory analysis of the sorbed compounds. Active sampling, by contrast, involves the collection of a known volume of gas or air over a short period of time (from a few minutes for a sub-slab sample up to 24 hours for an indoor air sample), typically by pumping the gas through a tube filled with sorbent media, or by collecting the sample in an evacuated canister for further analysis.

Passive soil gas sampling can be useful for broad identification of sub-surface source areas (i.e., mapping "hot spots" of contamination for further detailed assessment), as samplers can be placed in shallow soil bores on a grid pattern across a potentially affected area and allowed to sorb contaminants as they migrate upwards through the vadose zone. Sorbent samplers are typically avoided for the collection of quantitative soil gas samples, due to the potential for sample starvation, which occurs when the uptake rate for the sampler is greater than the rate of VOC flux into the sample point. Because the effect of starvation on sample results is variable and difficult to quantify, passive samplers are most commonly used to obtain qualitative or semi-quantitative information on the distribution of VOCs in soil gas (McHugh, et al., 2017), as described above.

Active sampling is a quantitative method that allows for the collection of a sample that can be expressed as a concentration (mass per volume), which can be used to evaluate risk. Although canister sampling is the generally preferred method for collecting active soil gas and indoor air samples, passive sorbent samplers are also widely used around the world to quantify indoor air VOCs. The benefit of sorbent samplers for indoor air sampling is that they are easier to manage and can be left in place for longer period of time reducing the effects of short-term temporal variability by yielding a time-integrated average VOC concentration (McHugh, et al., 2017). A study conducted by McAlary, et al. (2015) also showed favourable agreement between active and passive sampling of indoor air.

Sorbent tubes can also be used for active soil gas sampling by connecting the tubes to a pump and drawing a known volume of air through the sorbent media (either activated carbon or multi-sorbent material) to collect the sample. The sorbent tubes are then analysed for VOCs using either a solvent extraction method (i.e. activated carbon tubes) or thermal desorption (multi-sorbent material tubes). In general, the thermal desorption method can achieve similarly low detection limits to canister sampling; however, the detection limits achievable for activated carbon tubes are generally at least an order of magnitude higher. The drawbacks of sorbent tube sampling are that the tubes can become flooded with vapour, where high concentrations are present, making analysis inaccurate. In addition, sorbent tubes are limited to the sorption and detection of VOCs only, whereas, canister samples can also be used for analysis of fixed gases, such as oxygen, nitrogen, carbon dioxide and methane, which can be useful in understanding biodegradation processes in sub-slab and soil gas samples. A further advantage of canister sampling is that multiple samples can be collected from a single canister, whereas sorbent tubes only allow a single analysis.

5.4 Vapour Intrusion Sampling

5.4.1 Indoor Air Sampling

Indoor air sampling results are used to determine whether vapour intrusion is occurring, and to assess the nature and concentrations of VOCs to determine level of risk to human health. A potential shortcoming of indoor air testing is that indoor or outdoor sources unrelated to the subsurface contamination (i.e. background concentrations) may contribute to the presence of VOCs in occupied buildings. Therefore, to determine whether VI is occurring in a building, it is generally recommended to collect sub-slab soil gas samples together with indoor air samples and to compare the compounds detected. To eliminate the potential effects of unrelated background sources from outdoor air, it is further recommended to collect an outdoor air sample on the upwind side of the affected building concurrently with collecting the indoor air sample.

Indoor air sampling and analysis provide a direct approach to determining the concentrations of VOCs in indoor air to which building occupants can be exposed. Time-integrated sampling methods are preferred, since indoor air concentrations can be temporally variable. Because of this variability, a single indoor air sample is insufficient to estimate an average exposure. However, it is also impractical to collect indoor air samples continuously over a chronic exposure period (i.e., up to 30 years for a reasonable maximum exposure duration in a residence). Therefore, best practice is to collect multiple indoor air samples for the purposes of estimating long-term average (i.e., chronic) exposures and assessing human health risk (US EPA, 2015a).

In addition, indoor air concentrations are affected by airflow/exchange within buildings, and this is generally unaccounted for in VI assessments.

Evacuated Canister Sampling:

Typically, for vapour intrusion investigations, indoor air samples are collected using six-litre canisters using sub-atmospheric pressure sampling (evacuated canisters under vacuum) over a 24-hour period in residences or over an 8-hour period (or workday equivalent) in commercial and industrial settings. Canisters are connected with flow controllers to restrict flow to the desired level to allow collection of the sample over the full sample period while maintaining a vacuum in the canister of at least 5 inches of mercury.

Sorbent Tube Sampling:

Sorbent sampling devices are hollow containers that hold one or more adsorbent media that can bind vapour-forming chemicals. They have been developed and tested over several decades for industrial hygiene monitoring and have more recently been employed for other purposes, including vapour intrusion investigations. Sorbent samplers can be used in an active or passive mode (US EPA, 2015a).

In the active mode, a pump is used to draw air at a known rate through the device. The flow rate and sampling volume are determined based on the type of sorbent used, the target constituent(s), and the amount of sorbent contained in the device. Care must be taken to ensure that the volume of air drawn through the tube does not exceed the “breakthrough” volume (i.e., the volume of air which may be passed through the sorbent tube before a detectable level of the analyte concentration elutes from the non-sampling end). This will result in the time-weighted average concentration being biased low by an unquantifiable amount (US EPA, 2015a).

5.4.2 Outdoor Air Sampling

Outdoor air concentration data can be useful in identifying potential contributions to indoor air concentrations from ambient air (outdoor) sources. Therefore, it is recommended to collect ambient air samples using similar sampling and analysis methods, whenever indoor air samples are collected. Normally, one or two outdoor air sample locations will be sufficient to characterize the conditions surrounding a single building or a few buildings; however, additional outdoor air samples may be warranted if the investigation is assessing multiple buildings over a wide area. It is also recommended that sample locations be designed to characterize representative conditions in the absence of site-related subsurface contamination (e.g., avoid collecting ambient air samples near locations of known or suspected chemical release(s), including any potential atmospheric releases from remediation equipment). It also is suggested that observable potential outdoor sources of pollutants (e.g., air emissions from nearby commercial or industrial facilities or proximity to busy roads) be recorded during all building surveys (US EPA, 2015a). It is recommended that ambient (outdoor) air samples are collected on the upwind side of the building/s of concern to asses potential sources that are unrelated to the building itself.

Because concentrations of vapour-forming chemicals in ambient air can vary with time, it is recommended that ambient air samples generally be collected over the same sampling period as indoor air, which will facilitate data evaluations when contaminant concentrations are compared between media. For residential buildings, it is generally recommended beginning ambient air sampling at least one hour before indoor air monitoring begins and continuing to sample until at least 30 minutes before indoor monitoring is complete. This is because most residential buildings have an hourly air exchange rate in the range of 0.25 to 1.0, causing air that enters the building before indoor air sampling begins to remain in the building for a long time (US EPA, 2015a).

Monitoring air exchange during ambient air sampling events can provide useful complementary data. Ideally, these data would be collected continuously starting before sampling and throughout the sample collection period. Information about air exchange can support insights about the amount of ambient air infiltration during sampling (US EPA, 2015a).

5.4.3 Sub-slab Soil Gas Sampling

Sub-slab sampling is intended to draw soil gas from the air space immediately below the floor slab of a building. Depending upon building construction and condition, this air space may be an air gap that forms beneath a concrete foundation due to differential settlement over time or a pore space within a granular layer that may have been placed below the concrete slab. Access to this air space is generally provided by drilling or coring through the concrete and inserting a probe, which is sealed into the floor (US EPA, 2015a).

Sub-slab soil gas samples can provide useful data for characterizing the levels of hazardous, vapour-forming chemicals that can enter a building via soil gas intrusion. When combined with an appropriate AF (refer to Section 3.6), sub-slab soil gas data can be used to estimate a potential upper-bound (worst case) indoor air concentration that may arise from vapour intrusion. In this way, sub-slab data can be used to assess the potential for the vapour intrusion pathway to pose a health concern. However, it is noted that sub-slab vapour samples are generally not located where vapours enter the building, hence, it is unlikely that the sub-slab vapour concentration will be well correlated with the indoor air concentration at the same location.

Field experience indicates that there may be substantial spatial variability in sub-slab soil gas concentrations even over an average-sized footprint of a residential building. It is therefore recommended to collect multiple samples per building when sub-slab soil gas sampling is conducted. As a general guide, three sub-slab samples are recommended for a typical size residential or commercial building less than 140 m^2 in area. It is also important to consider non-standard situations, which may influence the number of sub-slab sampling locations to select, such as the following:

- Very large or small homes or buildings;
- Buildings with more than one foundation floor type;
- Subsurface structures or conditions that might facilitate or mitigate vapour intrusion; and
- Multi-use buildings with distinct segmented areas that differ significantly by occupying population or exposure frequency (US EPA, 2015a).

It is recommended that sub-slab sampling include centrally located sub-slab samples in buildings where the subsurface vapour source is laterally extensive relative to the building footprint (e.g., a broad plume of contaminated groundwater). In addition, internal building partitions, HVAC layout, contaminant distribution, utility conduits, and openings for preferential soil gas entry should be considered in selecting any additional locations for collecting sub-slab samples (US EPA, 2015a).

Several rounds of sampling are generally recommended to develop an understanding of temporal variability of sub-slab soil gas concentrations, particularly when these data are used with the recommended attenuation factor to estimate a potential upper-bound indoor air concentration that may arise from vapour intrusion (US EPA, 2015a).

Quality Assurance / Quality Control for Sub-slab Sampling:

Prior to sub-slab sampling, the integrity of the vapour sampling point installation should be checked by means of a water dam placed over the sampling location. A sudden drop of water level is an indication of water entering the sub-slab, and suggests that the point installation is not competent and cannot be used for sampling. The water also provides a further “seal” throughout the duration of the sampling.

To test for leaks in the sample system, sampling should be carried out in a shroud, where a laboratory grade tracer gas is introduced (helium is typically used for this purpose, but other chemicals such as isopropyl alcohol can also be considered) and kept at a constant concentration of between 10% and 20% v/v. If the tracer is found to be present in a purged sample (as detected using a helium detection device), this is indicative of a loss of integrity in the sample train and the sample point should be re-sealed/re-installed.

Prior to commencing with sampling, a shut-in test is recommended to confirm the integrity of the sample train and check for leaks. If the shut-in test indicates a loss of pressure, then the system should be inspected, by tightening all the fittings and repeating the test, until it is validated before proceeding with sampling. A shut-in test is conducted by closing the sub-slab probe and canister valves, and evacuating the system to a measured vacuum of about 250 mbar using a syringe. The vacuum gauge should then be observed to hold the vacuum for one minute to confirm system integrity.

During sub-slab sampling, flow rates, canister vacuum readings and helium shroud concentrations should be recorded every two minutes throughout the sample collection period.

5.4.4 Soil Gas Sampling from Vapour Wells

Soil gas sampling generally consists of installing a vapour well into the ground and drawing gas from the well using an appropriate collection device (i.e. canister or sorbent sampler) for laboratory analysis. Vapour wells are typically installed within the vadose zone at shallow depth (e.g., between 0.5 m and 2.0 m) and the results are used to support with VI investigations. Inert materials (e.g., stainless steel, copper, brass, polyvinyl chloride, high-density polyethylene) are recommended for constructing the soil gas probes that form part of the vapour well. To ensure that the data collected are representative of conditions in situ (e.g., are not adversely impacted by artificial infiltration of ambient air), a reliable seal of the annulus between the probe inlet and the probe tubing/pipework is required, along with appropriate leak testing of the seal. In addition, purging of the probe before collecting the soil gas sample is recommended, analogous to purging of monitoring wells before collecting groundwater samples.

Grab samples are typically collected when sampling soil gas rather than time-integrated samples. It is recommended to allow the vapour well time to return to equilibrium conditions before sampling. The equilibration time may vary, but would typically be between 2 hours and 48 hours. To adopt a conservative approach, it is recommended to allow the well 48 hours to reach equilibrium prior to sampling.

It is recommended to document barometric pressure, precipitation information, temperature, and other site-specific information that can influence soil gas concentration patterns at the time of sampling, using readily available data sources. These data may be helpful correlating data between events. It is recommended to take the soil gas samples as close to the areas of interest as possible and preferably from directly beneath the building structure. As vapours are likely to migrate upward through the most coarse or dry material in the vadose zone, soil gas samples should be collected from these materials, where possible (US EPA, 2015a).

5.4.5 Flux Chamber Sampling

A flux chamber (or flux hood) is a device that is placed on an open ground or floor surface, which enables the measurement of vapour flux discharging through that surface (CRC CARE, 2009b). Flux chamber sampling includes either static or dynamic chamber methods.

The static chamber method is conducted by placing the flux chamber on the surface of the ground or building slab, sealing it to the surface, and not passing any air through it. This allows vapours to become trapped in the chamber and to build up over time. Sampling of the chambers can be conducted either through active or passive sampling methods. The dynamic chamber method involves the use of an inert sweep gas, which is continually introduced into the chamber with an equivalent volume of gas allowed to escape. The system is allowed to reach steady state, which is assumed to be four to five chamber volumes, before the chamber is sampled, either as a discrete sample or as continuous monitoring (CRC CARE, 2009b).

The advantage of flux chamber sampling is that it enables the direct measurement of a vapour flux from the surface of the ground or building slab, as opposed to calculating this flux using sub-slab measurements. It therefore does not require additional subsurface investigations. Disadvantages of this method are that the device itself may induce potential changes in flux and it only covers a small footprint, which may not be indicative of the entire surface. It is therefore also difficult to know where to place the flux chamber (i.e. choosing a location that is indicative of the whole building or targeting areas of poor floor slab integrity, such as cracked areas). Flux chambers are also not useful for PHC vapours, which tend to attenuate completely before reaching the surface.

5.4.6 Emerging Sampling Methods

VI assessment is complicated by spatial and temporal variability, which can influence the vapour migration pathway from subsurface sources to indoor air. Conventional sampling methods do not account for airflow and the risks are based discrete 8 or 24-hour samples, collected on a relatively random basis. This can result in false negative determinations of potential risks in indoor air. Alternative sampling approaches are emerging that require a reduced sampling frequency while maintaining an acceptable level of confidence in exposure characterization (Schuver, *et al.*, 2018). Some recent emerging VI sampling approaches are summarised below.

Targeted Sampling:

Indicators, tracers, and surrogates (ITS), which include a collection of quantifiable metrics and tools, provide a potential solution for making VI pathway assessment and long-term monitoring more informative, efficient, and cost-effective, by helping to target when to collect a representative sample for risk assessment purposes. In the ITS method, a low numbers of indoor air CVOC samples can provide high levels of confidence for representing the reasonable maximum exposure (RME) levels (e.g., 95th percentile). Results from studies at residential buildings indicated that certain ITS metrics and tools, including measurements of differential temperature, differential pressure, and radon, provided benefits to VI assessment and long-term monitoring (Schuver, *et al*., 2018). The results provided a scientifically justifiable alternative to other commonly used VI sampling methods.

Manipulating Airflow:

Building pressure cycling (BPC) is a method that is used to manipulate indoor-outdoor pressure conditions to either induce or suppress VI and gain an understanding of potential VI impacts and risks. BPC has been used to distinguish between sub-slab and indoor sources of vapours as well as to define reasonable worst case VOC mass discharge into building structures (Lutes, *et al*., 2019). A number of data gaps have been identified with this method, which require further research that could be obtained through long-term observational studies at controlled sites.

Mass Flux Characterisation:

Geosyntec (2018) has proposed a mass flux characterisation approach to VI assessments. Data collection for this method includes spatially averaged indoor air and sub-slab measurements, cross-slab pressure differentials and building ventilation rates. The aim of this method is to identify building susceptibility to VI by characterising sub-slab transmissivity and identifying sub-slab areas with greater potential for VI.

A benefit of this method is that the potential for VI impacts can be effectively evaluated with one to two days of testing. Building-specific conditions can be better defined to assist in identifying background sources, indicate the presence of preferential pathways and thus make more accurate risk management decisions (Geosyntec, 2018).

5.5 Summary of Vapour Sampling Methods

A summary of key advantages and disadvantages of different vapour sampling methods is presented in Table 5 and described in more detail by CRC CARE (2009b).

Table 5 Summary of Vapour Sampling Methods (adapted from CRC CARE, 2009a)

Sampling Method	Advantages	Disadvantages
Passive sorbent tubes	• Can be used over a long period of time to reduce sample variability • Inexpensive method for identifying location of subsurface source areas • Simple to install, inexpensive and no mechanical parts • Can be used in a wide range of soils	• Can only provide qualitative results • Potential for saturation of sorbent • Potential for desorbing gases off fine-grained soils
Active sorbent tubes: Carbon	• Can be used for longer periods (8 – 12 hours) • Can be used to sample high concentrations • Lightweight and easy to use • Can be used with occupational monitoring pumps, which are easy to set up and use • Front and back portions of tube can be analysed to determine breakthrough • Lower cost option	• Cannot achieve the same detection limits as multi-sorbent and canister samples • Potential for saturation of media and breakthrough (although lower than for multi-sorbent tubes due to two portions of carbon within tube) • Possible cross contamination due to nature of solvent used for extraction in analysis
Active sorbent tubes: Multi-sorbent	• Low limits of reporting • Lightweight and easy to use • Can be used with occupational monitoring pumps, which are easy to set up and use • Can be used for a range of compounds	• Potential for saturation of media and breakthrough • Tubes easily affected by moisture in air resulting in loss of sample or elevated reporting limits • Short sampling time (1 – 2 hours)
Evacuated canisters	• Low limits of reporting • No pumps required • Samples can be collected over extended periods up to 48 hours • Not subject to interference from moisture, saturation or breakthrough • Reanalysis of same sample is possible • Can also collect and analyse other fixed gases (O_2, N_2, CO_2, CH_4, etc.)	• Expensive and bulky to ship • Must be certified to be clean by laboratory • Set up for sub-slab sampling requires trained personnel to ensure fittings are correctly used, potential leaks are identified, etc.
Flux chambers: Static chambers	• Equipment and procedures are simpler and less expensive than dynamic chambers • Can be used to provide time integrated samples over long periods reflecting flux variations and temporal variability • Minimises disturbance of natural flux conditions	• If concentration in chamber builds up to a significant fraction of the subsurface concentration, the flux will be impeded and the data will be underestimated • Small footprint of chamber compared to heterogeneity of ground/foundation

Sampling Method	Advantages	Disadvantages
	• Can be more sensitive than dynamic flux chambers, enabling the use of less expensive analytical techniques with higher detection limits	• Flux chambers are not useful for PHC vapours, which tend to attenuate completely before reaching the surface
Flux chambers: Dynamic chambers	• Little chance of chamber concentration build-up and therefore little chance of impeding flux • Validated sampling method for emissions from landfill sites	• Complex and expensive method that requires experience • Greater potential for QA issues • Dilution of chamber results in loss of sensitivity, requiring more expensive analytical techniques to achieve lower detection limits
Emerging methods: • Targeted Sampling (ITS) • Manipulating Airflow (BPC) • Mass Flux Characterisation	• The ITS method is efficient, cost effective and accurate by targeting when to collect samples • BPC can be used to distinguish between sub-slab and indoor vapour sources and to define VOC mass discharge into building structures • The mass flux method can better define building-specific conditions to identify background sources and preferential pathways in a short timeframe	• The emerging methods have not been commonly practiced and therefore do not have a track record of success

6. VAPOUR CONTROL AND MITIGATION

6.1 Overview of Vapour Intrusion Mitigation

The ITRC has produced the *Technical Resources for Vapor Intrusion Mitigation (VIM)* website, which is designed to aid regulators and project managers to understand the critical elements of selection, design, implementation, and operation of various VI mitigation systems (ITRC, 2021). The website includes a number of fact sheets addressing the following aspects of VIM:

- Rapid response and ventilation;
- Remediation and institutional controls;
- Active and passive mitigations methods;
- Design, post installation, and operation maintenance and monitoring strategies; and
- Emerging technologies.

Potential options to mitigate and manage vapour intrusion risks include the following:

- Subsurface remediation;
- Engineered exposure controls (i.e., building mitigation technologies) for existing and new buildings; and
- Institutional controls.

6.2 Subsurface Remediation

The preferred long-term response to the intrusion of vapours into buildings is to eliminate or reduce the vapour-forming chemicals in the subsurface sources (e.g., groundwater, subsurface soil, preferential pathways) to acceptable-risk levels, thereby removing the risk. Remediation of the groundwater plumes or other vapour sources in the vadose zone will eliminate potential exposure pathways and can be achieved through the following methods, among others:

- Removal of contaminated soil via excavation;
- Removal of contaminated groundwater with pump-and-treat technologies;
- Decontaminating and/or removing/blocking preferential pathways; and
- Treatment of contaminated soil and groundwater in situ, using technologies such as soil vapour extraction, multiphase extraction, and bioremediation, or monitored natural attenuation.

Because the focus of this guidance is on vapour intrusion and there is a large amount of information available on the selection, design, construction, and operation of technologies for remediation of subsurface vapour sources, details of these remediation topics will not be discussed in this guidance document.

Some remediation techniques (e.g. soil vapour extraction and multiphase extraction) also serve as mitigation methods. The benefits of remediation versus mitigation are:

- It is less intrusive than mitigation;

- Its performance and verification is unaffected by background VOC sources in indoor air;
- Remediation systems can be operated and maintained without resident assistance;
- It reduces the timeframe for mitigation (i.e., it can reduce/eliminate key contaminants in the vapour source);
- It can reduce or eliminate future liability;
- It can address multiple S-P-R linkages/risks; and
- It can improve the quality of the subsurface environment.

Key differences between remediation and mitigation are as follows:

- *Remediation:* Targets the vapour source in the subsurface (via mass reduction or elimination of key contaminants); provides a site-wide remedy; longer-term (e.g., months) installation; and requires pilot testing.
- *Mitigation:* Targets vapour control inside or immediately below a building or other structure; building-specific remedy; shorter term (e.g., weeks) installation; and generally does not require pilot testing.

Remediation that serves as mitigation is often desirable at PHC sites because it treats the source (i.e., closure can be achieved in a shorter timeframe than with mitigation methods) and potential issues with expensive off-gas treatment or the need for intrinsically safe equipment can be avoided. However, for CVOCs, the plumes are often more dilute and difficult to locate making them less amenable to remediation, and mitigation is often the only practical and cost effective option.

6.3 Engineered Exposure Controls

In cases where it is impractical or not possible to remediate subsurface vapour sources, it may be possible to implement interim mitigation measures in individual occupied buildings to reduce the potential risks to the health of the occupants. These interim measures can provide effective human health protection and could become part of a permanent clean-up solution. However, mitigating vapour intrusion to specific buildings is generally not a substitute for remediation of subsurface vapour sources, and the two approaches should be conducted in conjunction where possible.

6.3.1 Prompt Response Actions

Prior to addressing potential VI risks to indoor air, it may be necessary to assess the immediate safety risks (i.e. the presence of explosive or asphyxiating conditions), and this would typically be done by first responders. Once the indoor air environment has been deemed safe for access, prompt response actions related to VI can be implemented.

Where measured indoor air concentrations are found to pose an unacceptable human health risk for an acute or short-term exposure scenario, prompt action may be warranted to reduce or eliminate VI exposure, and the following response options could be considered (US EPA, 2015a):

- Sealing major openings for soil gas entry, where known and identified;
- Adjusting the heating, ventilation, and air conditioning (HVAC) systems to over-pressurize non-residential buildings;

- Installing, repairing, or maintaining vapour traps for sewer or drain lines that are sources of vapour intrusion;
- Increasing building ventilation, for example using fans or natural ventilation;
- Treating indoor air (e.g., adsorption using activated carbon); and
- Temporary relocation.

None of these options will reduce the level of vapour-forming contamination in the subsurface environment, and it is therefore generally recommended that these response options be replaced, where feasible, by installing, operating, and maintaining an engineered exposure control that reduces or eliminates vapour entry into the building, until remediation of subsurface vapour sources can be achieved (US EPA, 2015a).

6.3.2 Active Depressurisation Technologies for Existing Buildings

Active depressurization technology (ADT) systems are widely considered the most practical vapour intrusion mitigation strategy for most existing buildings, including those with basement slabs or slab-on-grade foundations. ADT systems are generally recommended for consideration as vapour intrusion mitigation methods because of their demonstrated capability to achieve significant concentration reductions in a wide variety of buildings and their moderate cost (US EPA, 2015a).

Sub-slab depressurization (SSD) systems, a common type of ADT system, function by creating a slight pressure increase beneath the building slab to prevent soil gas entry into the building. This pressure difference is created by extracting soil gas from beneath the slab and venting it to the atmosphere. For the system to be effective by this mechanism, this soil depressurization must be established and maintained at least near the primary openings for soil gas entry. Construction of SSD systems entails opening one or more holes in the existing slab, removing soil from beneath the slab to create a “suction pit” (typically around 30 cm radius), placing vertical suction pipes into the suction pits, and sealing the openings around the pipes (US EPA, 2015a). The pipes are then connected to a fan, or in the case of multiple suction pits being required in a building, the pipes are connected together as a manifold system and then connected to a fan outside the building. The fan draws soil gas from the sub-slab area through the piping and vents it to the outdoors. Sealing known and accessible openings in the slab and foundation can reduce the flow rate of conditioned indoor air that can be pulled into the sub-slab region by the suction wells and the sub-slab depressurization.

In buildings with a crawl space foundation or a basement with a dirt floor, a flexible membrane may be installed over the floor to facilitate depressurization of the soil gas beneath the membrane, which prevents vapours from intruding into the crawl space or basement air. To maximize the effectiveness of a sub-membrane depressurization (SMD) system, it is recommended that the membrane covers the entire floor area and that all seams and other openings in the membrane are sealed (US EPA, 2015a).

ADT systems are typically more effective for CVOCs but are often less effective for PHCs, based on the nature of the contamination. CVOC impacts are often dispersed or sporadic whereas sites where PVI mitigation is needed, typically involve LNAPL in close proximity to building foundations, and the application of ADT systems at these sites often requires some off-gas treatment and intrinsically safe equipment, which can be costly because of the entrainment of high PHC vapour concentrations. For this reason, soil vapour extraction (SVE) systems are often preferred over ADT systems at such sites.

6.3.3 *Approaches for New Buildings*

The ADT systems described above are also generally applicable to new buildings. However, a wider range of options is typically available to mitigate or avoid vapour intrusion in new buildings. These options potentially include the choice of building location and opportunities to modify the building design and construction, which are not available for existing buildings (US EPA, 2015a). Some examples include the following:

- *Avoiding building above contaminated areas:* At some sites, contaminated areas most likely to produce unacceptable vapour intrusion exposures can be avoided and designated for other purposes that pose less risk, such as recreational space or undeveloped landscape.
- *Design of heating/cooling systems:* The selection of suitable heating and cooling systems that are designed to maintain over-pressurization inside the building structure may be effective in mitigating vapour intrusion.
- *Passive barriers:* Passive barriers, such as low-permeability membranes, can be more readily installed between the soil and the building during new building construction. Passive barriers are intended to reduce vapour intrusion by limiting openings for soil gas entry. However, passive barriers as stand-alone technologies may not adequately reduce vapour intrusion owing to difficulties in their installation and the potential for perforations of the barrier during or after installation. They are commonly combined with ADT systems or with sub-membrane ventilation systems to help improve their efficiency.
- *Sub-slab venting layers:* Venting layers can be more easily installed between the soil and the building during new building construction.
- *Open ground-level designs:* New buildings may be designed to include highly ventilated, low-occupancy areas at ground level, such as open parking garages.
- *Increasing the vertical separation distance:* Remediation can include the importation of an extra layer of clean soil to be placed on the current surface to create sufficient distance between the contaminated material and the building.

6.4 Operation, Maintenance and Monitoring of VI Mitigation Systems

Operation, maintenance and monitoring (OM&M) is used generically to refer to periodic inspections (including monitoring of key operational parameters), component maintenance, replacements, or repairs, and related activities that are generally necessary to ensure continued operation and effectiveness of engineered exposure controls to mitigate vapour intrusion. It is generally recommended that such OM&M activities be conducted routinely, be documented in an OM&M plan, and consider the recommendations of equipment manufacturers, if any, and site-specific factors (US EPA, 2015a).

Design specifications for vapour mitigation systems may include (1) a maintenance frequency that varies over the operating period of the mitigation system; and/or (2) a provision to evaluate and modify the frequency based on data or information obtained during the initial period of monitoring and maintenance. For example, it may be acceptable to reduce the inspection or maintenance frequency once efficient system operation has been demonstrated for at least an initial year, with triggers for additional, unscheduled inspections following alarms (from warning devices fitted to mitigation systems) or building modifications, if any.

A typical OM&M plan should include the following information:

- The objectives of the system, including assumptions/starting conditions, and conditions for when the system is no longer considered necessary;
- An action plan for cases where the monitoring confirms that trigger values have been exceeded;

- Project team contact information;
- An overview of the design and layout of the system, including all componentry;
- An as-built design layout drawing;
- Standard operating procedures, including start-up, shut-down, emergency shut-down, and system error/trouble-shooting procedures. Where possible, these should be visual including photographs of actual components installed at the site;
- A monitoring plan, including system metrics, monitoring equipment, operational indicators, monitoring locations and frequency, and key equipment requiring visual inspection;
- Manufacturers' specifications for mechanical / electrical equipment installed within the system (e.g. fans); and
- Logging sheets for recording data.

Typical OM&M activities for either passive or active vapour intrusion mitigation systems may include, but are not limited to:

- Routine inspection of all visible components of the vapour intrusion mitigation system, including fans, piping, seals, membranes and collection points, to ensure there are no signs of degradation, damage or blockage. The as-built design layout drawing should be reviewed to verify that the system configuration has not been modified.
- Visual inspection of the building to evaluate whether any significant changes have been made that would affect the design of the system or the general environment in which it is operated.
- Visual inspection of the area of concern (including basement floor and wall seals, sumps, floor drains and utility penetrations) to ensure there are no significant changes in conditions that would warrant modification of the system design.
- Routine monitoring of vent risers for flow rates and pressures generated by the fan to confirm the system is working and moisture is draining correctly.
- Routine maintenance, calibration and testing of functioning components of the venting system consistent with the manufacturers' specifications:
    - Pressure readings for both active and passive depressurization systems as well as positive pressurization systems (e.g., periodic verification of measurable pressure differences across the slab).
    - Confirmation that the extraction fan is operating.
    - SSD system fans generally can function well for prolonged periods without maintenance; however, the operation of these fans should be monitored and replacement should be considered within a scheduled period (typically 5 – 10 years, the period of which could be set based on the observed performance of the fans at the site) to avoid unexpected breakdowns. A noisy fan is typically indicative of problems with bearings and will warrant replacement on that basis.
- Inspection of external electrical components to identify undesirable conditions, such as excessive noise, vibration, moisture, or corrosion, and to verify that the fan cut-off switch is operable.
- Confirmation of proper operation of warning devices, indicator lights and telemetry equipment, should it be fitted. Where telemetry equipment is fitted for remote warning alerts, it is important to verify that the contract with the service provider for the telecom services remains valid.
- Confirmation that building owner/occupants are knowledgeable about how to maintain system operation. To this end, OM&M inspections should include verification that a copy of the OM&M manual is present in the building and that the designated site contact person has conducted the necessary checks, as specified, to ensure its continued operation.

6.5 Institutional Controls

Institutional controls may be used to restrict certain land uses, buildings, or activities that could otherwise pose an unacceptable human exposure via the vapour intrusion pathway. These could be used as either an interim response until site clean-up goals are achieved or as part of a long-term response where vapour-forming sources remain in place or are difficult/impractical to remediate. Institutional controls are non-engineered instruments, such as administrative or legal controls, that help to minimize the potential for human exposure to contamination.

Institutional controls typically operate by imposing land or resource use restrictions at a given site or by conveying notice to stakeholders regarding subsurface contamination or the possible need to refrain from certain actions that may result in human exposure to hazardous chemicals (US EPA, 2015a). In terms of South African legislation, Part 8: Section 40 of NEMWA (2008) requires that no person may transfer contaminated land without informing the person to whom that land is to be transferred that the land is contaminated and, in the case of a remediation site, without notifying the DFFE and complying with any conditions that are specified by the DFFE. To ensure compliance with this section of NEMWA, the DFFE must notify the relevant Registrar of Deeds of any land that has been declared as a remediation site, and the necessary information must be entered in or on registers and documents kept by the Deeds Office.

7. VAPOUR INTRUSION SCREENING LEVELS

7.1 Approach to Deriving Screening Levels

The approach to developing vapour intrusion screening levels (VISLs) follows the US EPA recommended approach for human health risk assessment, as documented in the Risk Assessment Guidance for Superfund (RAGS) Part F and other US EPA publications (US EPA, 2021a; 2021b; 2015b; 2009).

The VISLs have been derived for the protection of human health from long-term (i.e., chronic) exposure to VOCs in indoor air, considering the potential for cancer and non-cancer effects. VISLs have also been derived for sub-slab soil gas concentrations using a recommended AF of 0.003 (refer to Section 3.6). However, it is noted that building-specific cross-slab attenuation factors can be applied if sufficient statistically robust data are available to indicate attenuation that is significantly different from the generic value adopted.

The VISLs were developed considering the following generic conceptual model for vapour intrusion:

- A source of vapours underneath the building(s) in the vadose zone;
- Vapour migration via diffusion upwards through unsaturated soils from the source toward the ground surface and overlying buildings; and
- Buildings with poured concrete foundations (e.g., basement or slab-on-grade foundations) that are susceptible to soil gas entry.

7.2 Screening Level Equations and Input Parameters

VISLs were derived for indoor air in both residential and commercial/industrial scenarios using the following US EPA equations (US EPA, 2021c):

Non-carcinogenic Indoor Air Screening Level: **Equation 1**

$$C_{nc} = \frac{THQ \; x \; RfC \; x \; AT_{nc} \; x \; \frac{365 \; days}{year} \; x \; \frac{24 \; hours}{day} \; x \; \frac{1000 \; \mu g}{mg}}{ED \; x \; EF \; x \; ET}$$

Carcinogenic Indoor Air Screening Level: **Equation 2**

$$C_c = \frac{TCR \; x \; AT_c \; x \; \frac{365 \; days}{year} \; x \; \frac{24 \; hours}{day}}{ED \; x \; EF \; x \; ET \; x \; IUR}$$

Trichloroethylene (TCE) Carcinogenic Residential Indoor Air Screening Level: **Equation 3**

$$C_c = \frac{TCR \; x \; AT_c \; x \; \frac{365 \; days}{year} \; x \; \frac{24 \; hours}{day}}{EA + \; EC_2 + EC_6 + EC_{16} + EC_{26}}$$

Vinyl Chloride Carcinogenic Residential Indoor Air Screening Level: **Equation 4**

$$C_c = \frac{TCR}{IUR + \left(\frac{IUR \; x \; EF \; x \; ED \; x \; ET}{AT_c \; x \; \frac{365 \; days}{year} \; x \; \frac{24 \; hours}{day}}\right)}$$

Where appropriate, the exposure parameters used in the development of the South African soil screening values (DEA, 2010) have been used to develop the VISLs. In the absence of South African parameters, applicable US EPA (2021c) parameters were used. The input parameters used in the VISL equations and the rationale for their use is summarised in Table A1, Appendix A.

7.3 Toxicological Data

Toxicity values were selected from the US EPA Regional Screening Levels (RSLs) tables (US EPA, 2021a), adopting their hierarchy of sources for toxicity values (US EPA, 2003). Where inhalation toxicity data (i.e. Reference Concentrations and Inhalation Unit Risk values) were not available for specific chemicals, a route-to-route extrapolation approach was applied (US EPA, 1994), by using the following equations:

Non-carcinogenic Route-to Route Extrapolation:

$$RfC\left(\frac{mg}{m^3}\right) = \frac{RfD\left(\frac{mg}{kg} - day\right) x \; 70kg}{20 \; m^3/day}$$

Carcinogenic Route-to Route Extrapolation:

$$IUR\left(\frac{\mu g}{m^3}\right)^{-1} = \frac{SF\left(\frac{mg}{kg} - day\right)^{-1} x \; 20 \, m^3/day}{70kg \; x \; 1000 \; mg/\mu g}$$

Where:

RfC = Reference concentration

RfD = Reference dose

IUR = Inhalation unit risk

SF = Slope factor

70 kg = Body mass

20 m^3/day = Air inhalation rate

The relevant toxicological reference values for the range of VOCs considered in this publication are presented in Table A2, Appendix A. For compounds where US EPA RSLs were not available, toxicity values were selected from the Michigan Department of Environmental Quality (MDEQ), as indicated in Table A2, Appendix A.

7.4 Vapour Intrusion Screening Levels

Using the methodology described above, VISLs were calculated for a range of VOCs and are presented in Table A3 and Table A4, Appendix A, for residential and commercial/industrial scenarios, respectively. Where compounds have both a non-carcinogenic (toxic) and carcinogenic mode of action, separate screening levels were calculated for each mode of action and the lowest (i.e. most conservative) of the two values was adopted as the screening level.

7.5 Occupational Exposure Limits

An occupational exposure limit (OEL) is defined as the time-weighted average concentration of a contaminant, measured in the employee's breathing zone, that is considered to be safe for the majority of healthy workers, for an eight-hour work shift and a forty-hour work week, for an entire working lifetime. OELs apply to employers who carry out work, which may expose their employees to the intake of hazardous chemical substances at the workplace, as defined in the Hazardous Chemical Substances Regulations (DOL, 1995). Under these regulations, before any employee is exposed or may be exposed, it is the duty of an employer to ensure that the employee is adequately and comprehensively informed and trained in the risks of exposure and the precautions to be taken to avoid exposure. It is also the duty of the employer to ensure that employees undergo medical surveillance if they may be exposed to a substance listed in the regulations, on commencing employment and at a frequency not exceeding two years, or at intervals specified by an occupational medical practitioner (DOL, 1995).

Most OELs were derived in the 1970s and were designed to protect the health of the majority of workers. They were not intended to protect sensitive workers, may not incorporate the most recent toxicological data available, and may differ from US EPA derivations of toxicity values with respect to weight-of-evidence considerations and use of uncertainty factors (US EPA, 2015a). It is therefore not recommended to use OELs for the purposes of assessing human health risk posed to workers by the vapour intrusion pathway, but rather to apply the risk-based VISLs proposed in Section 7.4 above.

8. SUMMARY

Overview of Vapour Intrusion

Vapour intrusion (VI) can be broadly defined as the migration of hazardous chemical vapours from sub-surface contamination sources into overlying buildings or occupied spaces. Chemical vapours can fall into two broad categories; 1) those that form toxic and/or carcinogenic threats to human health (chemicals typically associated with fuels and solvents); and 2) those that can pose an explosive or asphyxiation risk (e.g. methane, carbon monoxide and hydrogen sulphide). The focus of this guidance document is on VOC vapours from toxic and/or carcinogenic chemical compounds and not on vapours that may pose an explosive or asphyxiation risk.

Conceptual Site Model (CSM)

The CSM for VI assessment follows the same S-P-R approach as for other contaminated site assessments. The VI pathway is considered "complete" for a specific building when the following conditions are met:

- A sub-surface source of hazardous vapour-forming chemicals (i.e. VOCs) is present underneath the building;
- Vapours have a route along which to migrate;
- Openings exist for vapours to enter the building and "driving forces" exist to draw the vapours through the openings;
- One or more of the vapours derived from the sub-surface source(s) is present in the indoor air; and
- The building is occupied when the vapours are present in the indoor air.

Biodegradation and Separation Criteria

Biodegradation in the context of VI is particularly important for petroleum hydrocarbons, which are known to degrade in the subsurface environment in the presence of oxygen, which diffuses into the soil from the atmosphere. An understanding of the rates at which this degradation occurs and the dynamics of the processes can allow for subsurface separation criteria to be established where the risk of VI from petroleum hydrocarbon compounds becomes negligible. These separation criteria include vertical separation distances and lateral inclusion zones, which can be established to allow assessments to be focussed on areas of potential contamination while excluding those where contamination is unlikely (i.e. biodegradation is likely to preclude the possibility of VI).

Microorganisms capable of biodegrading petroleum hydrocarbon compounds (PHCs) are ubiquitous in most soil environments. In the presence of oxygen, the rate of degradation of petroleum vapours in the vadose zone is generally faster than the rate of upward diffusion of the PHCs, resulting in complete attenuation of the vapours before reaching building structures. The key difference with other non-petroleum VOCs is that they typically degrade under anaerobic conditions and are thus not attenuated in the same way as PHCs.

The lateral inclusion zone is referred to as the area surrounding a contaminant source through which vapour-phase contamination may travel to intrude into buildings. The lateral inclusion zone is defined as the area of contamination, which is delineated by clean monitoring points and includes a buffer zone to allow for uncertainty in the actual location of the edge of a contaminant source. For PVI sites, a lateral inclusion zone of 10 m is recommended from the edge of the source and for CVI sites, a lateral inclusion zone of 30 m is recommended. If a building is located within the lateral inclusion zone, then vertical screening distances can be applied. Buildings that are located outside of the lateral inclusion zone require no further VI evaluation provided that conditions do not change that would cause the contamination to enter the lateral inclusion zone.

The vertical separation distance is the distance between the top of a vapour source (or shallowest vertical extent of contamination) in soil or groundwater and the lowest depth of an overlying building. If the thickness of biologically active soil is sufficient and oxygen and soil moisture are present, aerobic degradation will typically degrade vapour-phase PHCs before they can intrude into buildings. Oxygen ingress from the atmosphere to the subsurface soil environment typically occurs through the open ground surrounding buildings followed by lateral penetration beneath the building slab. Extensive building foundation dimensions will lead to restrictions of oxygen penetration beneath the building. For sufficient oxygen to penetrate beneath a building where a PHC source is present, the minimum distance from the centre of the building to the edge of the building slab should be 7.5 m (i.e. the shortest dimension of a square or rectangular building should be no more than 15 m) and the PHC source zone should occur at a depth greater than 2 m below the building foundation slab.

The VI AF, designated alpha (α), is defined as the concentration in indoor air divided by the concentration in soil gas at the source. The attenuation factor can be used to estimate the concentration of a chemical in indoor air from the concentration measured in soil gas below a building slab. To predict the indoor air concentration, the measured concentration in soil gas is multiplied by a suitable AF for the particular building, or by using a suitably conservative default value. Based on reliable local and international datasets, a suitably conservative default VI AF of 0.003 is recommended, in the absence of calculating a building-specific attenuation factor.

Modelling

The appropriate role of a model is to explain observed behaviour. The 1-D models most frequently used for simulation of PVI include the Johnson & Ettinger (J&E) and BioVapor models, and more recently, the PVIScreen model. The key difference between these models is that the BioVapor and PVIScreen models account for aerobic biodegradation whereas the J&E model does not, making the J&E model overly conservative. Some frequently used two-dimensional models include PVI2D and the 2-D Chlorinated Vapour Intrusion model. A key feature of PVI2D is that this model allows for lateral migration of oxygen, which is known to be the most sensitive parameter to PHC transport. The 2-D Chlorinated Vapour Intrusion model can simulate lateral variation of subsurface soil gas concentrations in layered soils with homogenous sources, which cannot be achieved using 1-D models, and it also closely replicates the results of 3-D numerical models, but is more user friendly.

Where possible, site-specific values should be used for modelling. However, in some cases, default values will be required where site measurements are not possible or where changes to parameter values are less sensitive to the modelled results. When selecting appropriate numerical models, the mathematical formulations need to be consistent with site conditions and the CSM. Factors that influence model accuracy include geological heterogeneity, variation in building operation or construction, sub-surface moisture content and meteorological factors. Models can be used as one line of evidence that buildings are not impacted by vapours, but should typically be accompanied by other lines of evidence (i.e. by adopting a weight of evidence approach) where possible.

Vapour Sampling Methods

Sampling of indoor air, outdoor air, soil gas, and groundwater for analysis of VOCs is considered to be an important part of vapour intrusion investigations. In general, vapour sampling can be divided into passive and active techniques. Passive techniques generally involve the collection of samples using adsorbent samplers over a prolonged period of time (typically 7-14 days), whereas active techniques involve the collection of a known volume of gas or air over a short period of time (from a few minutes for a sub-slab sample up to 24 hours for an indoor air sample). Passive soil gas sampling can be useful for broad identification of sub-surface source areas, and the results are generally considered to be qualitative. Active sampling is a quantitative method that allows for the collection of a sample that can be expressed as a concentration (mass per volume), which can be used to evaluate risk. Active samples can be collected using evacuated canisters or sorbent tubes, containing carbon or multi-sorbent media. Canisters and multi-sorbent media tubes can generally achieve lower detection limits than carbon tubes. Vapour sampling should always be done with care and expertise, taking into account background conditions, to avoid misinterpretation of results.

Vapour Control and Mitigation

Potential options to mitigate and manage vapour intrusion risks include subsurface remediation, engineered exposure controls, and institutional controls. In cases where it is impractical or not possible to remediate subsurface vapour sources, it may be possible to implement interim mitigation measures, such as SSD systems, in individual occupied buildings to reduce the potential risks to the health of the occupants. By extracting soil gas from beneath the slab and venting it to the atmosphere, a SSD system creates a slight pressure decrease beneath the building slab to prevent soil gas entry into the building. SSD systems can provide effective human health protection and could become part of a permanent clean-up solution. It is important to implement an OM&M plan to a vapour mitigation system, including periodic inspections, component maintenance, replacements, repairs, and related activities, to ensure its continued operation and effectiveness.

To avoid vapour intrusion in new buildings, a wider range of options is typically available, including: avoiding building above contaminated areas; design of heating/cooling systems; passive barriers; sub-slab venting; and open ground-level designs (e.g. parking garages).

Institutional controls may be used to restrict certain land uses, buildings, or activities that could otherwise pose an unacceptable human exposure via the vapour intrusion pathway. They are non-engineered instruments, such as administrative or legal controls, that help to minimize the potential for human exposure to contamination.

Vapour Intrusion Screening Levels (VISLs)

VISLs were developed for both residential and commercial/industrial scenarios, following the US EPA recommended approach for human health risk assessment, and taking into account exposure parameters used in the development of the South African soil screening values, where available. Toxicity values were selected from the US EPA Regional Screening Levels tables, adopting their hierarchy of sources for toxicity values. Where compounds have both a non-carcinogenic (toxic) and carcinogenic mode of action, separate screening levels were calculated for each mode of action and the lowest (i.e. most conservative) of the two values was adopted as the screening level.

An occupational exposure limit (OEL) is a time-weighted average concentration of a contaminant, measured in the employee's breathing zone, that is considered to be safe for the majority of healthy workers, for a working lifetime of exposure. OELs apply to employers who carry out work at a workplace which may expose their employees to the intake of hazardous chemical substances in this environment. OELs were not intended to protect sensitive workers and may not incorporate the most recent toxicological data or approaches available. It is therefore not recommended to use OELs for the purposes of assessing human health risk posed to workers by the vapour intrusion pathway, but rather to apply risk-based VISLs.

9. REFERENCES

Abreu, L.D.V., and Johnson, P.C. (2005). Effect of vapor source–building separation and building construction on soil vapor intrusion as studied with a three-dimensional numerical model. *Environ Sci Technol.* 2005; *39*: 4550–4561.

API (2010). *BIOVAPOR – A 1-D Vapor Intrusion Model with Oxygen-Limited Biodegradation.* Version 2.0. American Petroleum Institute, Washington, DC.

CRC CARE (2009a). *Biodegradation of Petroleum Hydrocarbon Vapours: Technical Report No. 12.* Cooperative Research Centre for Contamination Assessment and Remediation of the Environment. March 2009.

CRC CARE (2009b). *Field Assessment of Vapours: Technical Report No. 13.* Cooperative Research Centre for Contamination Assessment and Remediation of the Environment. August 2009.

CRC CARE (2011). *Health Screening Levels for Petroleum Hydrocarbons in Soil and Groundwater: Part 1 Technical Development Document.* Cooperative Research Centre for Contamination Assessment and Remediation of the Environment. September 2011.

CRC CARE (2013). *Petroleum Hydrocarbon Vapour Intrusion Assessment: Australian Guidance: Technical Report No. 23.* Cooperative Research Centre for Contamination Assessment and Remediation of the Environment. July 2013.

Davis, R. (2009). Bioattenuation of Petroleum Hydrocarbons in the Subsurface: Update on Recent Studies and Proposed Screening Criteria for the Vapor Intrusion Pathway. *LUSTLine Bulletin* 61 (May 2009), 11–14.

DEA (2010). *Framework for the Management of Contaminated Land.* Department of Environmental Affairs, Republic of South Africa. May 2010.

DEA (2014). *National Norms and Standards for the Remediation of Contaminated Land and Soil Quality in the Republic of South Africa.* Department of Environmental Affairs, Republic of South Africa. Government Notice (GN) R331, published 2 May 2014.

DeVaull, G.E. (2007a). Indoor Vapor Intrusion with Oxygen-Limited Biodegradation for a Subsurface Gasoline Source. *Environmental Science and Technology* 41(9): 3241-3248.

DeVaull, G.E. (2007b). *Indoor Air Vapor Intrusion: Predictive Estimates for Biodegrading Petroleum Chemicals.* Presentation at: Air and Waste Management Association (A&WMA) Specialty Conference: Vapor Intrusion: Learning from the Challenges, Providence, Rhode Island. 26-28 September 2007.

DeVaull, G.E. (2011). *Biodegradation Rates for Petroleum Hydrocarbons in Aerobic Soils: A Summary of Measured Data.* Proceedings of Battelle 8th International Symposium on Bioremediation and Sustainable Environmental Technologies, Reno, Nevada, 27-30 June 2011.

DOL (1995). *Hazardous Chemical Substances Regulations, 1995.* Occupational Health and Safety Act. Act No. 85 of 1993. South African Department of Labour. Government Notice 1179. 25 August 1995.

Geosyntec (2018). *Mass Flux Characterization for Vapor Intrusion Assessment.* Unpublished presentation by Geosyntec Consultants: Theresa Gabris, Helen Dawson, William Wertz, Todd McAlary, and Daniel Carr (DBCarr Consulting). AEHS East, 16 October 2018.

ITRC (2014). *Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management.* The Interstate Technology & Regulatory Council Petroleum Vapor Intrusion Team. Ref: PVI-1. October 2014.

ITRC (2021). Technical Resources for Vapour Intrusion Mitigation (VIM) website. Currently available online at: https://vim-1.itrcweb.org/

Johnson, P.C. and R.J. Ettinger. (1991). Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings. *Environmental Science and Technology* **1991**, *25*(8):1445-1452.

Lahvis, M.A., and Ettinger, R.A. (2021). Improving Risk-Based Screening at Vapor Intrusion Sites in California. *Groundwater Monitoring and Remediation* 41, no. 2, 73-86, Spring 2021.

Lahvis, M.A., Hers, I., Davis, R.V., Wright, J., and DeVaull, G.E. (2013). Vapor Intrusion Screening at Petroleum UST Sites. *Groundwater Monitoring & Remediation* 33, no. 2, 53-67, Spring 2013.

Lutes, C.C., Holton, C.W., 1, Truesdale, R., Zimmerman, J.H., Schumacher, B. (2019). Key Design Elements of Building Pressure Cycling for Evaluating Vapor Intrusion—A Literature Review. *Ground Water Monit Remediat.* 39(1): 66–72, 28 February 2019.

Ma, J., McHugh, T., Beckley, L., Lahvis, M., DeVaull, G., and Jiang, L. (2020). Vapor Intrusion Investigations and Decision-Making: A Critical Review. *Environmental Science & Technology* **2020,** *54*(12),7050-7069. May 8, 2020.

McAlary, T., Groenevelt, H., Disher, S., Arnold, J., Seethapathy, S., Sacco, P., Crump, D., Schumacher, B., Hayes, H., Johnson, P., and Górecki, T. (2015). Passive sampling for volatile organic compounds in indoor air-controlled laboratory comparison of four sampler types. *Environ Sci Process Impacts* May 2015; 17(5):896-905.

McHugh, T., Davis, R., DeVaull, G., Hopkins, H., Menatti, J., and Peargin, T. (2010) Evaluation of Vapor Attenuation at Petroleum Hydrocarbon Sites: Considerations for Site Screening and Investigation. *Soil and Sediment Contamination* 19:725–745.

McHugh, T., Loll, P., and Eklund, B. (2017). Recent Advances in Vapor Intrusion Site Investigations. *Journal of Environmental Management* 204 (2017) 783-792.

McKeown, R.S. and Naude, K.L. (2019). *Local Cross-Slab Soil Vapour Attenuation Data to Support Assessment of Vapour Intrusion Risks.* Proceedings, Fifth Annual Conference of the Network for Industrially Contaminated Land in Africa (NICOLA), Gordon's Bay, South Africa. 31 October – 1 November 2019.

MDEQ (2015a). *Chemical Update Worksheet: t-Amyl methyl ether.* Michigan Department of Environmental Quality. 24 September 2015.

MDEQ (2015b). *Chemical Update Worksheet: t-Butyl alcohol.* Michigan Department of Environmental Quality. 16 September 2015.

MDEQ (2015c). *Chemical Update Worksheet: Diisopropyl ether.* Michigan Department of Environmental Quality. 24 September 2015.

MDEQ (2015d). *Chemical Update Worksheet: Ethyl-tert-butyl ether.* Michigan Department of Environmental Quality. 23 November 2015.

Mohr, S., and McKeown, R.S. (2014). *Assessing Petroleum Vapor Intrusion in Emerging Market Countries - Challenges, Solutions and Insights from a PVI Dataset Collected in Southern Africa.* Proceedings, Ninth International Conference on the Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, USA. Battelle. 19-22 May 2014.

Molins, S., Mayer, K.U., Amos, R.T., and Bekins, B.A. (2012). Vadose zone attenuation of organic compounds at a crude oil spill site — Interactions between biogeochemical reactions and multicomponent gas transport. *Journal of Contaminant Hydrology* 112 (2010) 15–29.

NEMA (1998). *National Environmental Management Act.* Act No. 107 of 1998.

NEMWA (2008). *National Environmental Management: Waste Act.* Act No. 59 of 2008.

NWA (1998). *National Water Act.* Act No. 36 of 1998.

Patterson, B.M., and Davis, G.B. (2009). Quantification of Vapor Intrusion Pathways into a Slab-on-Ground Building under Varying Environmental Conditions. *Environmental Science & Technology* **2009**, *43*, 650-656.

Peargin, T., and Kolhatkar, R. (2011). *Empirical Data Supporting Groundwater Benzene Concentration Exclusion Criteria for Petroleum Vapor Intrusion Investigations.* International Symposium on Bioremediation and Sustainable Environmental Technologies, Reno, Nevada, USA.

Schuver, H.J., Lutes, C., Kurtz, J., Holton, C., and Truesdale, R.S. (2018). Chlorinated Vapor Intrusion Indicators, Tracers, and Surrogates (ITS): Supplemental Measurements for Minimizing the Number of Chemical Indoor Air Samples – Part 1: Vapor Intrusion Driving Forces and Related Environmental Factors. *Remediation* **28**, *3*, 7-31. 6 June 2018.

US EPA (1994). *Methods for Derivation of Inhalation Reference Concentrations and Application of Inhalation Dosimetry*. Environmental Criteria and Assessment Office, Office of Health and Environmental Assessment, Office of Research and Development, United States Environmental Protection Agency, Research Triangle Park, North Carolina. Ref: EPA/600/8-90/066F. October 1994.

US EPA (2003). *Human Health Toxicity Values in Superfund Risk Assessments.* United States Environmental Protection Agency, OSWER Directive 9285.7-53. 5 December 2003.

US EPA (2009). *Risk Assessment Guidance for Superfund: Volume I: Human Health Evaluation Manual: (Part F, Supplemental Guidance for Inhalation Risk Assessment).* Office of Superfund Remediation and Technology Innovation, United States Environmental Protection Agency, Washington, D.C. Ref: EPA-540-R-070-002 OSWER 9285.7-82. January 2009.

US EPA (2011). *Exposure Factors Handbook: 2011 Edition.* United States Environmental Protection Agency, National Center for Environmental Assessment, Office of Research and Development, Washington, D.C. Ref: EPA/600/R-09/052F. September 2011.

US EPA (2012). Vapour Intrusion Database. https://www.epa.gov/vaporintrusion/vapor-intrusion-database Last updated in 2012.

US EPA (2013a). *Evaluation of Empirical Data to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds.* United States Environmental Protection Agency, Office of Underground Storage Tanks, Washington, D.C. Ref: EPA 510-R-13-001. January 2013.

US EPA (2013b). *3-D Modeling Of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration Below the Slab.* United States Environmental Protection Agency, Office of Underground Storage Tanks, Washington, D.C. Ref: EPA 510-R-13-002. June 2013.

US EPA (2014). *Vapor Intrusion Screening Level (VISL) Calculator User's Guide.* United States Environmental Protection Agency, Office of Solid Waste and Emergency Response, Office of Superfund Remediation and Technology Innovation, Washington, D.C. May 2014.

US EPA (2015a). *OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air.* United States Environmental Protection Agency, Office of Solid Waste and Emergency Response. Publication 9200.2-154. June 2015.

US EPA (2015b). *Technical Guide For Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites.* United States Environmental Protection Agency, Office of Underground Storage Tanks, Washington, D.C. Ref: EPA 510-R-15-001. June 2015.

US EPA (2016). *Petroleum Vapor Intrusion Modeling Assessment with PVIScreen.* United States Environmental Protection Agency, Office of Underground Storage Tanks, Washington, D.C. Ref: EPA/600/R-16/175. August 2016.

US EPA (2018). *Update for Chapter 19 of the Exposure Factors Handbook: Building Characteristics.* United States Environmental Protection Agency, National Center for Environmental Assessment, Office of Research and Development, Washington, D.C. Ref: 20460EPA/600/R-18/121F. July 2018.

US EPA (2021a). *Regional Screening Levels User's Guide website.* Currently available online at: https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide

US EPA (2021b). *Vapour Intrusion Screening Level Calculator.* Currently available online at: https://www.epa.gov/vaporintrusion/vapor-intrusion-screening-level-calculator

US EPA (2021c). *Vapour Intrusion website.* Currently available online at: https://www.epa.gov/vaporintrusion

Weaver, J. (2013). *PVIScreen.* 24th National Tanks Conference and Expo, Denver Sheraton Downtown Hotel, 16-18 September 2013.

Yao, Y., Shen, R., Pennell, K.G., and Suuberg, E.M. (2013). Examination of the U.S. EPA's Vapor Intrusion Database Based on Models. *Environmental Science & Technology* **2013**, *47(3)*: 1425-1433. Feb 5, 2013.

Yao Y., Verginelli, I., and Suuberg, E.M. (2016a). A two-dimensional analytical model of petroleum vapor intrusion. *Water Resour Res.* 2016; 52: 1528–1539.

Yao, Y., Wang, Y., Verginelli, I., Suuberg, E. M., and Ye, J. (2016b). Comparison between PVI2D and Abreu–Johnson's Model for Petroleum Vapor Intrusion Assessment. *Vadose Zone J.* 2016; 15(11).

Yao, Y., Verginelli, I., and Suuberg, E. M. (2017). A two-dimensional analytical model of vapor intrusion involving vertical heterogeneity. *Water Resour. Res*., 53, 4499–4513. 22 May 2017.

Appendix A: Vapour Intrusion Screening Level Tables

Table A1. Input Parameters for VISL Calculation (adapted from DEA, 2010 ; US EPA, 2021c)

Parameter	Symbol	Unit	Adopted Value	Comment
Screening level (cancer)	C_c	µg/m³	NA	Chemical specific value calculated using screening level equation
Screening level (non-cancer)	C_{nc}	µg/m³	NA	Chemical specific value calculated using screening level equation
Target cancer risk	TCR	none	0.00001	Set to equal target cancer risk adopted by South African guidelines, i.e. 1E-05
Target hazard quotient	THQ	none	1	Default target hazard quotient adopted by South African guidelines
Averaging time (cancer)	AT_c	years	70	Set to equal lifetime of exposure
Averaging time (non-cancer)	AT_{nc}	years	30	Set to equal exposure duration
Exposure duration	ED	years	30	Value adopted by South African guidance for standard adult resident
Exposure duration (child 0 – 2 years)	$ED_{(0\text{-}2)}$	years	2	Default value for 0 – 2 year age child resident (US EPA)
Exposure duration (child 2 – 6 years)	$ED_{(2\text{-}6)}$	years	4	Default value for 2 – 6 year age child resident (US EPA)
Exposure duration (child 6 – 16 years)	$ED_{(6\text{-}16)}$	years	10	Default value for 6 – 16 year age child resident (US EPA)
Exposure duration (child 16 – 26 years)	$ED_{(16\text{-}26)}$	years	10	Default value for 16 – 26 year age child resident (US EPA)
Exposure frequency (residential)	EF	days/year	350	Value adopted by South African guidance for standard adult resident
Exposure frequency (industrial)	EF	days/year	250	Value adopted by South African guidance for standard worker
Exposure time (residential)	ET	hours/day	24	Default value for standard resident (US EPA)
Exposure time (industrial)	ET	hours/day	8	Default value for standard worker (US EPA)
Cancer Adjustment Factor Inhalation	CAF_i	unitless	0.756	Default value for child resident (US EPA)
Mutagenic Adjustment Factor Inhalation	MAF_i	unitless	0.244	Default value for child resident (US EPA)
Component of TCE equation	EA	NA	0.78	Calculated value using: ED x EF x ET x IUR x CAF_i (US EPA)
Component of TCE equation	EC_2	NA	0.017	Calculated value using: ED x EF x ET x IUR x MAF_i x 10 (US EPA)
Component of TCE equation	EC_6	NA	0.034	Calculated value using: ED x EF x ET x IUR x MAF_i x 3 (US EPA)

Parameter	Symbol	Unit	Adopted Value	Comment
Component of TCE equation	EC_{16}	NA	0.084	Calculated value using: ED x EF x ET x IUR x MAF_i x 3 (US EPA)
Component of TCE equation	EC_{26}	NA	0.084	Calculated value using: ED x EF x ET x IUR x MAF_i x 1 (US EPA)
Reference concentration	RfC	µg/m³	NA	Chemical specific
Inhalation unit risk	IUR	$(\mu g/m^3)^{-1}$	NA	Chemical specific

Table A2. Toxicological Reference Values used for Deriving VISLs (after US EPA, 2021a; MDEQ, 2015a-d)

Compound	RfD (mg/kg-day)	RfC (mg/m^3)	SF $(mg/kg\text{-}day)^{-1}$	IUR $(ug/m^3)^{-1}$
tert-Amyl methyl ether	0.13	0.062 [A]	-	-
Benzene	0.004	0.03	0.055	7.80E-06
Bromobenzene	0.008	0.06	-	-
Bromochloromethane	-	0.04	-	-
Bromodichloromethane	0.02	0.07*	0.062	3.70E-05
Bromoform	0.02	0.07*	0.0079	1.10E-06
Bromomethane	0.0014	0.005	-	-
tert-Butyl alcohol	0.18	0.072 [B]		
n-Butylbenzene	0.05	0.175*	-	-
sec-Butylbenzene	0.1	0.35*	-	-
tert-Butylbenzene	0.1	0.35*	-	-
Carbon disulphide	0.1	0.7	-	-
Carbon tetrachloride	0.004	0.1	0.07	6.00E-06
Chlorobenzene	0.02	0.05	-	-
Chloroform	0.01	0.098	0.031	2.30E-05
Chloromethane	-	0.09	-	-
2-Chlorotoluene	0.02	0.07*	-	-
4-Chlorotoluene	0.02	0.07*	-	-
Dibromochloromethane	0.02	0.07*	0.084	2.40E-05*
1,2-Dibromo-3-chloropropane	0.0002	0.0002	0.8	6.00E-03
1,2-Dibromoethane	0.009	0.009	2	6.00E-04
Dibromomethane	-	0.004	-	-
1,2-Dichlorobenzene	0.09	0.2	-	-
1,4-Dichlorobenzene	0.070	0.80	0.0054	1.10E-05
Dichlorodifluoromethane	0.2	0.1	-	-
1,1-Dichloroethane	0.2	0.7*	0.0057	1.60E-06
1,2-Dichloroethane	0.006	0.007	0.091	2.60E-05
1,1-Dichloroethene	0.05	0.2	-	-
cis-1,2-Dichloroethene	0.002	0.007*	-	-
trans-1,2-Dichloroethene	0.02	0.04	-	-
Dichloromethane	0.006	0.6	0.002	1.00E-08
1,2-Dichloropropane	0.04	0.004	0.037	3.70E-06
1,3-Dichloropropane	0.02	0.07*	-	-
1,3-Dichloropropene	0.03	0.02	0.1	4.00E-06
Diisopropyl ether	0.27	0.7 [C]	-	-

Compound	RfD (mg/kg-day)	RfC (mg/m^3)	SF $(mg/kg\text{-}day)^{-1}$	IUR $(ug/m^3)^{-1}$
Ethylbenzene	0.1	1	0.011	2.50E-06
Ethyl-tert-butyl ether	0.092	0.006 [D]	-	-
Hexachlorobutadiene	0.001	0.0035*	0.078	2.20E-05
Methyl tert-butyl ether	-	3.0	0.0018	2.60E-07
Naphthalene	0.02	0.003	0.12	3.40E-05
n-Propylbenzene	0.1	1	-	-
Styrene	0.2	1	-	-
1,1,1,2-Tetrachloroethane	0.03	0.11*	0.026	7.40E-06
1,1,2,2-Tetrachloroethane	0.02	0.07*	0.2	5.80E-05
Tetrachloroethene	0.006	0.04	0.0021	2.60E-07
Toluene	0.08	5	-	-
1,2,3-Trichlorobenzene	0.0008	0.0028*	-	-
1,2,4-Trichlorobenzene	0.01	0.002	0.029	8.29E-06*
1,1,1-Trichloroethane	2	5	-	-
1,1,2-Trichloroethane	0.004	0.0002	0.057	1.60E-05
Trichloroethene	0.0005	0.002	0.046	4.10E-06
Trichlorofluoromethane	0.3	1.05*	-	-
1,2,3-Trichloropropane	0.004	0.0003	30	8.57E-03*
1,2,4-Trimethylbenzene	0.01	0.06	-	-
1,3,5-Trimethylbenzene	0.01	0.06	-	-
Vinyl chloride	0.003	0.1	0.72	4.40E-06
o-Xylene	0.2	0.1	-	-
m,p Xylenes	0.2	0.1	-	-

Notes:

All values taken from the US EPA (current as of Nov 2020), apart from compounds listed below:

[A] Chemical Update Worksheet: t-Amyl methyl ether (MDEQ, 2015a)

[B] Chemical Update Worksheet: t-Butyl alcohol (MDEQ, 2015b)

[C] Chemical Update Worksheet: Diisopropyl ether (MDEQ, 2015c)

[D] Chemical Update Worksheet: Ethyl-tert-butyl ether (MDEQ, 2015d)

* Route to route extrapolation method used to derive RfCs and IURs from RfDs and SFs, respectively

Table A3. Vapour Intrusion Screening Levels for the Residential Scenario

Compound	Carcinogenic SL (TR = 1E-05) C_c (µg/m³)	Non-carcinogenic SL (THQ = 1) C_{nc} (µg/m³)	Adopted Indoor Air Screening Level (µg/m³)	Adopted Sub-slab Screening Level (µg/m³)
tert-Amyl methyl ether	Not carcinogenic	64.6	64.6	21 552
Benzene	3.12	31.3	3.12	1 040
Bromobenzene	Not carcinogenic	62.6	62.6	20 857
Bromochloromethane	Not carcinogenic	41.7	41.7	13 905
Bromodichloromethane	0.66	73.0	0.66	219
Bromoform	22.12	73.00	22.1	7 374
Bromomethane	Not carcinogenic	5.21	5.21	1 738
tert-Butyl alcohol	Not carcinogenic	75.1	75.1	25 029
n-Butylbenzene	Not carcinogenic	183	183	60 833
sec-Butylbenzene	Not carcinogenic	365	365	121 667
tert-Butylbenzene	Not carcinogenic	365	365	121 667
Carbon disulphide	Not carcinogenic	730	730	243 333
Carbon tetrachloride	4.06	104	4.06	1 352
Chlorobenzene	Not carcinogenic	52.1	52.1	17 381
Chloroform	1.06	102	1.06	353
Chloromethane	Not carcinogenic	93.9	93.9	31 286
2-Chlorotoluene	Not carcinogenic	73.0	73.0	24 333
4-Chlorotoluene	Not carcinogenic	73.0	73.0	24 333
Dibromochloromethane	1.014	73.0	1.014	338
1,2-Dibromo-3-chloropropane	0.0041	0.21	0.0041	1.35
1,2-Dibromoethane	0.041	9.4	0.041	13.5
Dibromomethane	Not carcinogenic	4.17	4.17	1 390
1,2-Dichlorobenzene	Not carcinogenic	209	209	69 524
1,4-Dichlorobenzene	2.21	834	2.21	737
Dichlorodifluoromethane	Not carcinogenic	104	104	34 762
1,1-Dichloroethane	15.2	730	15.2	5 069
1,2-Dichloroethane	0.94	7.30	0.94	312
1,1-Dichloroethene	Not carcinogenic	209	209	69 524
cis-1,2-Dichloroethene	Not carcinogenic	7.30	7.30	2 433
trans-1,2-Dichloroethene	Not carcinogenic	41.7	41.7	13 905
Dichloromethane	2 433	626	626	208 571
1,2-Dichloropropane	6.58	4.17	4.17	1 390
1,3-Dichloropropane	Not carcinogenic	73	73.00	24 333
1,3-Dichloropropene	6.08	20.9	6.08	2 028
Diisopropyl ether	Not carcinogenic	730	730	243 333
Ethylbenzene	9.73	1 043	9.73	3 244
Ethyl-tert-butyl ether	Not carcinogenic	6.26	6.26	2 086

Compound	Carcinogenic SL (TR = 1E-05) C_c (µg/m³)	Non-carcinogenic SL (THQ = 1) C_{nc} (µg/m³)	Adopted Indoor Air Screening Level (µg/m³)	Adopted Sub-slab Screening Level (µg/m³)
Hexachlorobutadiene	1.11	3.65	1.11	369
Methyl tert-butyl ether	93.6	3 129	93.6	31 197
Naphthalene	0.72	3.13	0.72	239
n-Propylbenzene	Not carcinogenic	1 043	1 043	347 619
Styrene	Not carcinogenic	1 043	1 043	347 619
1,1,1,2-Tetrachloroethane	3.29	110	3.29	1 096
1,1,2,2-Tetrachloroethane	0.42	73.0	0.42	140
Tetrachloroethene	93.6	41.7	41.7	13 905
Toluene	Not carcinogenic	5 214	5 214	1 738 095
1,2,3-Trichlorobenzene	Not carcinogenic	2.92	2.92	973
1,2,4-Trichlorobenzene	2.94	2.09	2.09	695
1,1,1-Trichloroethane	Not carcinogenic	5 214	5 214	1 738 095
1,1,2-Trichloroethane	1.52	0.21	0.21	69.5
Trichloroethene	6.13	2.09	2.09	695
Trichlorofluoromethane	Not carcinogenic	1 095	1 095	365 000
1,2,3-Trichloropropane	0.0028	0.313	0.0028	0.95
1,2,4-Trimethylbenzene	Not carcinogenic	62.6	62.6	20 857
1,3,5-Trimethylbenzene	Not carcinogenic	62.6	62.6	20 857
Vinyl chloride	1.61	104	1.61	537
o-Xylene	Not carcinogenic	104	104	34 762
m,p Xylenes	Not carcinogenic	104	104	34 762

Table A4. Vapour Intrusion Screening Levels for the Commercial/Industrial Scenario

Compound	Carcinogenic SL (TR = 1E-05) C_c (µg/m³)	Non-carcinogenic SL (THQ = 1) C_{nc} (µg/m³)	Adopted Indoor Air Screening Level (µg/m³)	Adopted Sub-slab Screening Level (µg/m³)
tert-Amyl methyl ether	Not carcinogenic	272	272	90 520
Benzene	13.1	131	13.1	4 368
Bromobenzene	Not carcinogenic	263	263	87 600
Bromochloromethane	Not carcinogenic	175	175	58 400
Bromodichloromethane	2.76	307	2.76	921
Bromoform	92.9	307	92.9	30 970
Bromomethane	Not carcinogenic	21.9	21.9	7 300
tert-Butyl alcohol	Not carcinogenic	315	315	105 120
n-Butylbenzene	Not carcinogenic	767	767	255 500
sec-Butylbenzene	Not carcinogenic	1 533	1 533	511 000
tert-Butylbenzene	Not carcinogenic	1 533	1 533	511 000
Carbon disulphide	Not carcinogenic	3 066	3 066	1 022 000
Carbon tetrachloride	17.0	438	17.0	5 678
Chlorobenzene	Not carcinogenic	219	219	73 000
Chloroform	4.44	429	4.44	1 481
Chloromethane	Not carcinogenic	394	394	131 400
2-Chlorotoluene	Not carcinogenic	307	307	102 200
4-Chlorotoluene	Not carcinogenic	307	307	102 200
Dibromochloromethane	4.26	307	4.26	1 419
1,2-Dibromo-3-chloropropane	0.017	0.88	0.017	5.68
1,2-Dibromoethane	0.17	39.4	0.17	56.8
Dibromomethane	Not carcinogenic	17.5	17.5	5 840
1,2-Dichlorobenzene	Not carcinogenic	876	876	292 000
1,4-Dichlorobenzene	9.29	3 504	9.29	3 097
Dichlorodifluoromethane	Not carcinogenic	438	438	146 000
1,1-Dichloroethane	63.9	3 066	63.9	21 292
1,2-Dichloroethane	3.93	30.7	3.93	1 310
1,1-Dichloroethene	Not carcinogenic	876	876	292 000
cis-1,2-Dichloroethene	Not carcinogenic	30.7	30.7	10 220
trans-1,2-Dichloroethene	Not carcinogenic	175	175	58 400
Dichloromethane	10 220	2 628	2 628	876 000
1,2-Dichloropropane	27.6	17.5	17.5	5 840
1,3-Dichloropropane	Not carcinogenic	307	307	102 200
1,3-Dichloropropene	25.6	87.6	25.6	8 517
Diisopropyl ether	Not carcinogenic	3 066	3 066	1 022 000
Ethylbenzene	40.9	4 380	40.9	13 627
Ethyl-tert-butyl ether	Not carcinogenic	26.3	26.3	8 760

Compound	Carcinogenic SL (TR = 1E-05) C_c (µg/m³)	Non-carcinogenic SL (THQ = 1) C_{nc} (µg/m³)	Adopted Indoor Air Screening Level (µg/m³)	Adopted Sub-slab Screening Level (µg/m³)
Hexachlorobutadiene	4.65	15.3	4.65	1 548
Methyl tert-butyl ether	393	13 140	393	131 026
Naphthalene	3.01	13.1	3.01	1 002
n-Propylbenzene	Not carcinogenic	4 380	4 380	1 460 000
Styrene	Not carcinogenic	4 380	4 380	1 460 000
1,1,1,2-Tetrachloroethane	13.8	460	13.8	4 604
1,1,2,2-Tetrachloroethane	1.76	307	1.76	587
Tetrachloroethene	393.08	175	175	58 400
Toluene	Not carcinogenic	21 900	21 900	7 300 000
1,2,3-Trichlorobenzene	Not carcinogenic	12.3	12.3	4 088
1,2,4-Trichlorobenzene	12.3	8.76	8.76	2 920
1,1,1-Trichloroethane	Not carcinogenic	21 900	21 900	7 300 000
1,1,2-Trichloroethane	6.39	0.88	0.88	292
Trichloroethene	24.9	8.76	8.76	2 920
Trichlorofluoromethane	Not carcinogenic	4 599	4 599	1 533 000
1,2,3-Trichloropropane	0.012	1.31	0.012	3.97
1,2,4-Trimethylbenzene	Not carcinogenic	263	263	87 600
1,3,5-Trimethylbenzene	Not carcinogenic	263	263	87 600
Vinyl chloride	23.2	438	23.2	7 742
o-Xylene	Not carcinogenic	438	438	146 000
m,p Xylenes	Not carcinogenic	438	438	146 000