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no. 23
technical
report

**Petroleum hydrocarbon vapour intrusion assessment:
Australian guidance**



CRC for Contamination Assessment and Remediation of the Environment

Technical Report no. 23

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Australian guidance**

July 2013



Cooperative Research Centre for Contamination Assessment and Remediation of the Environment, Technical Report series, no. 23

July 2013

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ISBN: 978-1-921431-35-7

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This report should be cited as:

CRC CARE 2013, *Petroleum hydrocarbon vapour intrusion assessment: Australian guidance*, CRC CARE Technical Report no. 23, CRC for Contamination Assessment and Remediation of the Environment, Adelaide, Australia.

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Acknowledgement:

CRC CARE acknowledges the contribution made by Jackie Wright and Therese Manning of Environmental Risk Sciences, and Blayne Hartman of Hartman Environmental Geoscience, USA, towards the writing and compilation of this report.

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Abbreviations

$\mu\text{g}/\text{m}^3$	Micrograms per cubic meter
bgl	Below ground level
bgs	Below ground surface
BTEX	Benzene, toluene, ethylbenzene and total xylenes
CO_2	Carbon dioxide
CSM	Conceptual site model
DQO	Data quality objectives
GC/FID	Gas chromatography / flame ionisation detector
GC/MS	Gas chromatography / mass spectroscopy
GC/TCD	Gas chromatography / thermal conductivity detector
HDPE	High density polyethylene
HI	Hazard index
HSL	Health Screening Levels
ID	Inner diameter
LDPE	Low density polyethylene
LEL	Lower explosive limit
LFG	Landfill gas
LNAPL	Light non-aqueous phase liquid
m	Metre
mg/kg	Milligrams per kilogram
mg/L	Milligrams per litre
mg/m^3	Milligrams per cubic meter
MOS	Margin of safety
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
O_2	Oxygen
OD	Outer diameter
PHC	Petroleum hydrocarbon
PID	Photo-ionisation detector
ppb	Parts per billion
ppm	Parts per million
PVI	Petroleum vapour intrusion
QA/QC	Quality assurance/quality control
SVOC	Semi-volatile organic compounds
TCE	Trichloroethene
TO	Toxic organics
TPH	Total petroleum hydrocarbons
TPHCWG	Total Petroleum Hydrocarbons Criteria Working Group

TRH	Total recoverable hydrocarbons
USA	United States of America
UST	Underground storage tank
VI	Vapour intrusion
VOC	Volatile organic compounds

Executive summary

This document provides a clear decision framework for the conduct of petroleum vapour intrusion assessments resulting from contamination of soil and groundwater by petroleum hydrocarbons.

Drawing on the best available guidance and science relating to the current understanding of petroleum vapour intrusion from Australia and other jurisdictions, this document outlines approaches that should be considered in the assessment of acute and chronic risks. These approaches may be on the basis of either an initial screening or a more detailed assessment as appropriate.

This decision framework incorporates flow diagrams and “decision boxes”, with additional detail provided in appendices. It is expected that this decision framework will assist the user in making appropriate and sound decisions in the assessment of petroleum vapour intrusion, including the collection and evaluation of vapour data.

The potential for petroleum vapour intrusion may vary considerably with different situations, as petroleum hydrocarbons readily biodegrade in the subsurface when sufficient oxygen is available, and this guidance provides the means to take such variability into account.

While several aspects of this guidance are general and can be applied to a range of volatile compounds, the guidance is intended to specifically address petroleum vapour intrusion, and should not be applied to sites contaminated with other compounds not sourced from petroleum, such as chlorinated hydrocarbons and landfill gas.

While the decision framework and the methods and approaches listed or presented in the guidance are specifically oriented towards assessment of petroleum vapours, this does not mean that methods and approaches not presented in the guidance cannot be utilised. Rather, other approaches can be used, where relevant, and adequately justified and agreed with regulators, auditors or third party reviewers prior to use.

By following the guidelines outlined in this document, the assessment of petroleum vapour intrusion will be adequately robust and will meet regulatory (and auditor/third party reviewer) requirements for the completion of such assessments.

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1. Introduction

1.1 Scope of Guidance

This document provides a clear decision framework for the conduct of petroleum vapour intrusion (PVI) assessments. In relation to the assessment of vapour risk, petroleum hydrocarbons and chlorinated hydrocarbons differ in their potential for vapour intrusion (VI) risks, primarily because petroleum hydrocarbons (PHCs) readily biodegrade in the subsurface when sufficient oxygen is available (USEPA 2011, 2012a). Hence while a number of aspects of this guidance are general and can be applied to a range of volatile compounds, the guidance is intended to specifically address PVI and should not be applied to sites contaminated with other compounds including chlorinated hydrocarbons and landfill gas.

Where mixed contaminant sites are being evaluated (e.g. petrol station and dry cleaner) this guidance can be used for just the assessment of the petroleum hydrocarbon component of the overall risk. Additional consideration of risks posed by the other contamination may be required including additional sampling and analysis (outside the scope of this guidance). This document only describes the process for assessing the risks posed by the petroleum hydrocarbons. At sites with mixed contamination it will still be important to assess the total risk for all the relevant contaminants in-line with normal regulatory guidance so following this guidance will potentially not be sufficient for assessing risks posed by all the contamination at the site.

This guidance does not apply to fresh spills of petroleum products. Such scenarios need to be addressed on a site-specific basis (including the use of an immediate qualitative evaluation) ensuring that all imminent and/or acute hazards/risks are adequately and appropriately assessed and mitigated.

In addition, while the procedures outlined in this guidance are relevant to the assessment of PVI risks on an active service station site, applying them to such sites can require a more sophisticated assessment and, in many cases, such an assessment may not be needed. At active service stations vapour exposures derived from subsurface sources are often relatively insignificant when compared to those derived from emissions associated with the operation and maintenance of the service station. The collection of meaningful (in relation to exposure) soil gas and indoor air data is highly questionable on these sites. While the assessment of on-site PVI risks may not be required, it is important to note that data may be collected from the boundary of an active service station site to address off-site PVI risks (where the application of this guidance is relevant).

The information in this guidance is also relevant for use when validating sites after remediation. No detailed guidance about when to undertake such validation is included in this document as it is regulated by each jurisdiction.

This document draws on the best available guidance/science from Australia and other jurisdictions (as summarised in **Appendix A**) that relates to the current understanding of PVI.

The guidelines presented in this document are intended to be concise and prescriptive for the circumstances described herein. This does not mean that methods/approaches

not specifically listed/presented in the guidance cannot be utilised. Rather these other approaches can be used where relevant and adequately justified and agreed with regulators, auditors or third party reviewers prior to use.

This guidance document has been developed to specifically address vapour migration and intrusion risk associated with petroleum hydrocarbon contamination.

As such the guidance does not consider other exposure pathways that may be relevant at a site, or aesthetic issues (such as odours). These must be assessed where relevant and should be considered separately on a site-specific basis.

For other issues relevant to site characterisation, including the characterisation and remediation of LNAPL and dissolved phase contamination refer to other CRC CARE technical reports (http://www.crccare.com/publications/technical_reports/index.html).

1.2 Approach

This guidance has been prepared to provide a decision framework where flow diagrams, with reference to decision boxes and appendices (where additional detail is presented), have been provided to assist the user in making appropriate and sound decisions about the PVI assessment, including the collection and evaluation of vapour data. It is intended that by following these flow diagrams (and associated boxes and appendices) the assessment of PVI will be adequately robust and will meet regulatory (and auditor/third party reviewer) requirements for the completion of such assessments.

Data Quality Objectives (DQO) establish arguments for collection of data, and can guide investigations and planning of individual tasks that make up various phases of site assessments. DQOs appear in a number of guidelines (AS 4482.1-2005; USEPA 2006) and the underlying concepts of the DQO approach have been incorporated into the approach to PVI assessments presented in this document.

1.3 Description of PVI pathway

The migration of petroleum hydrocarbon vapours from a source to a building is governed by the processes of diffusion (i.e. flow from higher concentrations to lower concentrations) and advection (i.e. pressure-driven flow at shallow soil depths). In addition, for petroleum hydrocarbons there is the potential for significant additional attenuation due to aerobic biodegradation (Davis, Patterson & Trefry 2009; USEPA 2011, 2012a). Aerobic biodegradation has the potential to reduce (or attenuate) vapour concentrations by several orders of magnitude over distances as short as a few meters or less (USEPA 2012a), and often at very high rates (Davis, Patterson & Trefry 2009).

Aerobic biodegradation occurs where natural microbial biota consume oxygen as they use petroleum hydrocarbons as food breaking them down into non-toxic degradation products like carbon dioxide and water. Because soil microbes consume oxygen to degrade petroleum hydrocarbons, oxygen may become depleted where contaminant concentrations are elevated, such as within or close to an LNAPL plume. An aerobic biodegradation zone is generally present around the perimeter of a petroleum hydrocarbon plume, where oxygen transport from the atmosphere or oxygenated groundwater can replenish oxygen consumed by degradation in this zone. As with the migration of vapours from a source zone, atmospheric oxygen migrates into the

subsurface from the atmosphere through processes of gaseous diffusion and advection (i.e. pressure driven vapour migration), and dissolved in infiltrating rainwater. These processes are generally illustrated in **Figure 1**.

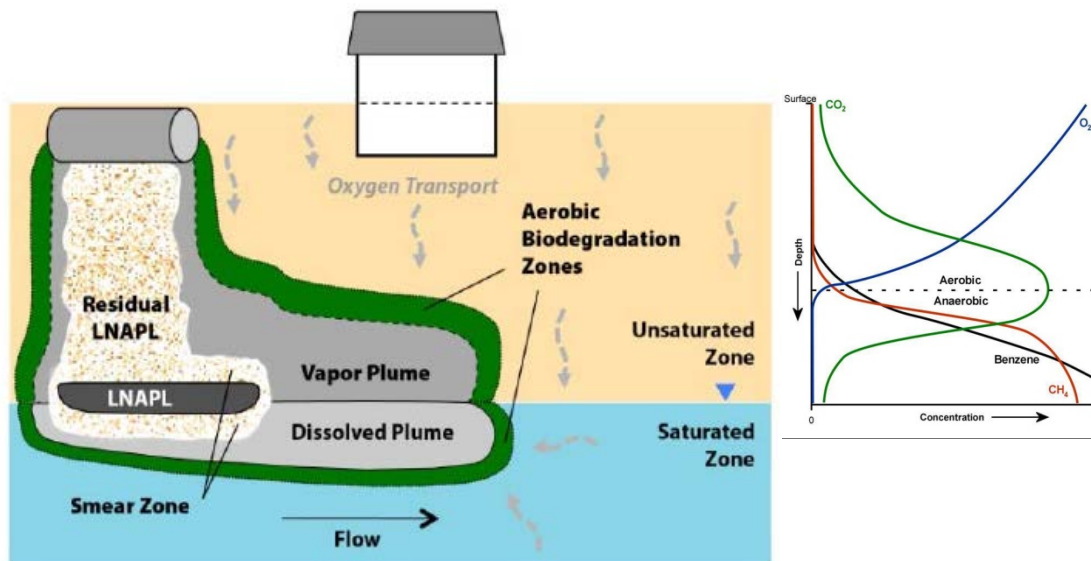


Figure 1 Typical Petroleum Hydrocarbon Vapour Transport Scenario and Vertical Concentration Profile in Unsaturated Zone (USEPA 2011)

Some petroleum hydrocarbons may also degrade anaerobically, which is a slower process and may produce methane (particularly if the source is from an ethanol-blended fuel) (Ma et al. 2012). Anaerobic biodegradation is typically the predominant mechanism within the source zone. While the production of methane is of potential importance in relation to explosive hazards in confined spaces (and such issues should be considered in a PVI assessment), methane also biodegrades under aerobic conditions (in the same way other PHCs biodegrade).

Petroleum hydrocarbon plumes in the saturated (groundwater) and unsaturated (vadose) zones can reach a relatively stable condition, with oxygen replenished and contaminants biodegraded at the same rate chemicals are released from a source through dissolution and volatilisation (USEPA 2011). Hence the migration of petroleum hydrocarbon vapours is significantly influenced by the availability of oxygen in the soil profile.

There are a number of factors that have the potential to affect the level of oxygen in the subsurface such as low permeability zones or the presence of large impermeable surfaces (Davis 2013; Davis, Patterson & Trefry 2009) that require further consideration when conducting PVI assessments. The presence of high levels of natural organic material may also limit the availability of oxygen for degradation of petroleum hydrocarbons because whatever oxygen moves into the unsaturated zone is used up in the degradation of those natural organic compounds. When conducting PVI assessments, the potential for aerobic biodegradation is an important aspect of the assessment and has been included in the guidance provided in this document.

Odour is an important aspect that should be addressed in any assessment. Petroleum hydrocarbons are often odorous at lower levels than those that pose a health risk. It is possible that soils that meet the adopted screening criteria may be odorous. It is also

likely odours will be released during excavations at sites that have petroleum contamination even if the soils have been found to not pose an unacceptable risk.

2. Development of a Conceptual Site Model

2.1 Purpose

The development and continual refinement of a conceptual site model (CSM) that is relevant to the assessment of PVI risk at the site being investigated is necessary to enable and support decisions that are made in relation to the assessment of PVI risk. A CSM is a site-specific description of the exposure pathway elements, namely how the contamination present at the site can reach people living, working or recreating at the site. The CSM describes the source(s) of contamination, the pathway(s) by which contaminants may migrate through the various environmental media, and the populations (human or ecological) that may potentially be exposed.

The development of a CSM for a PVI assessment requires a good understanding of:

- Source (where did the contamination come from – leaking UST, leaking infrastructure, spill)
- Nature and extent of contamination
- Geology and hydrogeology at the site (including topography and drainage)
- Receptors – people who may be affected by the contamination
- Preferential pathways that may exist
- Building/structures existing/proposed

Developing a CSM does assume that the information available is of an appropriate quality and that the investigations undertaken to date are appropriate for the situation. Guidance is available, and should be consulted (Clements, Palaia & Davis 2009) to further assist in the characterisation of sites impacted by petroleum hydrocarbons to ensure that appropriate data is available for consideration in the PVI assessment.

2.2 CSM requirements

Table 1 presents a summary of the minimum requirements a vapour CSM must provide relevant to each of the different stages of the PVI assessment presented in this report.

It is expected that the CSM prepared for the conduct of the PVI assessment:

- Is presented in a simple manner using figures/diagrams and text;
- Include a plan view and cross section of the site; and
- Is reviewed and updated throughout the site assessment and PVI assessment stages based on any new data or information that may be obtained from the site.

Table 1 Minimum requirements for CSMs for PVI assessments

Aspect of CSM	Requirement for Stage of PVI Assessment			
	Preliminary Evaluation (Section 3)	Screening Level Assessment (Section 4)		Detailed Assessment (Section 5)
		Application of HSLs	Application of Screening Distances	
Source characterisation (see Box 2.1, 2.2 and 2.3)				
Origin of primary source (i.e. the likely petroleum product(s))	y	y	-	y
Age of primary source (recent [<2 years] or older)	p	p	p	y
Location of primary source	p	c	y	y
Mass of contamination	-	-	-	p
Remediation of source (i.e. what activities have been undertaken to remediate the source, and how successful have these been) – indicative is sufficient but as much information as is available	p	p	p	y
Nature and extent of contamination (see Boxes 2.1 to 2.5)				
LNAPL	y	y	y	y
lateral extent and mobility	y	y	y	y
depth to LNAPL (including smear zones)	y	y	y	y
vertical extent	p	p	p	p
characterisation of product (e.g. age, type, additives if known)	p	p	p	y
Dissolved phase	y	y	y	y
lateral extent and mobility	c	c	c	y
Soil Impacts	p	y	y	y
Location of other contamination sources	p	p	p	y
Strength of source (see Box 2.3)				
Sufficient data to determine concentrations	-	c	c	y
Seasonal variability	-	c	c	y
Is overlying soil contaminated?	-	y	y	y
Geology and hydrogeology ¹				
Permeability, hydraulic gradient, porosity	-	p	p	y
Actual depth to groundwater	y	y	y	y
Presence of confining layer	y	y	y	y
Groundwater fluctuations (seasonal and climatic) (see Box 2.6)	-	y	y	y
Direction of groundwater flow	-	c	c	y
Plume stability	-	y,c	y,c	y
Presence of abstraction wells	-	p	p	y
Geology overlying source	-	y		y
Presence of natural preferential vapour pathways	-	c	c	y
Presence of fuel infrastructure (onsite areas)	-	-	y	y
Buildings and receptors (see Box 2.7, 2.8 and 2.9)				
Identify onsite receptors	y	y	y	y
Onsite building types (current and future)	-	y	y	y
Identify offsite receptors	y	y, c	y, c	y
Offsite building types (current and future)	-	y, c	y, c	y
Potential for preferential pathways into buildings	-	c	c	y
Evidence of biodegradation				
Collection of soil gas vapour through soil profile				y, p
Collection of oxygen (and other gases) data through soil profile		x	z	y, p

Notes for Table 1:

- y Information/data required for level of CSM
- p Preferred information/data for level of CSM, however these aspects may not be fully developed and are not critical to the level of PVI assessment undertaken
- c Preferred information/data for level of CSM, however these aspects may not be fully developed and conservative assumptions may be adopted for the purpose of completing preliminary or screening level assessments. **Such conservative assumptions may include (but are not limited to):**
 - Assuming the maximum concentration in groundwater beneath the site is present beneath off-site areas
 - Assuming the extent of groundwater migration extends to adjacent more sensitive receptors
 - Using the maximum concentrations where a limited data set is available
 - Consideration of variability factors of 5 to 10 fold to account for lack of data to characterise seasonal variability (based on IRTC recommendation for USA)
 - Assuming the presence of more permeable soil types that assist in the preferential migration of vapours to the building
 - Assuming the presence of buildings (with basements) on a site where future development plans are not known
- x The HSLs suggest that collecting oxygen does help demonstrate biodegradation but, in reality, to collect appropriate data requires installation of soil vapour wells so in the screening stage of a PVI assessment it is appropriate to adopt the conservative assumption that no degradation is occurring.
- z Screening distances are based on empirical data where biodegradation has been considered and so application of these distances does not require collection of oxygen data
- 1 Appropriate documentation from published sources, including geology sheets and notes, soil landscape sheets and notes, groundwater bore searches and the like can be used in early stages of the development of a CSM while detailed field information can be used in the later stages of an assessment

2.3 Key aspects of CSMs for PVI assessment

The following boxes (as referenced throughout this guidance) provide additional and more specific guidance in relation to the terms used throughout this document and key aspects that need to be considered in the development of the CSM for undertaking PVI assessments. More specifically, as PHCs are readily degraded under aerobic conditions, there are a number of key aspects (presented in **Boxes 2.3 to 2.8**) within the CSM that have the potential to affect the potential for biodegradation to effectively attenuate vapours prior to exposure.

Box 2.1 Definitions

Source

At a site where petroleum hydrocarbons have been used there is the potential for contamination to be present. The term “primary source”, as used in this guidance, refers to the infrastructure such as a UST from which petroleum hydrocarbons have escaped into the environment.

The term “secondary source”, as used in this guidance, refers to contamination that remains in the subsurface as LNAPL (product or free phase), dissolved phase (in groundwater) or sorbed phase (in soil). These sources are often referred to as “contaminated soil”, “contaminated groundwater” or “LNAPL”.

It is from the edge of these secondary sources (e.g. the maximum extent of the dissolved phase plume including smear zones) that the zone of influence and/or vertical screening distance should be measured. The zone of influence may also be referred to as the impacted zone.

Soil with low potential for bioattenuation

The application of a number of aspects of the PVI guidance requires the identification of soil overlying a contaminated area or contaminated plume that has a low or high potential for bioattenuation. The presence of uncontaminated soil provides a bioactive zone that is available for the effective biodegradation (i.e. attenuation) of petroleum hydrocarbons in the subsurface prior to entry into a building. However the presence of contaminated soil (comprising volatile and non-volatile PHC fractions) can limit the biodegradation of vapours from an impacted zone as the bioactive zone is occupied degrading the PHCs from the contaminated soil. Hence where processes of aerobic biodegradation are being relied upon for decisions in relation to PVI potential it is important that the quality of the overlying soil (as defined below) is understood.

Soil that has a low potential for bioattenuation is defined on the basis of the following (any one of these measures is suitable):

- TPH/TRH C6-C16 >100 mg/kg or TPH/TRH >C16-C40 > 200 mg/kg
- Petroleum odours (detectable odours in soil samples)
- PID (associated with PHCs in soil, measured in soil sample head-space) > 100 ppm (refer to **Appendix E** for additional guidance on the use of a PID for PHC evaluations)

In addition to the above, where vapour wells have been properly installed (refer to **Appendix D**), low levels of oxygen at depths appropriate for assessment (i.e. not near surface), <5% in the subsurface soil also indicate conditions where there is a low potential for bioattenuation. Conversely the measurement of oxygen ≥5% can be used to demonstrate the presence of an effective bioactive soil zone (i.e. soil with high potential for bioattenuation).

There are also naturally occurring situations where soil may have a low potential for bioattenuation, such as those with large amounts of organic carbon due to the presence of wetlands or near depositional zones in creeks (alluvial areas or deltas).

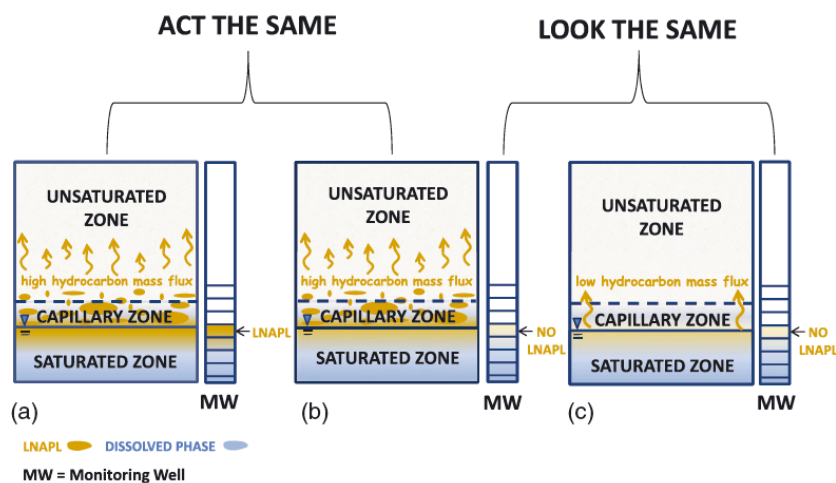
Box 2.1 Definitions

Soil with high potential for bioattenuation

For the purposes of conducting a PVI assessment, soil with a high potential for bioattenuation is soil that does not meet any of the above criteria. These conditions can also be used to identify an area that is already undergoing bioattenuation.

LNAPL

The assessment and evaluation of potential PVI risks require the identification of LNAPL (or product). Most site investigations identify the possible presence of LNAPL only with visual confirmation of LNAPL in monitoring wells. This is not the only or most reliable indicator of the presence of LNAPL. Where PVI risks are being evaluated it is important that other indicators are also considered to ensure that vapours that may be derived from an LNAPL source are adequately identified (refer to illustration in the figure below (Lahvis et al. 2013)).



Indicators of LNAPL presence

The following are indicators of the presence of LNAPL sources (where the presence of any of them in the zone of influence indicates the presence of LNAPL):

Direct Indicators (USEPA 2013):

- Field observations of product in nearby (<6 m) groundwater wells (when taking well measurements). Consideration should also be given to the potential for product migration and past measurements of product prior to changes in water table that may indicate the potential for a smear zone

Indirect Indicators:

- Proximity (<6 m in any direction) to a known product release (or UST/fuel infrastructure) unless evidence exists to justify smaller or larger size;
- Groundwater concentrations that are a significant portion (i.e. >20%) of the effective solubility in the product (Bruce, Miller & Hockman 1991). For common sources this means (Lahvis et al. 2013; USEPA 2013)
 - Benzene > 3 to 5 mg/L
 - BTEX (petrol source) > 20 mg/L
 - TPH/TRH (petrol source, i.e. C6-C14 or TRH C6-C16) > 30 mg/L
 - TPH/TRH (diesel source, C10-C14 or TRH >C10-16) > 5 mg/L
- Field data shows PID > 500 ppm (Alaska DEC 2011; Lahvis et al. 2013) – in bore logs or soil samples (refer to **Appendix E** for additional guidance on the use of a PID for PHC evaluations)
- If soil gas is available, significant concentrations of individual aliphatic hydrocarbons in

Box 2.1 Definitions

soil gas (i.e. hexane, cyclohexane or heptane > 100 mg/m³)

- Where soil gas profile data has been collected, PHC and CO₂ concentrations that show no decrease (or O₂ concentrations that show no increase) or remain relatively constant with distance from the source (Lahvis et al. 2013)

Where any of these indicators exist at a site, it should be assumed that LNAPL is present at the site even if it has not actually been observed in any of the wells at the site.

Dissolved phase

Conditions in groundwater (where there are detections of PHC in groundwater) that do not meet any of the criteria listed above to indicate LNAPL shall be considered as dissolved phase contamination.

TPH/TRH

Total petroleum hydrocarbons (TPH) is a summary term for all the hydrocarbon compounds present due to release of a petroleum product. The analytical method does not identify every individual compound that might be present but bands the compounds into size fractions using a surrogate compound to estimate the concentration of each size fraction. Until recently the commonly used sized fractions were:

- C6-9 aliphatic/aromatic;
- C10-14 aliphatic/aromatic;
- C15-28 aliphatic/aromatic; and
- C29-36 aliphatic/aromatic.

Recently, a review of the terminology (CRC CARE 2009), analytical method components and relevant size fractions was undertaken as part of the development of the HSLs. It was agreed that the terminology would be changed to Total Recoverable Hydrocarbons (TRH) for the normal analysis and the size fractions would change to:

- C6-10 aliphatic/aromatic;
- >C10-16 aliphatic/aromatic;
- >C16-34 aliphatic/aromatic; and
- >C34-40 aliphatic/aromatic.

The use of the silica gel cleanup step was discussed. This step is designed to remove naturally occurring hydrocarbons from a sample. It is based on these compounds being more polar than petroleum hydrocarbons so they can be separated. It gives a better estimate of contamination related hydrocarbons. Using this additional step in the analysis is usually only needed if a sample has detections of TRH but there is no evidence of petroleum hydrocarbon contamination.

Laboratories have begun reporting the results of the normal analysis both ways – as the original TPH and the more recent TRH. Throughout this guidance document TPH/TRH will be used. Unless otherwise noted in this guidance, TPH/TRH refers to the total TPH/TRH concentrations (for the fractions specified) without subtracting benzene, toluene, ethylbenzene and xylenes (BTEX).

Box 2.2 Source type

Petroleum hydrocarbons can be present in soil or they may have moved vertically through the soil into the groundwater, where they may be present as an LNAPL (product), dissolved phase or sorbed phase. The nature of the primary source, namely the type of petroleum products (petrol, diesel, lubricating oils, fuel oil, and aviation fuel) likely to have resulted in contamination on and off the site is important to determine/understand so that the assessment can address the range of volatile chemicals likely to be present.

In relation to secondary sources, the following can be noted:

- Soil contamination may pose a PVI risk on the site but is less likely to be relevant to a risk assessment in off-site areas unless contaminated soil from the site has been moved off-site for some reason prior to the investigation or there are other sources in the area.
- Groundwater contamination may pose a PVI risk both on and off site. Contamination in groundwater can be present as an LNAPL (where non-aqueous phase liquid is present within soil pores at the capillary fringe – effectively floating on the surface of the water table – often termed a smear zone) or as dissolved phase hydrocarbons mixed into the groundwater.
- A smear zone can also be formed if significant changes in the water table occur leaving LNAPL in the soil above the saturated zone.

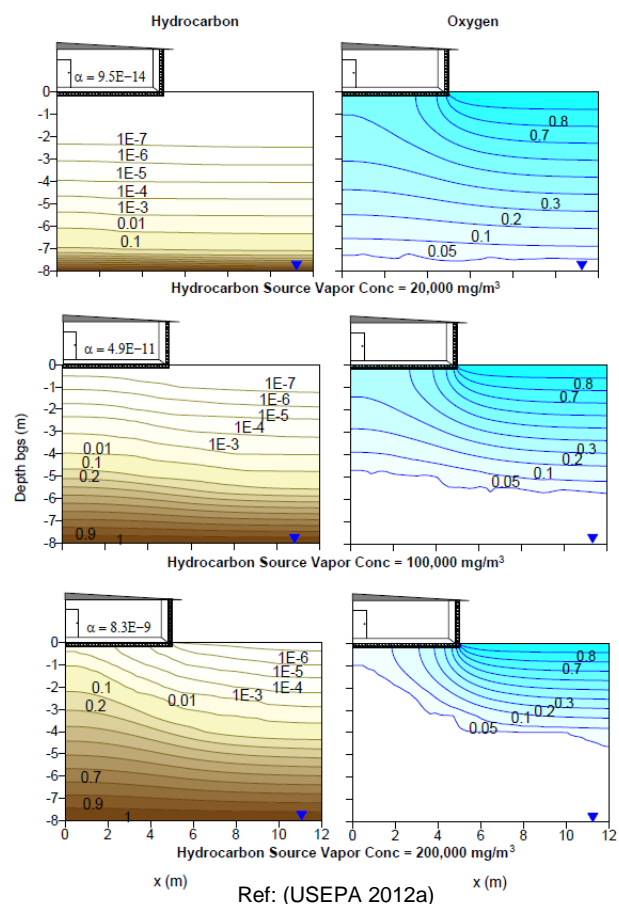
Box 2.3 Strength of contamination

The potential for PVI risks depends on the strength or magnitude of the contamination.

Where the oxygen level is sufficient for biodegradation, oxygen is used as hydrocarbons are broken down. High hydrocarbon source concentrations can lead to a high mass flux of vapours vertically upward through the soil profile. This upward flux of hydrocarbon vapours may deplete the mass flux of oxygen into the soil. This can lead to the depletion of oxygen to create an anaerobic zone where there is limited potential for degradation. In such cases, vapour transport is similar to that for recalcitrant (chlorinated) compounds. The figures show the development of such an anaerobic zone just below the building for sites with high contamination but not for sites with less contamination.

In simple terms, the higher the concentration, the less likely it is that the bacteria will be able to degrade all of the hydrocarbons before the vapour reaches the surface (or receptor).

The location of the highest contamination and the range of concentrations present on and off the site should be identified in the CSM.



Box 2.4 Contamination depth

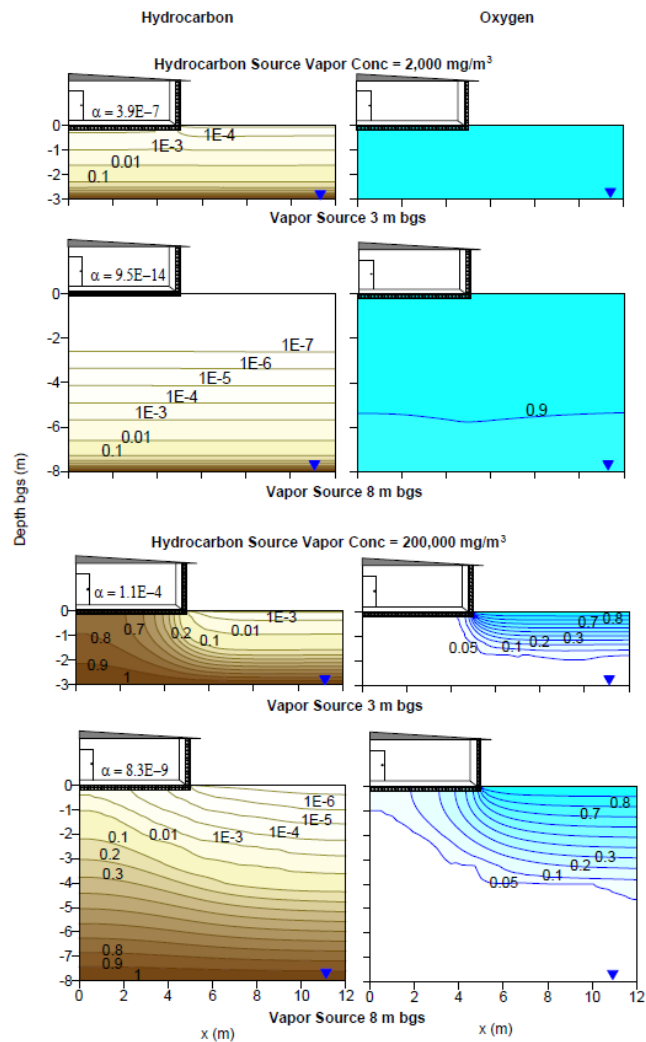
Another important parameter in evaluating PVI risks is the depth to the contamination. Generally, the shallower the contamination, the more likely that PVI may pose a risk.

Biodegradation is likely to be more complete in settings where the separation between the contamination source and the receptor is greater. Having the contamination source at a greater depth for a given source concentration flattens the concentration gradient and reduces the hydrocarbon flux. Additionally, having the source at a greater depth is more likely to allow greater penetration of oxygen into the soil or beneath any building foundations. This is the underlying basis for being able to apply vertical separation criteria to evaluate PVI risks. There may be situations (such as beneath very large buildings) where this straightforward relationship may not apply but commonly it does.

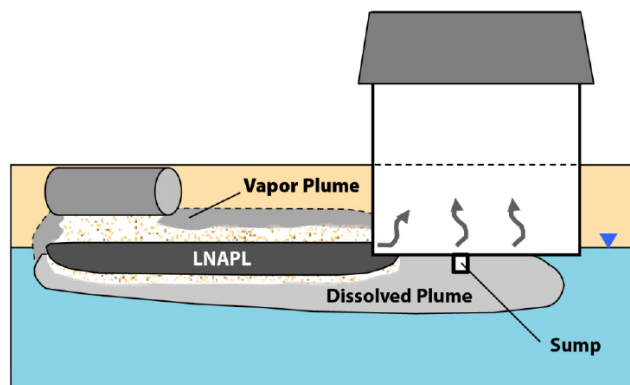
The depth of the secondary source should be identified in the CSM.

Where the secondary contamination source, specifically contaminated groundwater or LNAPL may be in direct contact with building foundations it may lead to seepage of LNAPL or dissolved phase into the building and direct volatilisation within the building. As there is no unsaturated soil zone, aerobic biodegradation of vapours cannot occur. The only degradation of vapours once inside the building is that which occurs in the atmosphere which occurs at a much lower rate.

Therefore any biodegradation factors (such as those outlined in the HSL guidance) do not apply. Such a situation should be made clear in the CSM.



Ref: (USEPA 2012a)



Ref: (USEPA 2011)

Box 2.5 Zone of influence (i.e. what receptors may be affected by the contamination)

The zone of influence is the lateral extent of the contamination defined as LNAPL, sorbed (soil) contamination and dissolved phase. It is within this area where receptors may be affected by PVI.

Identification of the zone of influence requires good site characterisation and delineation (including understanding of stability) of the groundwater plume and LNAPL. The edge of the dissolved phase plume is defined as the locations where dissolved concentrations are not detected (or similarly justified). In addition:

- the extent (size and location) of any LNAPL needs to be identified; and
- the extent (size and location) of soil contamination needs to be identified.

Once the area affected by contamination is clearly defined then the receptors that may be affected by the contamination can be identified.

Current evidence indicates that petroleum hydrocarbon vapours do not migrate more than one to two metres laterally from the edge of a dissolved phase plume, unless there are preferential pathways (refer to **Appendix B**). As long as the extent of the contamination is known with appropriate certainty (i.e. there is a high level of confidence) there is no requirement to evaluate any additional distance beyond the extent of the contamination. The extent of the contamination is then used to define the zone over which the assessment needs to address PVI risks.

In the situation where the groundwater plume is not stable, it is important that the definition of the zone of influence consider future migration, and/or conservative assumptions in relation to the receptors that may be affected.

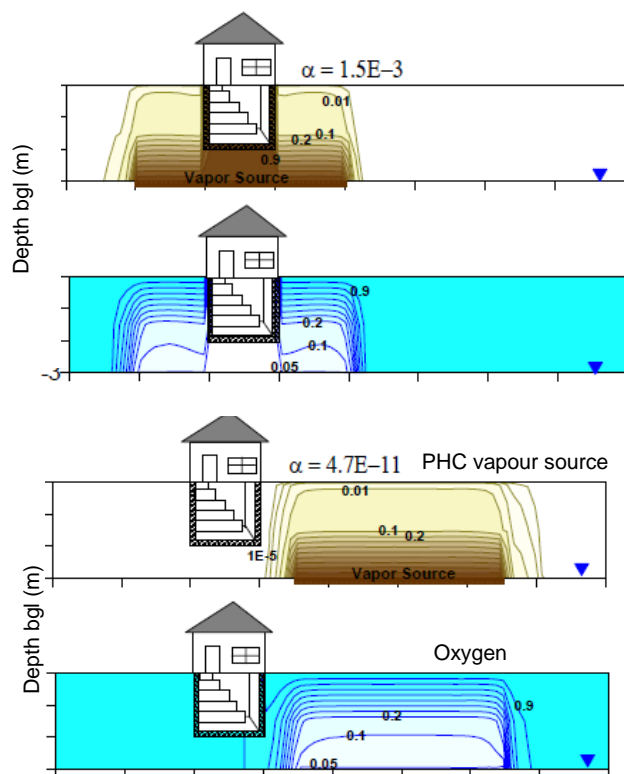


Figure (USEPA 2012a) illustrating difference between a receptor being located above contamination and adjacent to contamination.

Box 2.6 Groundwater fluctuations

Groundwater can rise and fall a small or large amount depending on the location (e.g. where tidal influences may be present), season, geology, lithology, rainfall or climatic conditions. It can also change direction, particularly if there are preferential pathways present that enable the groundwater to shortcut the normal flow direction

It is important to know approximately how much the groundwater level changes in the area of interest. The sort of fluctuation that makes a difference to modelling or measurement is more than about 10-20% of the depth to groundwater. So ± 0.5 m would be important if the depth to groundwater was 1-1.5 m but not if the depth to groundwater is 10-15 m.

It's also important to be aware of the presence of bores where groundwater is abstracted in the nearby area. If large amounts of water are abstracted or there is a large variation in the amount of water abstracted this can also cause fluctuations which can change the risk profile.

Box 2.7 Presence and type of building

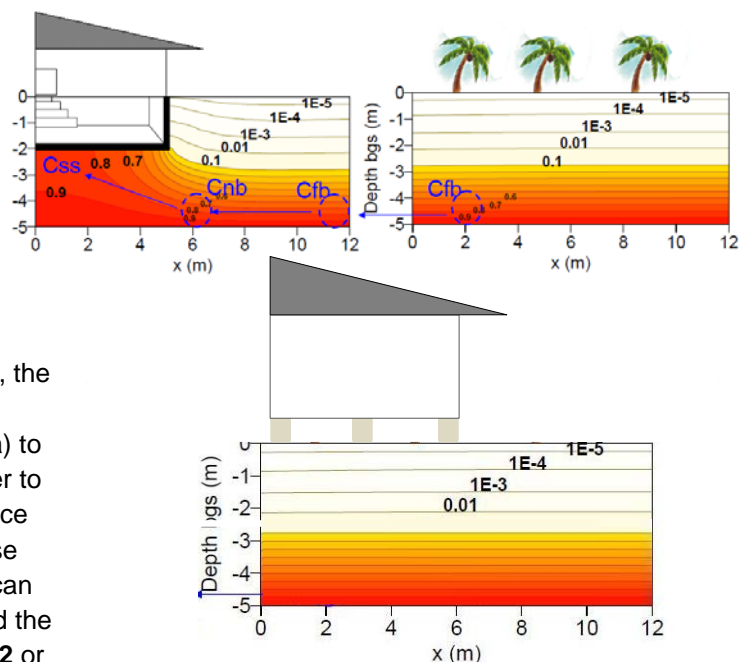
As discussed above, the presence of a foundation slab has the potential to inhibit the downward diffusion of oxygen. Hence the presence of buildings and structures that comprise continuous sound/sealed slabs (including basements) need to be identified in the CSM.

For strong contamination sources, the presence of large slabs has the potential (based on empirical data) to inhibit oxygen diffusion more (refer to **Appendix B2**). Hence the presence of large slabs is important for these sources. A large slab or building can be determined using the CSM and the approach outlined in **Appendix B2** or using a default value (particularly for future low-density residential developments) of ≥ 7.5 m as the distance between the centre and edge

of the continuous slab. A continuous sealed slab may include a building and/or other sealed surface such as an adjacent pathway or concrete driveway (but not including gaps [including those between different slabs], garden beds/landscaping or smaller pavers).

Buildings constructed on piers with a crawl space enable the effective diffusion of oxygen into the subsurface so they need to be identified separately in the CSM.

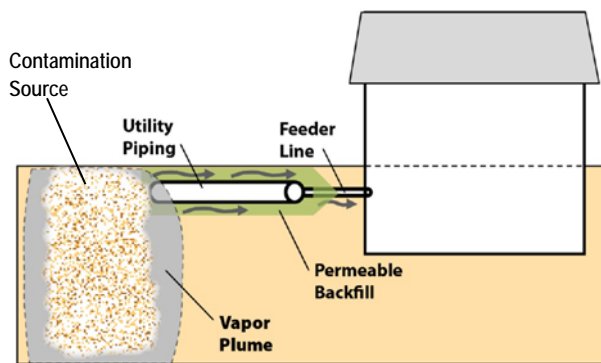
These issues need to be considered when selecting representative depths for the collection and interpretation of soil gas data, particularly when sampling from open ground for an assessment of exposures within future (or existing) building.



Illustrative conceptual figure for building with basement, open space and crawl space (modified from: (Abreu, Johnson & McAlary 2006))

Box 2.8 Potential preferential pathways

These are pathways of least resistance to the migration of vapours. These pathways short-circuit migration pathways that would normally be subject to slower rates of diffusion and/or biodegradation. It is noted that some preferential pathways also act to allow more rapid migration of oxygen into the subsurface enhancing biodegradation.



Ref: (USEPA 2011)

Potential preferential pathways provide a direct connection from the contamination through to the building and may include:

- Natural features such as sand or gravel stringers, bedding planes, weathered surfaces and continuous fractures; or
- Artificial features that include utility corridors and trenches that directly connect secondary source areas to a building, as well as building slab penetrations (for utilities and sumps) and drains.

Box 2.9 Receptors

The focus of this guidance is on potential exposures to vapours within buildings; however the guidance can also be used to evaluate exposures in other areas (such as outdoors). The use of individual sites/properties for different purposes has the potential to result in the assessment of different groups of people, with different sensitivities to the inhalation of vapours. Such groups may include adults (workers and residents) and young children (residents, within childcare centres and schools). The identification of receptors that are relevant to the areas overlying the zone of influence of the petroleum hydrocarbon contamination (within the zone of influence identified as per **Box 2.5**) is therefore important.

3. Preliminary PVI assessment

3.1 Purpose

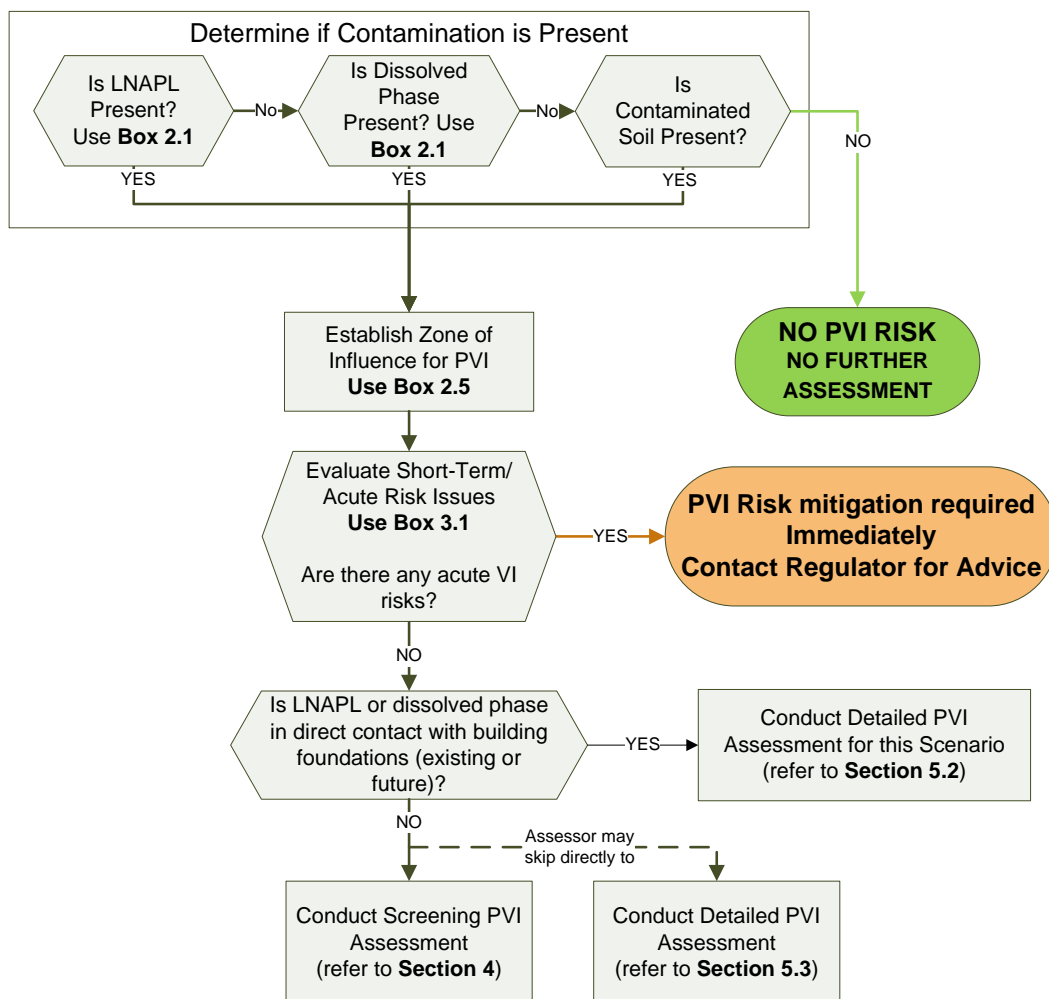
The purpose/aim of conducting a preliminary PVI assessment is to:

1. identify if contamination that might pose a PVI risk is present;
2. identify if there are any short-term/acute risks that must be addressed immediately (rather than proceeding on to further assessment); and/or
3. identify if any other issues relevant to the site would require detailed assessment and to determine if the screening PVI assessment step should be skipped.

At this stage of the investigation data relating to secondary sources (i.e. presence of LNAPL and soil and groundwater concentrations) are available. It is not expected that soil vapour data will be collected/available at this stage. However in some cases soil vapour data or indoor air data may be available and will require preliminary evaluation.

3.2 Conduct of preliminary PVI assessment

The following decision diagram, and associated reference boxes, presents the approach to be adopted for the conduct of the preliminary PVI assessment.



Decision Diagram 1 Preliminary PVI Assessment

Box 3.1 Assessment of short-term/acute risks

It is important that the potential for immediate or imminent risks are evaluated early in the process to determine whether emergency assessment and/or immediate response is required. This may be through the implementation of qualitative surveys (e.g. inspections of accessible drainage and utility pits using visual/olfactory indicators and/or PID/LFG meters). It is important that imminent and acute public safety hazards are identified and managed/mitigated as a priority and should be undertaken prior to the conduct of any additional investigations.

The following situations need to be identified as they may require an immediate response:

- Migration of product directly into a building, sump or services;
- Strong petroleum hydrocarbon odours (not necessarily a health risk but an easily accessed indicator of high concentrations);
- Presence of potentially flammable or explosive conditions (due to petroleum hydrocarbon vapours and/or methane) in enclosed spaces such as sewer or other utilities (refer to **Table 2** below and **Appendix C**);
- Where soil gas or indoor air data has been collected during the assessment of PVI risks (refer to **Box 5.2**), exposure concentrations are detected near or above acute health based guidelines refer to summary **Table 2** below and **Appendix C** for list of relevant criteria, including those relevant to TPH/TRH;
- Complaints of dizziness, nausea or headaches by occupants.

In addition to the assessment of immediate hazards, an evaluation of potential short-term/acute risks should be undertaken when any additional data may be collected from the site (such as soil gas or indoor air data).

The table below contains parameters that can be measured on site by hand held meters and others that need detailed sampling and laboratory analysis. It is not expected at this stage of the assessment that specific soil gas, odour or indoor air measurements would be collected, but if they have been then the results can be compared to the values listed. Where only the parameters from hand held meters are available then the top part of this table can be used to determine the potential for short-term/acute risks.

Table 2 Action Levels for immediate or short-term response

Parameter/ PHC	Odour Threshold	Action Level Indoor Air	Action Level Confined Space	Action Level Crawl-Space	Action Level subsurface – near foundations ²
Potential Safety Risk					
<i>Units</i>	<i>ppm</i>	<i>%LEL</i>	<i>%LEL</i>	<i>%LEL</i>	<i>%LEL</i>
Methane	None	1% (500 ppm)	10% (5 000 ppm)	1% (500 ppm)	25% (12 500 ppm)
TPH/TRH – petrol (PID, see Appendix E)	500 – 2500	--	10% (1 400 ppm)	--	25% (3 500 ppm)
Potential Health Risk⁴					
<i>Units</i>	<i>µg/m³</i>	<i>µg/m³</i>	<i>µg/m³</i>	<i>µg/m³</i>	<i>µg/m³</i>
Benzene	8,700	30-170	30-170	75-425	34,000
Toluene	600	Note 1	Note 1	Note 1	Note 1
Ethylbenzene	700	22,000	22,000	55,000	4,400,000
Total Xylenes	200	8,800	8,800	22,000	1,760,000
Naphthalene	400	1,600	1,600	4,000	320,000
Hexane	5,300	Note 1	Note 1	Note 1	Note 1
Heptane	625,000	Note 1	Note 1	Note 1	Note 1
Cyclohexane	87,000	Note 1	Note 1	Note 1	Note 1
Trimethylbenzenes	2,000–12000	660	660	1,650	132,000

Notes for Table 2:

LEL = Lower Explosive Limit, which is the lower end of the range where combustible gasses may be explosive

%LEL = percentage of the LEL used to determine the action level for acute (explosive) hazards, based on a percentage of the LEL for the gas (for example the LEL for methane is 5% in air and the action level for indoor air is set at 1% of the LEL, which is 500 ppm)

Note 1 – no suitable value is currently available. It is noted that by meeting action levels for other PHCs, odour and short-term risks for these compounds are also expected to be addressed, given that this guidance is particularly targeting contamination by various fuel types. If acute risk from contamination by a solvent (such as hexane alone) was to be assessed then a literature review to develop suitable criteria would be required.

Note 2 – subsurface action levels are based on acute indoor air criteria and application of 200 fold attenuation factor. This action level is relevant to soil gas data collected directly adjacent to a building foundation. For deeper soil gas data an additional 10 fold attenuation factor can be incorporated into the action levels above (i.e. samples taken at greater than 4m).

Note 3 – crawl-space action levels are based on acute indoor air criteria and application of 2.5 fold attenuation factor (refer to **Box 5.7**).

Note 4 - Refer to **Appendix C** for details and references for these values, and relevant values for TPH/TRH

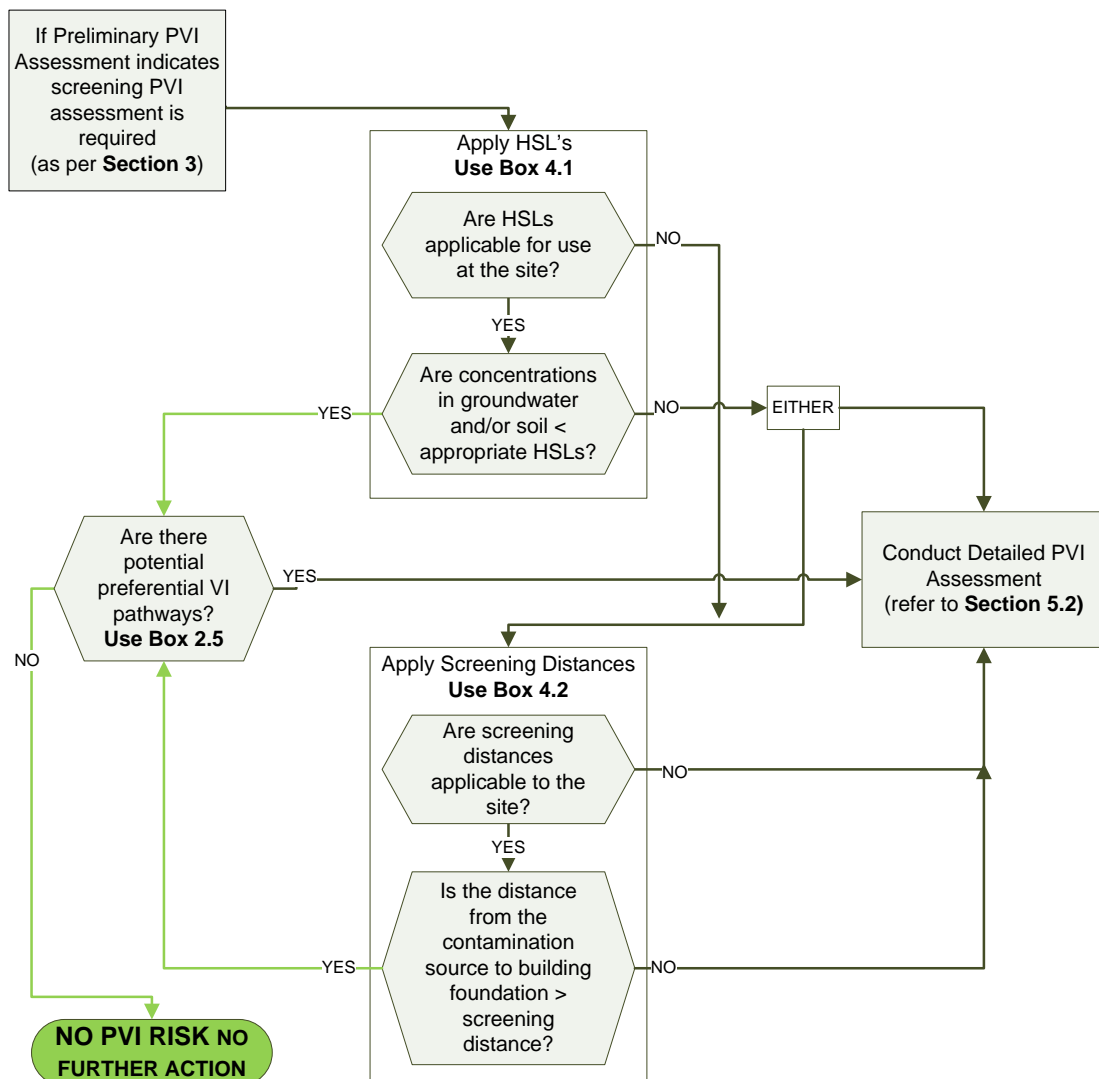
4. Screening PVI assessment

4.1 Purpose

The purpose/aim of the screening PVI assessment is to screen the site data to identify if there is the potential for PVI risks, which would trigger further assessment. The screening PVI assessment is based on the CSM and source data, namely soil and groundwater concentrations. This phase of the assessment does not involve the sampling of vapour.

4.2 Conduct of screening PVI assessment

The following decision diagram, and associated reference boxes, presents the approach to be adopted for the conduct of the screening PVI assessment.



Decision Diagram 2 Screening PVI assessment

Box 4.1 Application and use of Health Screening Levels (HSLs)

To apply the HSLs (Friebel & Nadebaum 2011a, 2011b, 2011c, 2011d) the following need to be met (refer to the application guide in the HSLs documentation for further details):

- The application checklist must be used to determine if the HSLs can be applied to your site. It is noted that when using the application checklist the specific issues that may be present at the site which means the HSLs cannot be used, or require more careful consideration, and include:
 - presence of LNAPL
 - shallow groundwater (<2 m bgl)
 - presence of fractured rock (refer to Section 4.6 of the HSLs application document)
 - source of contamination is a non-petroleum mix of hydrocarbons or an atypical mix of petroleum hydrocarbons
- The use of HSLs at the screening phase should not include additional factors for biodegradation, unless conditions outlined in HSL documents (Friebel & Nadebaum 2011a, 2011b) or CRC CARE Tech Report no. 12 (Davis, Patterson & Teffry 2009) apply.

Where the HSLs do not apply or there are exceedances of HSLs (when applied in accordance with HSL checklist) then consider the use of screening distances (as per **Box 4.2**) or conduct a detailed PVI assessment (refer to **Section 5**).

Where soil gas data is available at depths such as 1.5 or 3 m, the relevant HSLs to use are as follows:

- Soil gas data at 1.5 m should be compared to the HSL for 1-2 m
- Soil gas data at 3 m should be compared to the HSL for 2-4 m

Box 4.2 Application and use of screening distances

A screening distance is the minimum thickness of soil with a high potential for bioattenuation (vertically) that is sufficient to effectively attenuate petroleum vapours such that they do not pose a risk to human health (i.e. the potential for VI is considered negligible), and no further assessment of PVI is required.

Screening distances can be used to screen out sites where PVI is not of significance. The screening distances can be used where HSLs do not apply or where HSLs have not screened out the site.

Appendix B1 provides an explanation as to how these vertical screening distances have been developed. They are based on analysis of empirical data obtained from hydrocarbon spill sites in Australia, USA and Canada.

To apply screening distances (as outlined in **Appendix B1**), the following must apply at the site:

- Soil between the source and the receptor (building foundation – ground surface for slab on grade, or foundation of basement, if present) needs to have a high potential for bioattenuation as defined in **Box 2.1**;
- These screening distances should not be used for large contaminant plumes such as those derived from major pipeline leaks (e.g. high pressure pipelines) or refinery/bulk terminal sites, where an LNAPL plume may cover a significant area as there is insufficient data in the databases to determine if vapours from these sources behave such that the derived screening distances are relevant. In such situations it is more

Box 4.2 Application and use of screening distances

appropriate to do a detailed PVI assessment as outlined in **Section 5**;

- For LNAPL sources the presence of large slabs should be determined for the site. If large slabs/big buildings are present then these screening distances should not be used and the site assessment should proceed to the detailed PVI assessment outlined in **Section 5**. A large slab/big building can be determined using a default (of ≥ 7.5 m which is the minimum distance from centre to the edge of a continuous sealed slab); or using the CSM and the approach as outlined in **Appendix B2**. For future low-density residential developments it is appropriate to adopt the default slab size.

Table 3 presents the screening distances that can be applied in the assessment of PVI risks. These are also illustrated in the following figure.

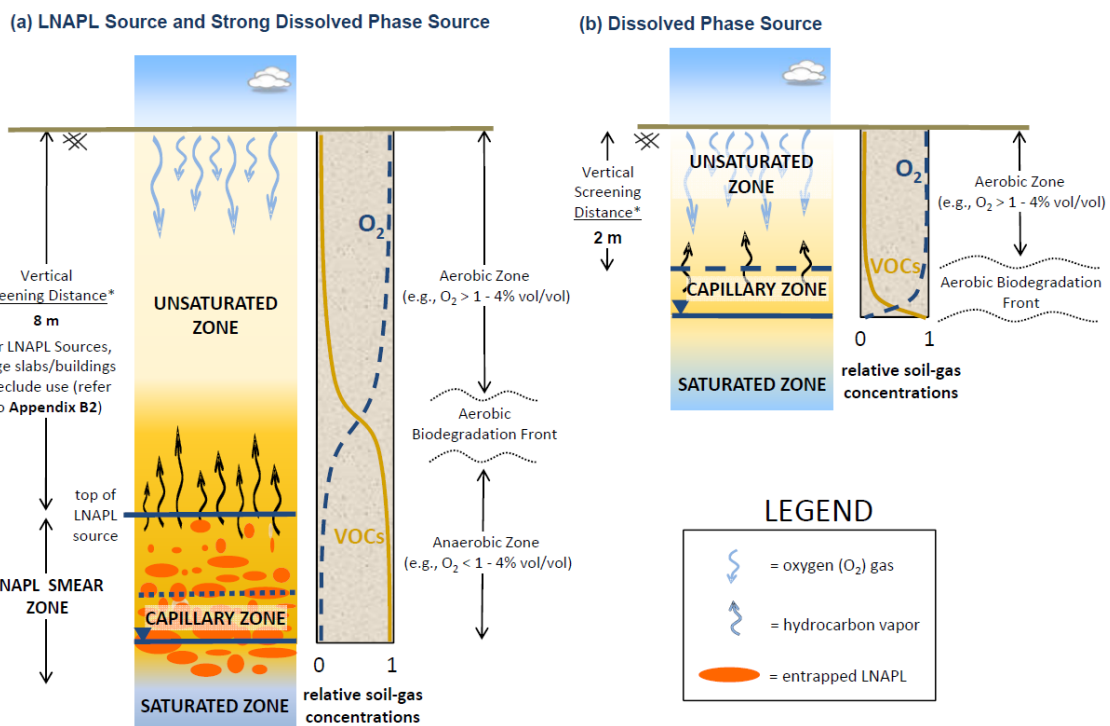
Table 3 Screening Distances

Source	Concentrations	Screening distance*
Dissolved Phase	Benzene*** ≤ 1 mg/L TPH/TRH (C6-C16) ≤ 10 mg/L (as reported by the laboratory – do not subtract benzene or BTEX)	2 m
LNAPL or Strong Dissolved Phase	LNAPL** or Dissolved sources where: Benzene*** >1 mg/L TPH/TRH (C6-C16) > 10 mg/L (as reported by the laboratory – do not subtract benzene or BTEX)	8 m

* Screening distances adopted have included an uncertainty factor of approximately 1.5 fold, refer to **Appendix B1**.

** Where LNAPL is present, if a large slab (refer to **Appendix B2** or use a default of ≥ 7.5 m from centre to slab edge) is present and LNAPL is (or may be) beneath at least 50% of the slab then this screening distance does not apply (refer to **Appendix B1** for further detail). It is noted that the available data shows that the presence of slabs (regardless of size) has not been shown to be of importance for dissolved phase sources (at all strengths below that used to define the presence of LNAPL). Hence the consideration of slab is only relevant for LNAPL or strong dissolved phase sources.

*** Benzene only is used in the application of screening distance (rather than BTEX) as commonly it is a driver of risk.



5. Detailed PVI assessment

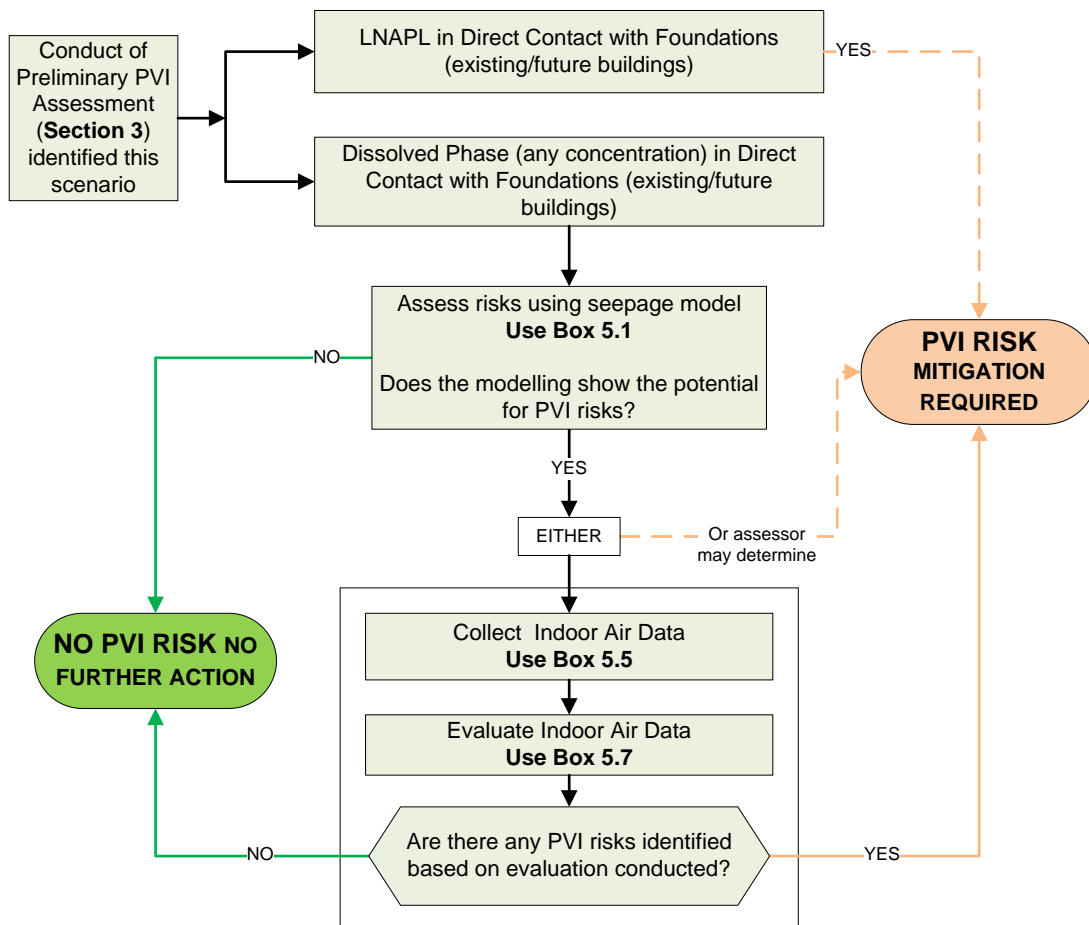
5.1 Purpose

The conduct of a detailed PVI assessment may include the collection of vapour data and/or vapour modelling. The detailed assessment of PVI risks is relevant in the following circumstances:

- The LNAPL or groundwater source is directly adjacent to the building foundations as identified in **Section 3** (refer to **Section 5.2**);
- The preliminary or screening PVI assessment indicates the potential for PVI risks as outlined in **Section 4** (refer to **Section 5.3**);
- There have been reports of odours or health effects from occupants; or
- Detailed PVI assessment is required by the site owner/operator, auditor or regulator as part of the site assessment works.

5.2 Assessment of PVI risks where contamination is in direct contact with building

The following decision diagram, and associated reference boxes, presents the approach to be adopted for the assessment of PVI risks where LNAPL or dissolved phase contamination is in direct contact with an existing or future (proposed or worst case) building.



Decision Diagram 3 PVI assessment for LNAPL or groundwater contamination in direct contact with foundations

Box 5.1 Evaluate PVI risks using seepage model

This model is only appropriate for use with dissolved phase plumes to assess VI. If a LNAPL is present and in contact with the building and its foundations, the seepage model as outlined below will indicate the potential for an unacceptable risk whether the source of contamination is petrol or diesel. Instead of running the model, indoor air samples should be collected to assess the risk or a decision taken that remediation for PVI risks is required. Planning for such remediation should be commenced immediately.

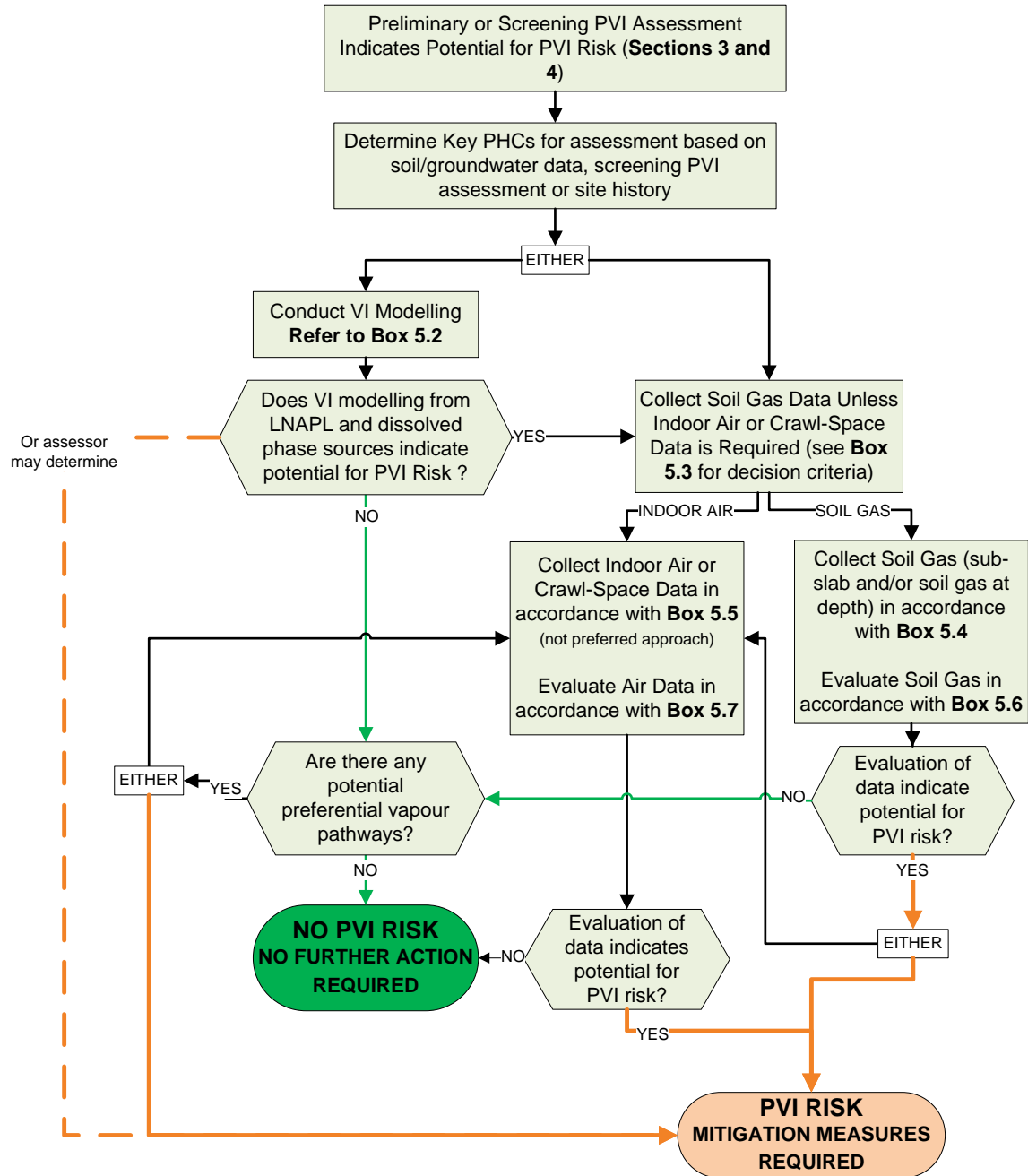
As the dissolved phase plume is in contact with the building, this assessment must assume that some seepage will occur. The assessment should be undertaken using the volatilisation models as outlined below:

- Emission rates of PHCs from seepage water are to be calculated using volatilisation equations (for a non-aerated, non-biologically active system) derived from Australian and US guidance (Guo & Roache 2003; NPI 2011; USEPA 1994, 1997);
- In most cases it is reasonable to assume that the volume of seepage will be low, hence the calculations can assume small areas of seepage water in drains or on basement floors (to a maximum of 5% of basement floor area) (unless there are exposed rock walls or there is some other evidence that seepage could be higher, in which case a higher value may be needed);
- If, for any reason, the seepage is high (due for example to some construction issue or need for repair or by design with pumping and other management measures) a higher value can be used in the modelling;
- The emission of PHC vapours can be mixed with the volume of air in the basement (based on dimensions of the basement and air exchange rate) to calculate an air concentration in the basement;
- For buildings where there is a good separation between the basement and upper floors the concentration of PHCs on the floors above the basement(s) are $1/10^{\text{th}}$ of the basement concentrations. For small buildings where there is more connection between a basement and upper floors (such as in a single family residence) the concentration of PHCs on the floors above the basement is 1 third of the basement concentration (Fang & Persily 1995; Olson & Corsi 2001);
- Default exposure parameters and dose-response parameters adopted for key PHCs should be obtained from HSL documentation (Friebel & Nadebaum 2011a, 2011b, 2011c, 2011d). The assessment of exposures within basements should consider site-specific uses (e.g. presence of car park attendants or other businesses in the basement, use of storage spaces for hobbies or short-duration use for parking only). For dose-response evaluations and quantitative data for other petroleum hydrocarbons select in accordance with National Environment Protection Measure (NEPM) Schedule B(4) (NEPC 1999 amended 2013) and enHealth (enHealth 2012) guidance (and updates);
- Calculation of non-threshold carcinogenic risk and threshold Hazard Index (summed over all contaminants for the exposure scenarios relevant to the receptors identified) and comparison against the following risk levels adopted as representative of acceptable risks, consistent with that adopted in the derivation of the HSLs and assessment of contaminated sites (enHealth 2012; Friebel & Nadebaum 2011a; NEPC 1999 amended 2013):
 - **Total incremental lifetime carcinogenic risk (non-threshold) $\leq 1 \times 10^{-5}$ or 1 in 100,000; and**
 - **Total threshold HI ≤ 1**

Alternate approaches may be used where justified. These may include qualitative evaluations of risks where groundwater seepage rates are very low (based on hydrogeology) or the building is constructed with specific engineering measures to prevent or capture seepage and any associated vapours in a separate enclosed system.

5.3 Assessment of PVI risks when the contamination is not in direct contact with a building

The following decision diagram, and associated reference boxes, presents the approach to be adopted for the detailed assessment of PVI risks where LNAPL or dissolved phase contamination is not in direct contact with an existing or future building.



Decision Diagram 4 Detailed PVI Assessment Process

Box 5.2 Conducting VI modelling to evaluate PVI risks from LNAPL and dissolved phase sources

Modelling is a very useful tool for assessing VI, where the model assumptions are appropriate for the situation. There is good evidence that the modelling of PHC vapours, where biodegradation is not considered provides a conservative assessment of PVI risk. This can provide a clear indication of whether the risk is very low and does not warrant further detailed assessment. In addition a model may also be used to indicate where PVI risks have the potential to be high enough to warrant the collection of site-specific data (such as soil gas data).

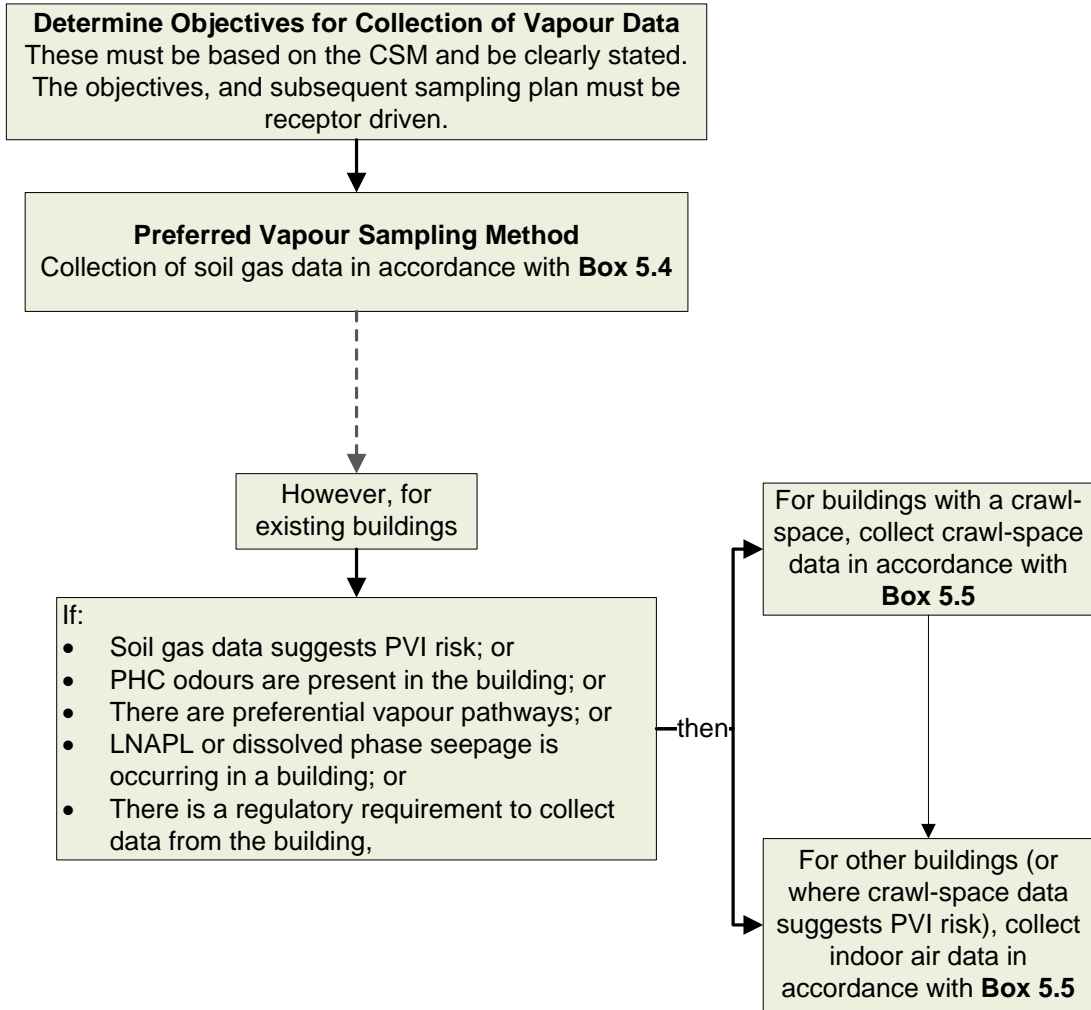
The preferred approach to the modelling of PVI is to adopt the vapour model as outlined in the HSL documentation (Friebel & Nadebaum 2011a, 2011b, 2011c, 2011d). This approach is appropriate for the modelling of PVI risks from LNAPL or dissolved phase sources. Where soil vapour measurements are available they can also be used in modelling of PVI. However, it is not recommended that soil data (i.e. in mg/kg) be used in the models to assess PVI risks due to the greater uncertainties in the model outcomes. Where soil contamination is present and requires further assessment, it is recommended that soil gas data is collected. However, where soil data is the only suitable data for making decisions on a site (e.g. validating the base of an excavation and soil gas data cannot be collected) the modelling of PVI from soil should be appropriately justified by the consultant and/or undertaken in consultation with the auditor/regulator.

Where modelling is utilised for the assessment of PVI, the following needs to be considered:

- Unless otherwise justified based on the CSM developed, use the default parameters presented in HSL documentation (Friebel & Nadebaum 2011a) for soil type, model assumptions, exposure parameters and dose-response data. For dose-response evaluations and quantitative data for other petroleum hydrocarbons select in accordance with NEPM (NEPC 1999 amended 2013) and enHealth (enHealth 2012) guidance (and updates);
- Calculation of non-threshold carcinogenic risk and threshold Hazard Index (summed over all contaminants for the exposure scenarios relevant to the receptors identified) and comparison against the following risk levels adopted as representative of acceptable risks, consistent with that adopted in the derivation of the HSLs and assessment of contaminated sites (enHealth 2012; Friebel & Nadebaum 2011a; NEPC 1999 amended 2013):
 - **Total incremental lifetime carcinogenic risk (non-threshold) $\leq 1 \times 10^{-5}$ or 1 in 100,000; and**
 - **Total threshold HI ≤ 1**

Alternate vapour models (such as BioVapor (API 2009)) can be used, however these need to be justified (and supported through the CSM presented) within the PVI assessment.

Box 5.3 Determine vapour sampling type



Box 5.4 Steps Required for Soil Gas Sampling

The sampling of soil gas needs to meet the objectives of the sampling program. The following presents the minimum requirements that must be considered. These are to be outlined in an appropriate sampling plan after completing an appropriate DQO planning process.

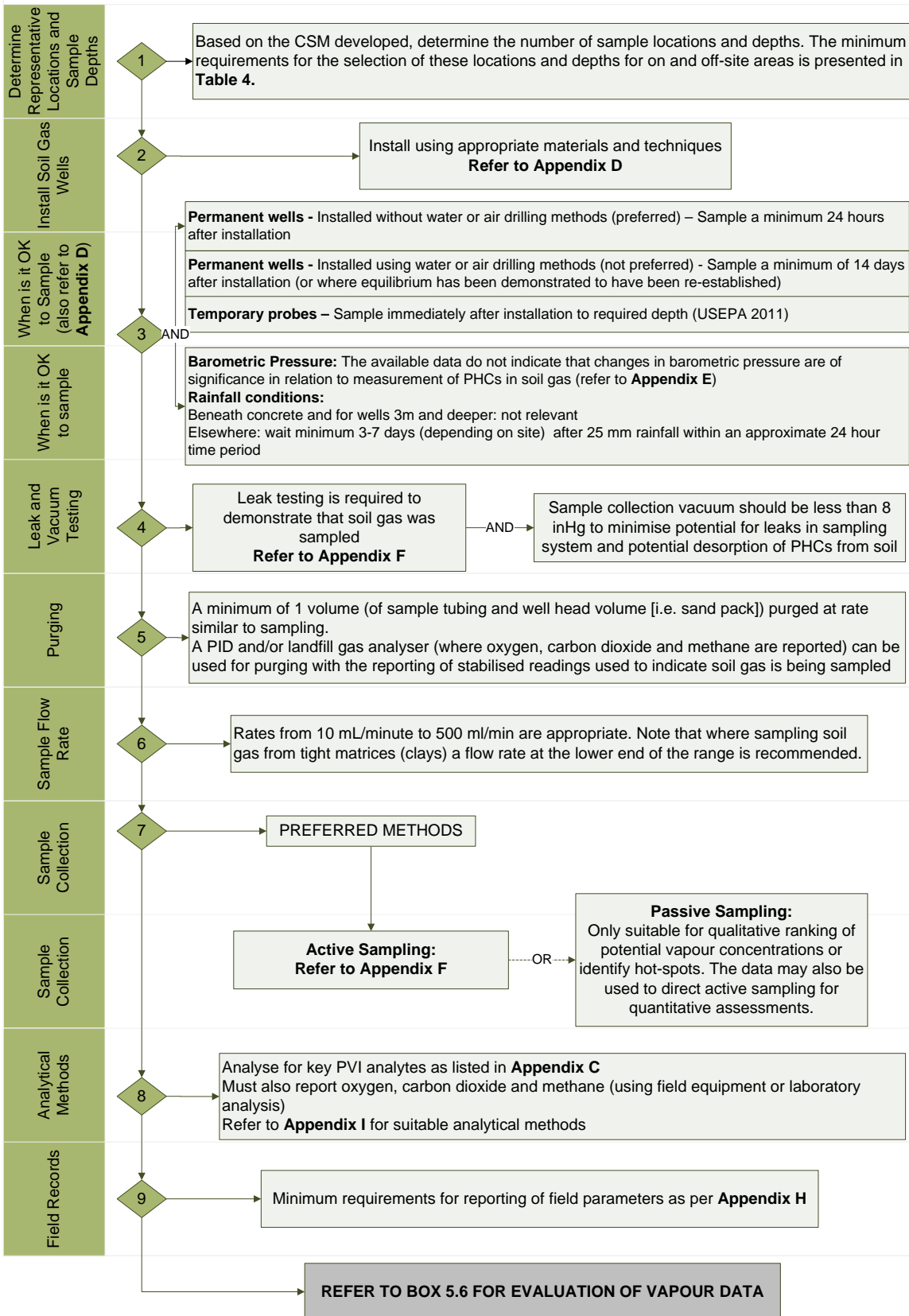


Table 4 Indicative minimum requirements for soil gas sample locations and depths

The minimum number of soil gas sample locations listed in this table is not a legally enforceable requirement, nor does it constitute regulatory approval for the minimum level of sampling required. It is an indication of what is likely to be relevant depending on the situation at any particular site. Investigators should document the appropriateness of the number and location of sample locations selected, where required. The CSM should always be the basis of the choice of locations and number of samples taken at any site but this table gives an indication of what should be considered as a minimum (also refer to **Note 1** below table). This table only addresses soil gas sample locations and depths and does not include any recommendations for additional sampling that may be required for soil or groundwater. These should be determined on the basis of the CSM and the rationale for any sampling plan should form part of the DQOs and included in the sampling and analysis quality plan.

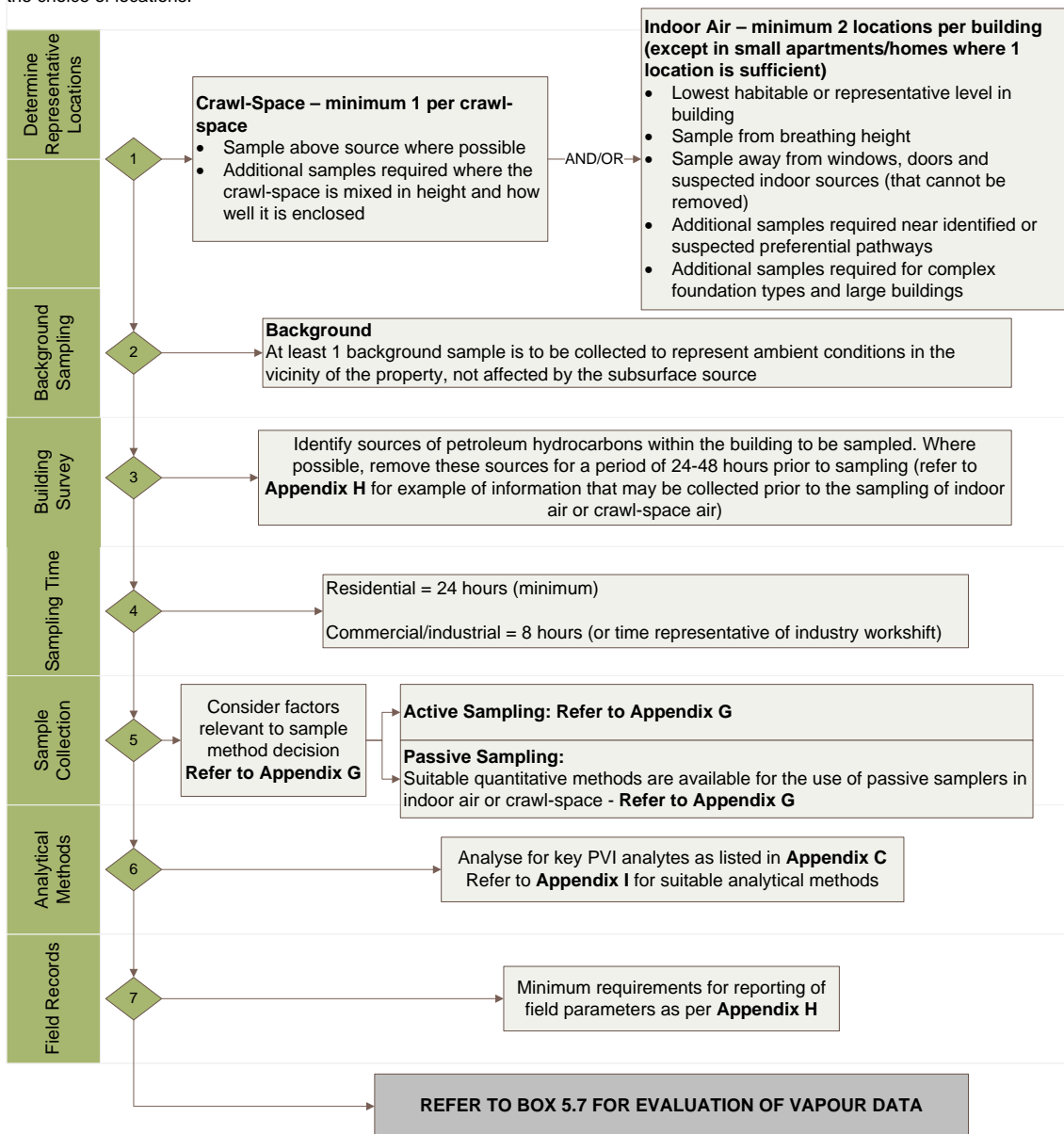
Scenario Evaluated in PVI Assessment	On-Site Sources						Off-Site Sources (Note 3)			
	LNAPL		Dissolved Phase		Soil		LNAPL		Dissolved Phase	
	Minimum number of locations (Note 1)	Depth (m bgl) (Note 2)	Minimum number of locations (Note 1)	Depth (m bgl) (Note 2)	Minimum number of locations (Note 1)	Depth (m bgl) (Note 2)	Minimum number of locations (Note 1)	Depth (m bgl) (Note 2)	Minimum number of locations (Note 1)	Depth (m bgl) (Note 2)
Assessment of existing buildings										
Building access granted - locations should be selected towards the centre of the building and/or above maximum concentrations										
small building	1	ss [#]	1	ss [#]	1	ss [#]	1	ss [#]	1	ss [#]
big building *	2	ss [#]	2	ss [#]	2	ss [#]	2	ss [#]	2	ss [#]
building has crawl-space	Collection of crawl-space air sample (refer to Box 5.5)						Collection of crawl-space air sample (refer to Box 5.5)			
No building access - locations should be selected adjacent to building above maximum concentrations										
small building and building with crawl-space	1-2	1.5	1-2	1.5	1 (or number of soil sources)	1.5 **	1-2	1.5	1-2	1.5
big building *	3	3	3	3		3 **	3	3	2	3
building with basement to depth X	3	X	3	X		X	3	X	3	X
No property access - locations should be selected on property boundary above maximum concentrations										
small building and building with crawl-space	1-2	1.5	1-2	1.5	1 (or number of soil sources)	1.5 **	1-2	1.5	1-2	1.5
big building *	2	3	2	3		3 **	2	3	2	3
building with basement to depth X	2	X	2	X		X	2	X	2	X
Assessment of future buildings										
Property access granted - locations should be above maximum concentrations and relevant to location of proposed building										
small building and building with crawl-space	2	1.5	2	1.5	1 (or number of soil sources)	1.5 **	2	1.5	2	1.5
big building or size not known *	3	3	3	3		3 **	3	3	2	3
building with basement to depth X	3	X	3	X		X	3	X	3	X
No property access - locations should be selected on property boundary above maximum concentrations										
small building and building with crawl-space	1-2	1.5	1-2	1.5	1 (or number of soil sources)	1.5 **	1-2	1.5	1-2	1.5
big building *	2	3	2	3		3 **	2	3	2	3
building with basement to depth X	2	X	2	X		X	2	X	2	X

Notes for Table 4:

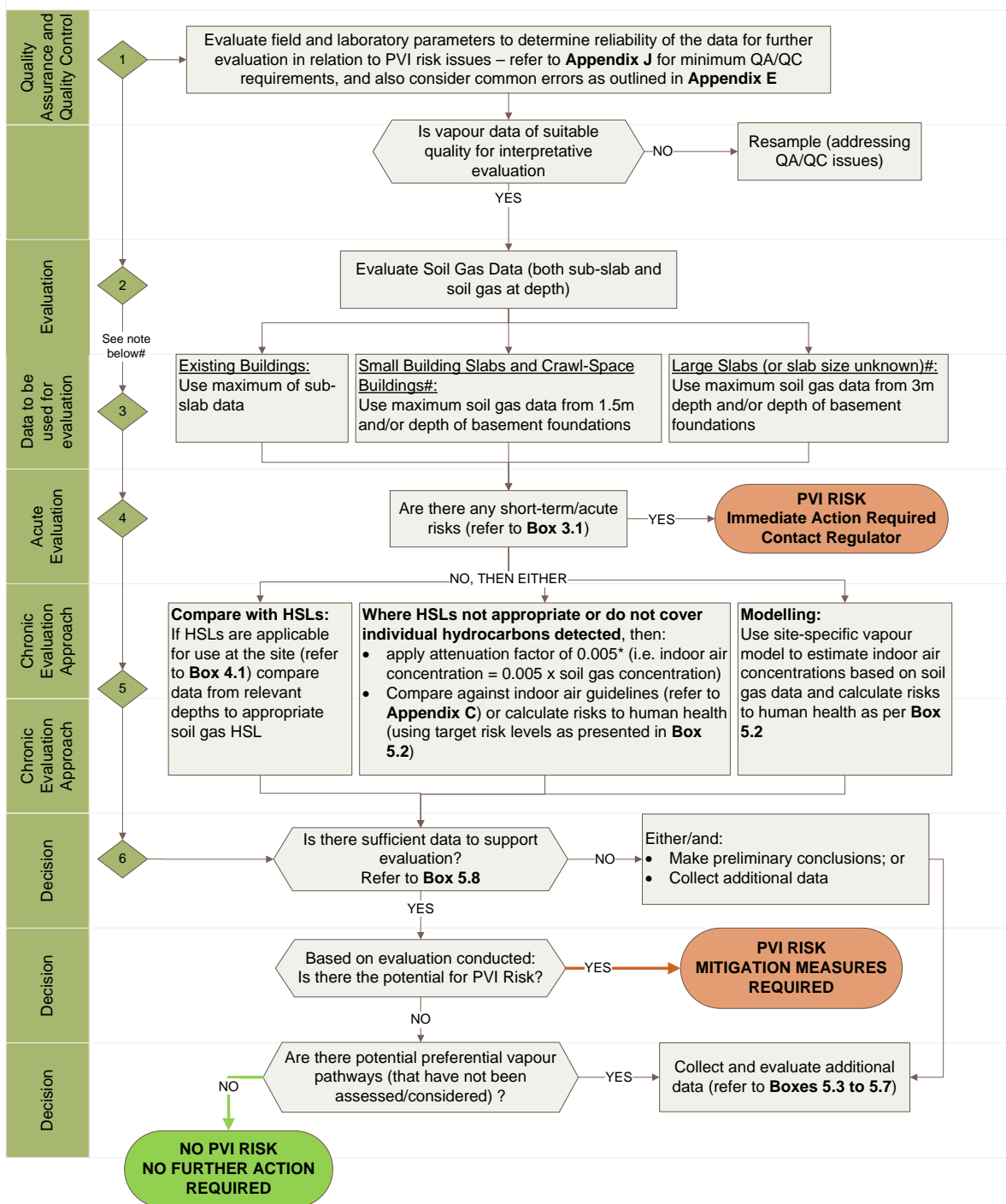
- Note 1 The sampling locations and number of samples collected should be based on the CSM, in particular the extent of the contamination and location of receptors (where there is the potential for human exposure). As PVI assessments are commonly undertaken based on maximum impacts the locations should focus on areas of maximum impact in groundwater and/or vadose zone. The maximum number of samples that may be appropriate for a site will depend on the nature and extent of contamination, building size and if there are any requirements to calculate statistics. Where the building size (or continuous slab) is large, targeting a location in the middle of the slab (or where oxygen migration is expected to be limited) is recommended wherever possible. It is expected that for most sites no more than 6 sample locations are required per receptor building.
- Note 2 The depth of samples required assumes that the groundwater contamination or LNAPL is below these depths. Where more shallow groundwater or LNAPL is present then the samples should be collected as close as practical to the source\groundwater table (above the capillary fringe). It is also noted that the minimum depths presented in this table are those required to be collected and considered in the PVI assessment. Additional depths may be included (as nested wells at each location) to demonstrate biodegradation (where relevant). The relevance of additional depths depends on the CSM (and in particular the potential presence of large slabs/buildings to affect the potential for biodegradation). For example, a soil vapour sample at 0.5m in open ground on which a house with a crawl space will be constructed is relevant to assess if biodegradation has occurred sufficiently, however, such a sample is not relevant if a large slab is to be constructed on the site. If the slab size is not of importance to the potential for biodegradation (refer to **Appendix B2**) then it may be relevant to installed nested wells that include more shallow wells (e.g. 1.5 m and 0.5 m depths). If the slab size is of potential importance (refer to **Appendix B2**) and may affect the potential for biodegradation then nested wells may be installed, for example, to A) also collect vapour data near the source to enable the refinement of the decision that slab size is important; B) also collect data closer to the surface (i.e. 0.5 m and/or 1.5 m depth) so that if sufficient evidence is provided that the slab size is not of importance data is available to support biodegradation; C) define the vertical extent/processes at and below a proposed basement depth (particularly where the source is deep. Examples of nested wells in these situations may be 5 m, 3 m and 1.5 m depths; or adjacent to source at 4 m, 3 m and 1 m. Note that where a building with a basement extends into (or is proposed to extend into) the groundwater source, the collection of soil gas data will not assist in the assessment of PVI risks (refer to **Section 5.2**).
- Note 3 The number of sample locations presented relate to a single property or two neighbouring/adjacent properties (with equal potential for PVI risk). The number of off-site properties that require consideration will depend on the CSM and the determination of the zone of influence. It is expected that as a minimum, off-site properties closest to the site (where off-site concentrations are highest) will be evaluated unless PVI risks are screened out as per **Section 4**.
- * Building/slab size that is of importance should be determined on the basis of site specific information and the approach as outlined in **Appendix B2**. Note that this is based on a continuous slab. The presence of gaps (such as those that are present between different/adjoining slabs), pavers, or garden beds provides sufficient pathways for oxygen to migrate beneath pavements and should not be included in the consideration of a continuous slab.
- ** Depth of sample targeting soil contamination should be as recommended or at the depth of the soil contamination.
- ss Sub-slab soil gas sample
- # While it is preferred that sub-slab data is collected from beneath an existing building, it is recognised that even when building access is available the collection of a sub-slab sample may not always be possible or practical to collect. In this situation the collection of soil gas samples directly adjacent to the building at depths as outlined under the category of no building access should be considered.

Box 5.5 Steps Required for Sampling Indoor Air and Crawl-Space Air

Due to the ubiquitous nature of PHCs in ambient/indoor air (from a range of sources) the sampling of indoor air is only recommended where it is the only measure that can be used to determine whether PVI risk is of concern (refer to **Box 5.3** for these scenarios). The minimum number of sample locations for indoor air or crawl-space sampling listed below is not a legally enforceable requirement, nor does it constitute regulatory approval for the minimum level of sampling required. Investigators should document the appropriateness of the number and location of the samples selected, where required. The CSM should always be the basis for the choice of locations.



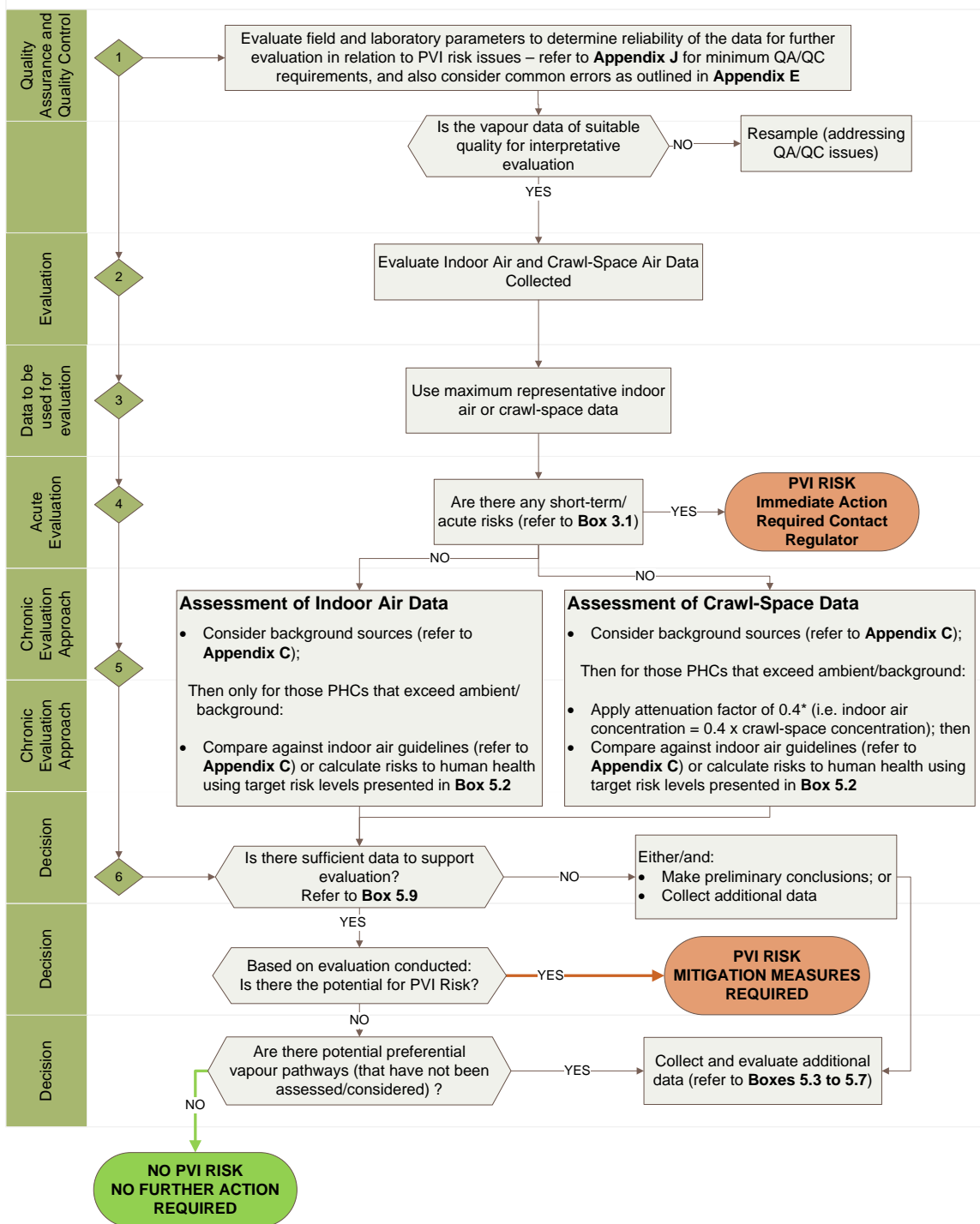
Box 5.6 Evaluation of Soil Gas Data



* Attenuation factor for soil gas to indoor air based on the evaluation undertaken in the derivation of the HSLs (Friebel & Nadebaum 2011a)

Soil gas depths recommended for use in the assessment of small and large buildings based on the minimum data requirements as outlined in **Table 4**. If additional soil gas data is collected to further evaluate the potential for biodegradation, and the data collected is relevant to the building scenario (and can be justified/supported), then this data may be used in the PVI assessment.

Box 5.7 Evaluation of Indoor Air and Crawl-Space Data



* attenuation factor of 0.4 for the movement of PHCs from the crawl-space to indoor air based on the median attenuation factor for crawl-space to indoor air determined as the median attenuation factor from the US EPA evaluation of chlorinated volatile compounds (USEPA 2012b)

Box 5.8 Determination of data adequacy for making PVI risk conclusions from soil gas data

Decisions are based on margin of safety (MOS) between either:

- Measured soil gas concentration and screening level guideline;
- Modelled soil gas concentration and screening level guideline; or
- Modelled inhalation risk and target risk (or acceptable risk as outlined in **Box 5.2**)

The MOS used to decide number of sampling rounds or other actions is the lowest one found for the various contaminants at the site.

$$\text{MOS} = \frac{[\text{relevant screening level guideline}]}{[\text{soil gas concentration}]} \text{ OR } \frac{[\text{target risk}]}{[\text{calculated inhalation risk}]}$$

Soil Gas Results	Number of sampling rounds or other actions required
MOS > 10 and CSM/ lines of evidence ¹	1 sampling event (with sound QA/QC) is adequate.
MOS >10 and limited supporting CSM/lines of evidence ¹	2 sampling events (with sound QA/QC) required over different conditions depending on CSM (e.g. seasons, depth to groundwater).
MOS >1 and <10	2-3 sampling events (with sound QA/QC) required over a minimum of 2 different conditions depending on CSM (e.g. seasons, depth to groundwater).
MOS >0.1 and <1	3-4 sampling events (with sound QA/QC) required over a minimum of 2 different conditions depending on CSM (e.g. seasons, depth to groundwater).
MOS < 0.1	Risk mitigation required to be considered/implemented (any additional sampling should be validation sampling). An additional confirmation round of sampling may be undertaken to assist in this process.

¹ CSM/lines of evidence – the understanding of the situation at the site (including evaluation of data that supports biodegradation) adds weight to the conclusions from the soil gas sampling

Box 5.9 Determination of data adequacy for making PVI risk conclusions from indoor air or crawl-space air data

It is noted that the sampling of indoor air is an intrusive method that can result in additional stress and concern for occupiers of the building. Hence the recommendations presented here reflect the need to ensure data is adequate but do not place onerous requirements on occupiers.

Where the assessment has involved the collection of indoor air or crawl-space air samples, evaluation of the data is complex. The evaluation should include the following key steps:

- Evaluate indoor air and crawl-space air data against ambient air/background air data, as per **Appendix C**.
- Where the measured concentrations in the crawl-space or indoor air are consistent with ambient air/background, then no further sampling is recommended.
- Where measured concentrations in the crawl-space or indoor air exceed ambient air/background by a factor of 5-10 fold or higher, then the following is recommended:
- Only for those compounds that exceed ambient air/background concentrations (evaluated as outlined in **Appendix C**), review the detected concentrations in relation to relevant screening level guidelines (for indoor air or crawl-space air) or calculate the inhalation risk;
- Calculate a MOS as outlined below; and
- Use the following table to assist in making decisions on the amount of data that may be required.

$$\text{MOS} = \frac{[\text{screening level guideline (indoors or crawl – space)}]}{[\text{measured indoor or crawl – space or background air concentration}]^{\#}}$$

OR

$$\text{MOS} = \frac{[\text{target risk}]}{[\text{calculated inhalation risk for relevant PHCs}]^{\#}}$$

calculated for only those PHCs that exceed ambient air/background concentrations. For benzene, where the risk from background often exceeds the target/acceptable risk level (refer to **Box 5.2** for definition of acceptable risk), calculating an inhalation risk is considered less useful (and meaningful) than a detailed investigation of potential sources (i.e. PVI or specific domestic products/storages). Where PVI is demonstrated, consideration of risk management options should be undertaken.

Indoor Air Results	Number of Sampling Rounds or other Actions Required
MOS > 10 and CSM/lines of evidence ¹	1 sampling event (with sound QA/QC) is adequate.
MOS >1 and < 10	2-3 sampling events ² (with sound QA/QC) required over different conditions depending on CSM (e.g. seasons, depth to groundwater).
MOS < 1	Risk mitigation required to be considered/implemented (any additional sampling should be validation sampling). An additional confirmation round of sampling may be undertaken to assist in this process.

¹ CSM/lines of evidence – the understanding of the situation at the site adds weight to the conclusion from the crawl-space or indoor air sampling

² Number of sampling rounds will depend on CSM and remedial/mitigation measures implemented. Where remedial/mitigation measures implemented additional rounds of sampling (over and above those listed above) will be required to demonstrate effectiveness.

6. Reporting

Once all steps relevant to the assessment of PVI risk have been completed, a report detailing the work should be prepared. A PVI assessment report can be part of the report detailing site investigations, part of a human health risk assessment or a standalone document. The level of detail provided and the report prepared will depend on the context required.

The report needs to demonstrate how each critical decision point outlined in this guidance has been addressed for the site, refer to **Appendix L** for a checklist. **Appendix K** includes a checklist for reviewing soil vapour data. Some aspects of this checklist may be useful in determining what information should be included in PVI assessment reports.

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- USEPA 2013, '*Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds*', Washington, DC.

APPENDIX A.

Literature Review of Available PVI Guidance

This appendix presents a summary of guidance that is currently available in Australia and International jurisdictions that addresses the assessment of PVI.

Australia

Detailed technical guidance in Australia for the assessment of PVI risks is limited, however the following are available that address PVI and more general VI guidance.

Health Screening Levels for Petroleum Hydrocarbons in Soil and Groundwater, Parts 1 to 4: CRC CARE Technical Report No. 10 (Friebel and Nadebaum 2011)

These documents outline the basis for the derivation of Health Screening Levels (HSLs) for petroleum hydrocarbons in soil, groundwater and soil vapour for 4 different land-use settings. The technical reports provide details on the approach used to derive the criteria including selection of the vapour model and parameters adopted. The HSLs have been derived on the basis that no biodegradation occurs in the subsurface, however biodegradation can be considered in the application of the criteria on the basis of the following:

- A factor of 10 may be applied for source depths from 2m to <4m or a factor of 100 may be applied for source depths of 4m and greater; where
- The maximum length of the shorter side of the concrete slab and surrounding pavement does not exceed 15m and measurement of oxygen in the subsurface supports the potential for biodegradation to occur.

The HSLs have been incorporated into the NEPM (1999 amended 2013).

NSW DECCW Vapour Intrusion Technical Guidance Note (NSW DECCW 2010)

The document provides general guidance to consultants in NSW in relation to the assessment of vapour issues. In relation to the assessment of petroleum hydrocarbons the guidance includes the following:

- The use of surface flux methods for the sampling and assessment of vapour risk issues often fail to detect petroleum hydrocarbons due to biodegradation in the near-surface surface soil;
- Biodegradation as a mechanism of risk reduction should not be assumed, but demonstrated through the collection of appropriate data;
- The collection of soil gas from depths more shallow than 1m should be avoided where near surface influences (such as biodegradation) may be of significance.

Field Assessment of Vapours: CRC CARE Technical Report No. 13 (Davis, Wright & Patterson 2009)

The report provides technical guidance on the sampling of vapours from a range of sources. The document provides a summary on the processes that underlie vapour behaviour, framework for the conduct of vapour assessments, design issues for undertaking field

assessments of vapours, and investigation and sampling techniques. More specifically for the assessment of petroleum hydrocarbons the document:

- Recognises the importance of aerobic biodegradation on the migration of petroleum hydrocarbon vapours particularly in relation to the development of CSMs;
- Provides recommendations on the most appropriate sampling techniques and depths for evaluating petroleum hydrocarbons. Primary investigation options include the collection of soil gas from >1.5m depth and <1.5m depth (where relevant). Secondary investigation options include sub-slab soil gas, indoor air (noting this may be complex as it may be influenced by background sources) and passive sampling.
- Provides discussion on exclusion/screening distances and recommends their use in Australia.
- Provides notes of caution in relation to sampling techniques where additional considerations may be required for sampling petroleum hydrocarbons.

Biodegradation of Petroleum Hydrocarbon Vapours: CRC CARE Technical Report No. 12 (Davis, Patterson & Teffry 2009)

This report reviews the role of biodegradation in reducing petroleum hydrocarbons vapour intrusion into buildings (slab-on-grade buildings) particularly in relation to the use of screening level criteria. The report provides an overview of the available science and provides the following recommendations:

- The presence of oxygen in the subsurface is an important indicator for the potential for biodegradation. Hence when utilising screening level criteria an additional exposure reduction factor may be incorporated where oxygen levels are measured in excess of 5%.
- The application of the above exposure reduction factor should only be considered where the vapour source is greater than or equal to 2m below the base of the building.
- The use of the exposure reduction factor should only be considered for slab lengths where the location of the furthest point of the house/building is no more than 7.5m from the edge of the slab.
- Where oxygen is present at the site and where the above exclusions do not apply it is appropriate that a factor of 10 may be applied for source depths from 2m to <4m or a factor of 100 may be applied for source depths of 4m and greater and the vapour source is less than 100 mg/L.

Petroleum Vapour Model Comparison: CRC CARE Technical Report No. 9 (Davis, Teffry & Patterson 2009)

This report presents an overview of the primary petroleum vapour processes, including biodegradation, and evaluation of available models for the estimation of vapour intrusion risks.

International:

Vapour intrusion, including PVI guidance is principally available from the United States with very limited guidance available from other jurisdictions. The available guidance is summarised below:

Draft Guidance:

USEPA 2011, Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites: Policy Guidance for EPA, States, and Tribes. Draft Discussion document prepared by the Office of Underground Storage Tanks (OUST), October 2011.

This guidance specifically relates to the assessment of PVI and includes guidance on the characterisation of sites (including the sampling of soil gas), preferential vapour pathways and approaches to the assessment of PVI that include:

- PVI screening criteria (including the use of exclusion/screening distances) and decision framework;
- Potential receptors and nearby buildings;
- Sub-slab sampling and analysis;
- Indoor air sampling and analysis;
- Appropriate use of models.

The guidance also provides some discussion on mitigation/remediation and community engagement.

Michigan DEQ 2012, Guidance Document for the Vapor Intrusion Pathway, Draft May 2012 prepared by the Michigan Department of Environmental Quality.

This document provides general guidance on the assessment of VI issues from a range of sources. The document however does address PVI issues including biodegradation, the use of exclusion or separation distances for the screening of PVI risks, preferential pathways, consideration of issues associated with larger buildings. Guidance for the modelling of PVI using the API BioVapor Model is also provided.

USEPA, 2002. OSWER Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance), EPA530-D-02-004.

The document provides general guidance on the assessment of VI issues from a wide range of sources. The guidance recognises the difference between VI from petroleum and chlorinated sources, however it states that many of the assumptions adopted may not be relevant to the assessment of PVI issues from UST sites and that US state and regional UST programs be consulted for the assessment of these issues. **This guidance excludes the assessment of PVI issues.**

Current Guidance:

California State Water Resources Control Board, 2012. Leaking Underground Fuel Tank Guidance Manual. September 2012.

The document provides detailed guidance on the assessment of PVI issues that include CSMs (including fate and transport of petroleum hydrocarbons and biodegradation), site assessment (soil, groundwater, soil vapour), laboratory assessment methods, risk evaluation (including the adoption of exclusion/separation distances for the screening level evaluation of PVI issues), management and remediation.

California State Water Resources Control Board, 2012. Low-Threat Underground Storage Tank Case Closure Policy (Effective August 17 2012)

The Policy establishes both general and media-specific criteria that have been established to be protective of (pose a low threat to) human health, safety and the environment. The Policy recognises, however, that even if all of the specified criteria in the Policy are met, there may be unique attributes of the case or site-specific conditions that increase the risk associated with the residual petroleum constituents which need to also be considered. The policy adopts the use of exclusion distances/screening distances (above LNAPL and dissolved phase contamination) where a bioattenuation zone is present.

USEPA, 2012, Conceptual Model Scenarios for the Vapor Intrusion Pathway, EPA 530-R-10-003.

This document presents key considerations for the development of CSMs for evaluating the VI pathway for a range of sources that include petroleum hydrocarbons (where biodegradation is of importance) and recalcitrant compounds (not subject to significant attenuation processes).

USEPA, 2012, EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings, EPA 530-R-10-002.

This document evaluates VI issues based on review of a database of vapour data for chlorinated compounds. The document relates only to chlorinated compounds and clearly states that it is **not relevant to the assessment of PVI**.

British Columbia, 2012, Guidance on Site Characterization and Evaluation of Soil Vapour Intrusion into Buildings. Report prepared by Golder Associates Ltd, submitted to the Ministry of Environment, Science Advisory Board for Contaminated Sites in British Columbia.

This document evaluates VI issues derived from a wide range of sources. The document addresses the development of CSMs for VI, subsurface characterisation and evaluation of VI, sampling of indoor air for evaluating VI, interpretation and data analysis. In relation to evaluating PVI issues the document:

- Importance of aerobic biodegradation processes that can result in orders of magnitude reduction in vapour concentrations over a relatively small distance within the vadose zone;

- Discussion on the aerobic biodegradation processes and key factors that affect the potential for biodegradation. These factors include source strength and separation distance between the source and building. Slab size and integrity may also be of importance;
- The field evaluation of petroleum hydrocarbons in soil gas should also consider oxygen and carbon dioxide levels; and
- Analytical approaches to assessment of TPH/TRH fractions in soil vapour and air.

USEPA, 2011, Petroleum Hydrocarbons And Chlorinated Hydrocarbons Differ In Their Potential For Vapor Intrusion, Office of Underground Storage Tanks, September 2011.

This document specifically discusses the differences between evaluating VI issues for petroleum and chlorinated compounds, with the focus on the issues that are specific to the assessment of PVI risks. These issues include characteristics of sources, biodegradation, identification of conditions where there is a greater potential for PVI and conducting screening level assessments.

California EPA, Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air. (Vapor Intrusion Guidance), prepared by the Department of Toxic Substances Control (DTSC), California Environmental Protection Agency, October 2011.

The document provides guidance on the assessment of VI issues from a range of sources. The guidance is presented as a series of steps (with a chapter for each step in the VI assessment process). For the evaluation of PVI issues the guidance refers to the California State Resources Control Board Leaking Underground Fuel Tank Guidance Manual. The LUFT guidance is a draft document, released in 2010.

New Jersey DEP, 2012, Vapor Intrusion Technical Guidance Document, New Jersey Department of Environmental Protection.

The document provides guidance on the assessment of VI risk issues from a range of sources. The document includes a decision framework for conducting VI assessments, investigative approaches to VI assessment, multiple lines of evidence and data evaluation, specific issues in relation to petroleum hydrocarbons and mitigation. In relation to the assessment of PVI the document includes biodegradation considerations including the use of exclusion criteria (vertical separation distances) for a screening level PVI assessment (including conditions where these are applicable). The document has included the ITRC CSM checklist.

ITRC, 2007, Vapor Intrusion Pathway: A Practical Guideline, Interstate Technology & Regulatory Council.

ITRC 2007, Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios (A Supplement to VI-1), Interstate Technology & Regulatory Council.

These documents provide a generalised framework for evaluating the VI pathway from a range of sources and describes the various tools available for investigation, data evaluation, and mitigation. The Investigative Approaches document presents approaches that may be considered for 6 typical scenarios.

API Documents:

- API (American Petroleum Institute). 1998. Assessing the significance of subsurface contaminant vapor migration to enclosed spaces: site-specific alternatives to generic estimates. API Publication No. 4674.

This initial guidance was developed by API in 1998 that specifically focused on petroleum hydrocarbon vapours.

- API (American Petroleum Institute). 2005. Collecting and interpreting soil gas samples from the vadose zone. A practical strategy for assessing the subsurface vapour-to-indoor air migration pathway at petroleum hydrocarbon sites. Regulatory Analysis and Scientific Affairs, API Publication No. 4741.

This document specifically relates to PVI issues and discusses petroleum vapour behaviour, transport and typical subsurface depth profiles; conceptual understanding based on this; sampling locations, depths and frequency; sample installations and sampling methods along with analytical methods and data interpretation.

In terms of sampling strategies, API (2005) emphasises the need to consider site specific issues. It suggests sampling at two or more depths will increase data confidence, transects and vertical profiles can be useful especially if the vapour source is distant from the site, that a soil gas sample should be collected immediately above the vapour source to obtain the highest concentration of the chemical of concern, and that a sample be obtained from adjacent to the building foundation.

Some more specific recommendations presented in the API (2005) document include:

- The shallowest sampling depth is recommended to be no less than 3 feet (about 1 m);
- A lateral separation distance of 100 feet (~30 m) is likely to be sufficient for petroleum hydrocarbon impacted sites provided the vapour source edge is well defined;
- Soil gas data collected immediately above the source can be useful in screening sites including those open sites where future buildings may be constructed; and
- Sufficient time must be allowed to pass following a spill to enable vapour concentrations to establish an equilibrium prior to sampling.

ASTM Documents:

- ASTM 1992. *Standard guide for soil gas monitoring in the vadose zone*. D5314-92 (Reapproved 2001), p. 1161-1196. American Society for Testing and Materials.
- ASTM 1995. *Standard guide for risk based corrective action applied at petroleum release sites*. Public No. E1739-95, (Reapproved 2002) American Society for Testing and Materials.
- ASTM 2005. *Standard practice for environmental site assessments: Phase I environmental site assessment process*. E1527 – 05, American Society for Testing and Materials.
- ASTM 2008. *Standard practice for assessment of vapor intrusion into structures on property involved in real estate transactions*, E2600 – 08, ASTM International.

- ASTM 2011. Standard Practice for Passive Soil Gas Sampling in the Vadose Zone for Source Identification, Spatial Variability Assessment, Monitoring, and Vapor Intrusion Evaluations. D7758-11, ASTM International.
- ASTM 2012. Standard Practice for Active Soil Gas Sampling in the Vadose Zone for Vapor Intrusion Evaluations. D7663-12, ASTM International.

UK Guidance:

- CIRIA 2007. Assessing risks posed by hazardous ground gases to buildings. Report C665.
- CIRIA 2009. The VOCs handbook: investigating, assessing and managing risks from inhalation of VOCs at land affected by contamination. Report C766. London.

There appears to be limited guidance on vapour assessment in the United Kingdom, although a “VOCs Handbook” was released in July 2009 (CIRIA, 2009). There has been a strong emphasis on ground gas hazards (CIRIA, 2007) in the United Kingdom – which relate primarily to methane in soil gas that may be an explosive hazard, but also carbon dioxide, hydrogen sulphide and carbon monoxide risks. CIRIA (2007) refers to vapours, but directs further investigations to the USEPA (2002) draft and UK EA (2005). The UK has well developed guidance on vapour intrusion modelling (Evans *et al.*, 2002).

In CIRIA (2009), a three tiered risk assessment approach is described. It includes: (i) a preliminary risk assessment effectively based on a Phase I ESA; (ii) a generic quantitative risk assessment based on site investigation data and possible use of generic screening criteria; and (iii) a detailed quantitative risk assessment based on further intrusive site investigations and data. It outlines a vapour investigation strategy, and a broad range of exploratory and analytical techniques. CIRIA (2009) stresses the need to consider site specific issues, and to be guided by the CSM and DQO developed for the site. For soil gas sampling, they recommend targeting potential hot spot locations, points of potential exposure, and uncontaminated areas to obtain soil gas background. API (2005) is referenced for guidance on locations and sampling systematics.

Other US State Guidance:

The following presents a list of other US State Guidance relevant to the assessment of PVI issues:

- Alaska Department of Environmental Conservation. July 2009. [Draft Vapor Intrusion Guidance for Contaminated Sites \(PDF\)](#).
- Arizona Department of Environmental Quality. July 2008, revised May 19 2011. [Soil Vapor Sampling Guidance \(PDF\)](#).
- California Environmental Protection Agency, Department of Toxic Substances Control. October 2011. [Vapor Intrusion Mitigation Advisory \(PDF\)](#).
- California Environmental Protection Agency. Department of Toxic Substances Control. November 2004. [Advisory on Methane Assessment and Common Remedies at School Sites \(PDF\)](#).
- California Environmental Protection Agency. Department of Toxic Substances Control. April 2012. [Advisory – Active Soil Gas Investigation](#).

- Colorado Department of Labor and Employment. December 2007. [Petroleum Hydrocarbon Vapor Intrusion Guidance Document \(PDF\)](#).
- Colorado Department of Public Health and Environment. September 2004. [Draft Indoor Air Guidance \(PDF\)](#).
- Delaware Department of Natural Resources and Environmental Control. March 2007. [Policy Concerning the Investigation, Risk Determination, and Remediation for the Vapor Intrusion Pathway \(PDF\)](#).
- Hawaii Department of Health. Summer 2008, updated March 2009. [Screening for Environmental Hazards at Sites with Contaminated Soil and Groundwater](#).
- Idaho Department of Environmental Quality. January 2011. [Draft Idaho Risk Evaluation Manual for Petroleum Releases](#).
- Indiana Department of Environmental Management. 2011. [Remediation Closure Guide. Section 5: Conceptual Site Model \(CSM\) Development: Vapor](#).
- Indiana Department of Environmental Management. April 2006. [Draft Vapor Intrusion Pilot Program Guidance \(PDF\)](#).
- Indiana Department of Environmental Management. February 2010. [Supplement to the Draft Vapor Intrusion Pilot Program Guidance \(PDF\)](#).
- Indiana Department of Environmental Management. March 2009. [Investigation of Underground Storage Tank Releases: Quality Assurance Program Plan \(PDF\)](#).
- Indiana Department of Environmental Management. October 2007. [Addendum to the Draft Vapor Intrusion Pilot Program Guidance](#).
- Iowa Department of Natural Resources. November 1996. [Tier 1 Guidance: Site Assessment of Leaking Underground Storage Tanks \(LUST\) Using Risk-Based Corrective Action \(RBCA\) \(PDF\)](#).
- Iowa Department of Natural Resources. November 1996. [Tier 2 Site Cleanup Report Guidance: For Assessing Leaking Underground Storage Tanks \(LUST\) Using Risk-Based Corrective Action \(RBCA\) \(PDF\)](#).
- Kansas Department of Health and Environment. June 2007. [Kansas Vapor Intrusion Guidance: Chemical Vapor Intrusion and Residential Indoor Air \(PDF\)](#).
- Maine Department of Environmental Protection. August 2009. [Draft Indoor Air Sample Protocol \(PDF\)](#).
- Maine Department of Environmental Protection. August 2009. [Procedure for Evaluating Vapor Intrusion at Dry Cleaner and Petroleum Sites \(PDF\)](#).
- Maine Department of Environmental Protection. January 2010. [Vapor Intrusion Evaluation Guidance \(PDF\)](#).
- Maine Department of Environmental Protection. November 2009. [Remediation Guidelines for Petroleum Contaminated Sites in Maine \(PDF\)](#).
- Maine Department of Environmental Protection. October 1998. [Trial Guideline for Protecting Residents from Inhalation Exposure to Petroleum Vapors: Trial Period Findings \(PDF\)](#).
- Massachusetts Department of Environmental Protection. April 2002. [Indoor Air Sampling and Evaluation Guide \(PDF\)](#).
- Massachusetts Department of Environmental Protection. August 2007. [Standard Operating Procedure for Indoor Air Contamination \(PDF\)](#).
- Massachusetts Department of Environmental Protection. December 1995. [Guidelines for the Design, Installation, and Operation of Sub-Slab Depressurization Systems \(PDF\)](#). Northeast Regional Office.

- Massachusetts Department of Environmental Protection. December 2011. [Interim Final Vapor Intrusion Guidance](#).
- Massachusetts Department of Environmental Protection. October 2002. [Characterizing Risks Posed by Petroleum Contaminated Sites: Implementation of the MADEP VPH/EPH Approach \(PDF\)](#).
- Michigan Department of Environmental Quality. June 2008. [Remediation and Redevelopment Division Operational Memorandum No. 4. Site Characterization and Remediation Verification Peer Review Draft \(PDF\)](#).
- Michigan Department of Environmental Quality. October 2004. [Indoor Air Designated Methods and Target Detection Limits \(PDF\)](#).
- Minnesota Pollution Control Agency. February 2009. [Indoor Air Sampling at Vapor Intrusion Sites: Introduction, Methods, and Interpretation of Results \(PDF\)](#).
- Minnesota Pollution Control Agency. September 2008. [Risk-Based Guidance for the Vapor Intrusion Pathway \(PDF\)](#).
- Minnesota Pollution Control Agency. August 2010. [Vapor Intrusion Technical Support Document \(PDF\)](#).
- Minnesota Pollution Control Agency. October 2010. [Vapor Intrusion Assessments Performed During Site Investigations \(PDF\)](#).
- Missouri Department of Natural Resources. April 2005. [Missouri Risk-Based Corrective Action for Petroleum Storage Tanks: Appendix C - Evaluation of Indoor Inhalation Pathway \(PDF\)](#).
- Missouri Department of Natural Resources. April 2005. [Missouri Risk-Based Corrective Action for Petroleum Storage Tanks: Soil Gas Sampling Protocol \(PDF\)](#).
- Missouri Department of Natural Resources. April 2006. [Missouri Risk-Based Corrective Action Technical Guidance \(PDF\)](#).
- Montana Department of Environmental Quality. April 2011. [Montana Vapor Intrusion Guide \(PDF\)](#).
- Nebraska Department of Environmental Quality. May 2009. [Risk-Based Corrective Action \(RBCA\) at Petroleum Release Sites: Tier 1/Tier 2 Assessments and Reports \(PDF\)](#).
- New Hampshire Department of Environmental Services. July 2011. [Waste Management Division Update RE: Vapor Intrusion Guidance \(PDF\)](#).
- New Jersey Department of Environmental Protection. 2005. [Field Sampling Procedures Manual](#).
- New York State Department of Health. February 2005. [Indoor Air Sampling and Analysis Guidance](#).
- New York State Department of Health. October 2006. [Guidance for Evaluating Soil Vapor Intrusion in the State of New York](#).
- North Carolina Department of Environment and Natural Resources. February 2011. [Vapor Intrusion Screening Levels](#).
- North Carolina Department of Environment and Natural Resources. October 2010. [Supplemental Guidelines for the Evaluation of Structural Vapor Intrusion Potential for Site Assessments and Remedial Actions Under the Inactive Hazardous Sites Branch \(PDF\)](#).
- Ohio Environmental Protection Agency. May 2010. [Sample Collection and Evaluation of Vapor Intrusion to Indoor Air: For Remedial Response and Voluntary Action Programs: Guidance Document \(PDF\)](#).

- Oregon Department of Environmental Quality. March 2004. [Screening Model for Volatilization from Soil to Indoor Air at Heating Oil Tank Sites.](#)
- Oregon Department of Environmental Quality. March 2010. [Guidance for Assessing and Remediating Vapor Intrusion in Buildings \(PDF\).](#)
- Oregon Department of Environmental Quality. September 2003. [Risk-Based Decision Making \(RBDM\) for the Remediation of Petroleum-Contaminated Sites.](#)
- Pennsylvania Department of Environmental Protection. February 2002. [Vapor Intrusion into Buildings from Groundwater and Soil under Pennsylvania \(PA\) Act 2 Statewide Health Standard \(SHS\) \(PDF\).](#)
- South Carolina Department of Health and Environmental Control. May 2001. [South Carolina Risk-Based Corrective Action for Petroleum Releases \(PDF\).](#)
- Tennessee Department of Environment and Conservation. January 2008. [Technical Guidance Document 018, Requirements for Conducting Soil Gas Surveys \(PDF\).](#)
- Tennessee Department of Environment and Conservation. May 2008. [Technical Guidance Document 020, Requirements for Petroleum Vapor Impact Management \(PDF\).](#)
- Utah Department of Environmental Quality. November 2010. [Guideline for Utah's Corrective Action Process for Leaking Underground Storage Tank Sites \(PDF\).](#)
- Virginia Department of Environmental Quality. August 2008. [Vapor Intrusion Screening Fact Sheet \(PDF\).](#)
- Washington State Department of Ecology. October 2009. [Draft Guidance for Evaluating Soil Vapor Intrusion in Washington State: Investigation and Remedial Action.](#)
- West Virginia Department of Environmental Protection. November 1999. [User Guide for Risk Assessment of Petroleum Releases \(PDF\).](#)
- Wisconsin Department of Health and Family Services. February 2003. [Chemical Vapor Intrusion and Residential Indoor Air: Guidance for Environmental Consultants and Contractors \(PDF\).](#)
- Wisconsin Department of Natural Resources. December 2010. [Addressing Vapor Intrusion at Remediation & Redevelopment Sites in Wisconsin \(PDF\).](#)

APPENDIX B.

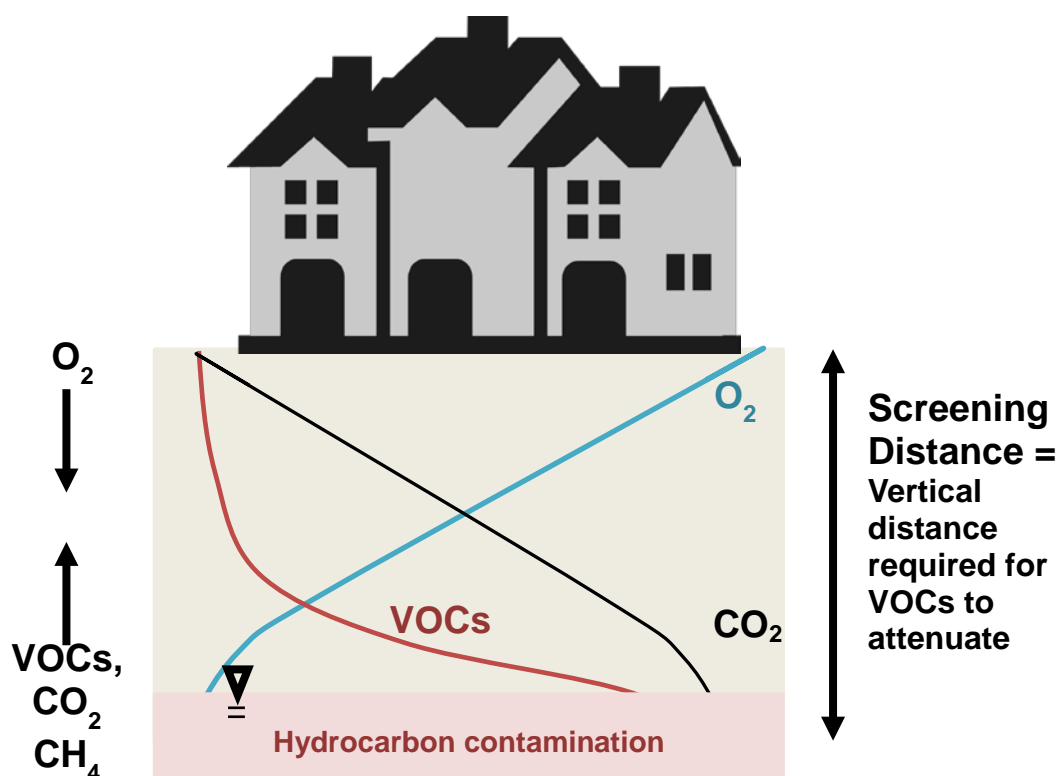
Determination of Screening Distances and Slab Size

B1 Screening Distances

Use of screening distances (which may also be referred to as separation distances and/or exclusion distances/criteria) recognises that petroleum hydrocarbons biodegrade, typically under aerobic conditions, and that this biodegradation occurs over relatively short vertical and lateral distances.

A screening distance is the minimum thickness of uncontaminated soil that is sufficient to effectively attenuate petroleum vapours such that they do not pose a risk to human health (i.e. the potential for vapour intrusion is considered negligible), and no further assessment of PVI is required.

In this guidance, screening distances are applied as vertical distances (i.e. distance vertically from the contamination to building foundation) as illustrated in the conceptual diagram below. However it is noted that the principles that underlie vertical screening distances apply in all directions from the contamination.



Screening distances have been determined for dissolved-phase and LNAPL hydrocarbon contamination using empirical soil gas and groundwater data from Australia, the United States and Canada that include:

- Davis (2009) estimated that 5 ft (1.5 m) and 30 ft (~10 m) thicknesses of clean soil are required to attenuate petroleum hydrocarbon vapours emanating from dissolved-phase and LNAPL sources, respectively, to non-detectable levels. The analysis was based on an evaluation of 259 benzene and 210 total petroleum hydrocarbon (TPH/TRH) vapour samples from 53 geographical locations in the US and Canada. Dissolved-phase sites were defined on the basis of benzene concentrations in groundwater < 1 mg/L. Further review of data from this database for UST sites only (excluding refineries) (Davis 2011; USEPA 2013) supported a screening distance of 5 ft (1.5 m) for dissolved phase sources (benzene < 1 mg/L and TPH/TRH < 10 mg/L) and further refined the screening distance for LNAPL sources to 8 to 15 ft (2.5 to 4.5 m).
- Peargin and Kolhatkar (2012) evaluated 218 pairs of benzene soil vapour and groundwater concentration data from 25 sites (20 in California). Potential risks for vapour intrusion, defined as benzene concentrations in soil gas > 300 µg/m³ (which corresponds to a 10⁻⁵ risk-based threshold concentration in deep soil gas, adopted from USEPA (USEPA 2002)), were only observed at locations where benzene concentrations in groundwater exceeded 1 mg/L. Benzene concentrations in soil gas < 300 µg/m³ were observed above dissolved-phase sources with benzene concentrations < 1 mg/L, regardless of the vertical separation distance, irrespective of hydrocarbon source type.
- Wright (2011) examined 1080 pairs of petroleum hydrocarbon (BTEX, TPH/TRH and hexane) soil vapour and groundwater concentration data collected at 124 primarily UST sites in Australia. Forty one per cent of the soil-gas data were associated with fractured rock aquifer systems and 12% were collected below building foundations (i.e., sub slab). Wright's analysis resulted in vertical screening distances of 5 ft (1.5 m) for relatively "low-strength" dissolved-phase sources (benzene < 1 mg/L and TPH/TRH < 10 mg/L) and around 30 ft (10 m) for: (a) all LNAPL sources; and (b) poorly characterised dissolved-phase sources. Further review of the LNAPL data by Wright (2012) identified that where data from fresh pipeline leaks/refineries and from beneath slabs were excluded a screening distance of 18 ft (5.6 m) could be supported by the empirical data where there were LNAPL or poorly characterised sources. The screening distances were defined assuming a vapour concentration that was 5% of the lowest HSL (Friebel & Nadebaum 2011) for all soil types and depths (e.g. for benzene the lowest HSL is 1 mg/m³, and 5% of this value is 0.05 mg/m³).
- Review of data from UST sites (excluding those with fractured rock) from the above databases (Lahvis et al. 2013) supported a screening distance from LNAPL sources of 13 ft (4 m).
- Review (USEPA 2013) of all the available databases from the US, Canada and Australia, which include the larger databases compiled by Davis (2009) and Wright (2011) supported a screening distance of approximately 5 ft (1.5 m) for dissolved-phase hydrocarbon sources and 15 ft (4.6 m) for LNAPL derived from UST sites and 20 ft (6.1 m) for LNAPL derived from non-UST sites. The review considers these distances to be robust as they are derived from high-quality data.

The reviews (as noted above) conducted on the available databases have shown that screening distances depend on the strength of the source as well as the thickness of the

overlying uncontaminated soil (between the source and receptor/building foundation). The screening distances are also relevant to all soil types, with no significant difference identified in the analysis of data from fine or coarse grained overlying soil types. In addition the review conducted by Wright (2011, 2012) showed that the screening distances were not significantly different for sites characterised with overlying fractured rock. The screening distances identified are consistent with outcomes determined with vapour modelling where biodegradation is considered (USEPA 2013; Wright 2012).

Based on the evaluations conducted, the following distances have been determined:

Dissolved Phase:

For dissolved phase sources, characterised with concentrations of benzene ≤ 1 mg/L and TPH/TRH ≤ 10 mg/L, the screening distance = 1.5 m (approximately 5 ft).

The established screening distance for these contamination sources is relevant to all soil types (including fractured rock). In addition, for these contamination sources, the presence of a slab (regardless of size) has not been shown to affect the criteria established.

LNAPL:

For LNAPL sources (and dissolved phase concentrations in excess of the concentrations presented above) where refinery sites and significant pipeline leaks (such as from high-pressure pipelines) and large slabs are excluded, the screening distance = 3 m to 5.6 m (approximately 10 to 18 ft).

While limited data is available, the available data suggests that the presence of large slabs may be of importance where LNAPL is present in the subsurface beneath a significant part of the building (i.e. more than 50% of the slab). The presence of large slabs has not been shown to be of importance for higher level dissolved phase sources that do not meet the criteria defined for LNAPL.

Soil:

It is not possible at this time to establish screening distances for PHC contamination sorbed to soil due to a lack of data on which to base an evaluation. Also it is more common that if significant soil contamination is present on a site, the most straightforward approach is to remediate it. If LNAPL is present in soil, and the extent is delineated, then the LNAPL criteria can be considered.

For the purpose of establishing screening criteria that can be adopted in Australia, it is acknowledged that the science involved in establishing these criteria, while showing consistent results and gaining acceptance, is relatively new in Australia. Hence the approach adopted in Australia is to apply an uncertainty factor to the above criteria. Once the use of screening distances is further understood and accepted in Australia the potential inclusion of an uncertainty factor can be re-evaluated.

When considering if an uncertainty factor is required or not the following points should be noted:

- The USEPA (2013) provided a detailed evaluation (and statistical analysis) of the available databases and concluded that screening distances could be derived based

on robust, good-quality data. The outcomes of the assessment were supported by modelling studies.

- The assumptions used to derive the screening distances (from the databases) are conservative, as noted below.
- At many of the sites in the empirical databases, the depth to LNAPL was overestimated because the height of the smear zone was not identified (i.e. the depth to groundwater was used as the depth to LNAPL). Actual screening distances at these sites would be less by up to a few feet or more depending on the extent of water-table fluctuations therefore the calculated screening distance for LNAPL will be conservative.
- The estimated vertical screening distances determined in the USEPA review were based on approximately a 95th percentile rather than an average which is very conservative.
- For the sites in the database, the only cases where PVI occurred when there was > 15 ft (4.6 m) vertical separation distance were for LNAPL sources where there was no clean soil present above the LNAPL source. Other sites where PVI has been observed in the databases are where LNAPL is in close proximity to a building foundation (<3 m) or high dissolved phase/LNAPL had seeped into the building.
- The indoor air screening level for benzene (or any carcinogen) is based on the assumption that the concentration will not change over a lifetime of 30 to 70 years (for a residential exposure). This assumption is very conservative for chemicals that are volatile and that emanate from a source that is depleting and weathering rapidly.
- The anaerobic biodegradation of ethanol blended fuels may produce significant amounts of methane (Freitas et al. 2010; Ma et al. 2012). Methane also biodegrades under aerobic conditions and consumes oxygen that otherwise could be available for the biodegradation of the PHC contaminants. This effect has not been well studied and while some of the data available in the databases include more recent leaks of ethanol blended fuels the influence (if any) of these fuels on screening distances has not been determined.

On the basis of the above, there is no clear technical reason to include an uncertainty factor, however it is important to recognise that the Australian regulatory environment has not conducted the same level of rigorous review of the information as has been undertaken by the USEPA. Screening distances are a new concept in Australia and hence to address this uncertainty a small uncertainty factor of 1.5 fold has been applied to the screening distances obtained from the analysis of the databases.

Following this approach the following screening criteria have been established for the conduct of screening level PVI assessments in Australia:

Source##	Screening Distance Based on Good Science	Uncertainty Factor#	Screening Distance Adopted in this Guidance
Dissolved Phase Benzene ≤ 1 mg/L TPH/TRH ≤ 10 mg/L	1.5 m	1.5	2 m
Higher dissolved phase and LNAPL excluding refineries, significant pipeline leaks and large slabs*	3 to 5.6 m	1.5	8 m (based on upper end of range)

Uncertainty factor applied. The adopted screening distances have been rounded to 1 significant figure (relevant for the level of accuracy for these measurements and application of the screening distances). This is expected to be further reviewed and refined.

Source concentrations considered in this table are based on the database evaluations conducted. Review by the USEPA (2013) has further refined the screening criteria to apply to all dissolved phase concentrations (<5mg/L benzene and <30 mg/L TPH/TRH). This aspect of the screening distances may be further refined.

* Review of the available data by Wright (2011) indicated that based on the limited data available for LNAPL sites where LNAPL is present beneath a significant part of the slab (i.e. more than 50% of the slab), for a screening distance of 8m, larger slabs (approximately 6-7 m from the centre to the closest building edge) showed the potential to limit biodegradation. This is consistent with the finding of Davis, Patterson & Teffry (2009a) where a slab size of 7.5 m from centre to edge was determined to be important in relation to the potential for biodegradation to occur everywhere beneath the slab. On the basis of these evaluations the slab size that has the potential to limit biodegradation beneath part of the slab needs to be considered in the application of the LNAPL screening distance. Refer to **Appendix B2** for further details on determining the slab size where it is appropriate to use the screening distance, and those where it is not.

It is noted that the available data show that the presence of slabs (regardless of size) has not been shown to be of importance for the determination of separation distances for dissolved phase sources (at all strengths below that used to define the presence of LNAPL). Hence the consideration of slab size in the application of screening distances has only been shown to be relevant for LNAPL sources.

B2 Slab Size

The question of whether the presence of slab (and what size of slab) has the potential to limit the migration of oxygen beneath the building to the point where biodegradation (observed when collecting soil gas data in open ground) is impeded and where petroleum hydrocarbons are not attenuated before they reach the slab has been the subject of ongoing discussion in PVI assessments.

Within the development of the Health Screening Levels (Friebel & Nadebaum 2011) a simple approach was adopted for determining the size of the slab that may have the potential to limit oxygen migration and biodegradation. This approach was based on one size of slab for all scenarios, where slabs that were a minimum of 7.5 m from the centre to the edge of the slab (including continuous concrete surrounding the building) were considered to be sufficient to limit oxygen migration and biodegradation (Davis Patterson & Jeffry 2009a).

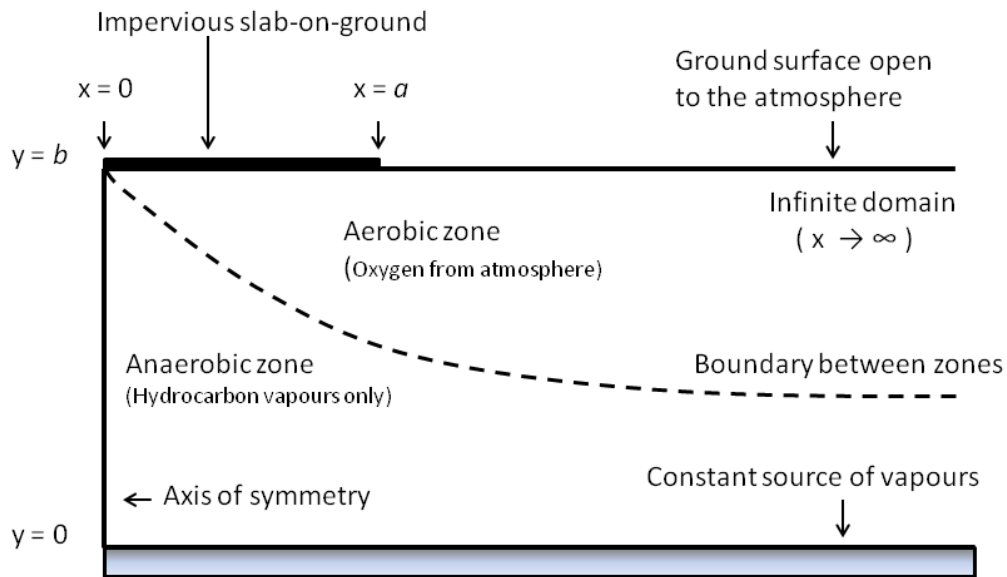
Some published studies indicate that the presence of the slab does have the potential to limit biodegradation at the centre of the slab (Luo et al. 2009; Patterson & Davis 2009), while others have not shown any effect with the presence of the slab (Lundegard, Johnson & Dahlen 2008; USEPA 2013).

Further review has indicated that the potential for slab size to be of importance in limiting the potential for biodegradation is not only related to the size of the slab, it is also related to the concentration of the source and the depth of the source (Davis 2013; Wright 2011).

Review of Australian and US databases (Lahvis et al. 2013; USEPA 2013; Wright 2011) have indicated that for low dissolved phase sources, the presence of a slab, regardless of size, does not affect the potential for biodegradation to occur beneath the building/slab. For higher strength dissolved phase sources the same reviews have not indicated that slab size is of significance, however the data available in relation to these scenarios is limited. The potential presence of LNAPL sources however has been identified as a situation where the size of the slab may be of importance in relation to biodegradation. The studies where biodegradation is limited at the centre of the slab are those where there is LNAPL present (Luo et al. 2009; Patterson & Davis 2009) and the source is relatively shallow.

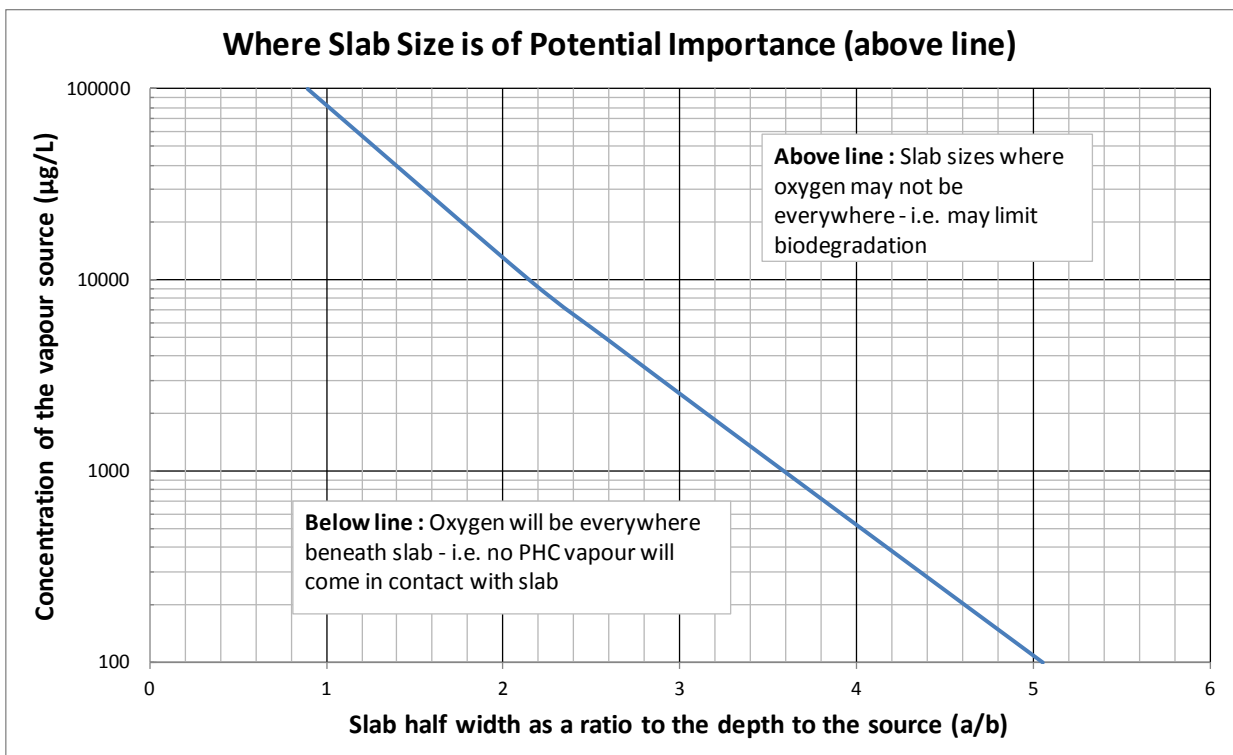
To further develop a more appropriate approach to determining when, and what size, a slab may be of importance in limiting biodegradation, the instantaneous-reaction model (Davis, Patterson & Jeffry 2009b) has been used with some conservative assumptions (i.e. that the concrete slab is continuous and impervious, there is no advection that may result in the pressure driven movement of oxygen beneath the slab and there is a constant and infinite source of vapours) to develop a relationship between the potential for biodegradation and distance from the edge of the slab and the depth of the source (Davis 2013; Knight & Davis 2013). This is simply illustrated in the following diagram (from Davis 2013).

In this appendix (and throughout the document) when determining if a slab is big enough to limit the potential for biodegradation beneath the whole slab, the slab referred to is a continuous sealed surface that may include a building and/or a continuous concrete pavement (such as a footpath around a building slab). Note that gaps for gardens, paving and even gaps between different paved surfaces are sufficient to allow oxygen migration into the subsurface and are not considered in the definition of a large slab.



Simple illustration of modelling undertaken to develop relationship between slab size/ source depth and potential for biodegradation to be important (from Davis, 2013).

Based on this model a relationship between the distance from the edge of the slab and the depth to the source (a/b , as illustrated above) and the potential for oxygen to be present everywhere beneath the slab has been developed for different hydrocarbon (total hydrocarbon) vapour source concentrations (Davis, 2013). This relationship is illustrated below:

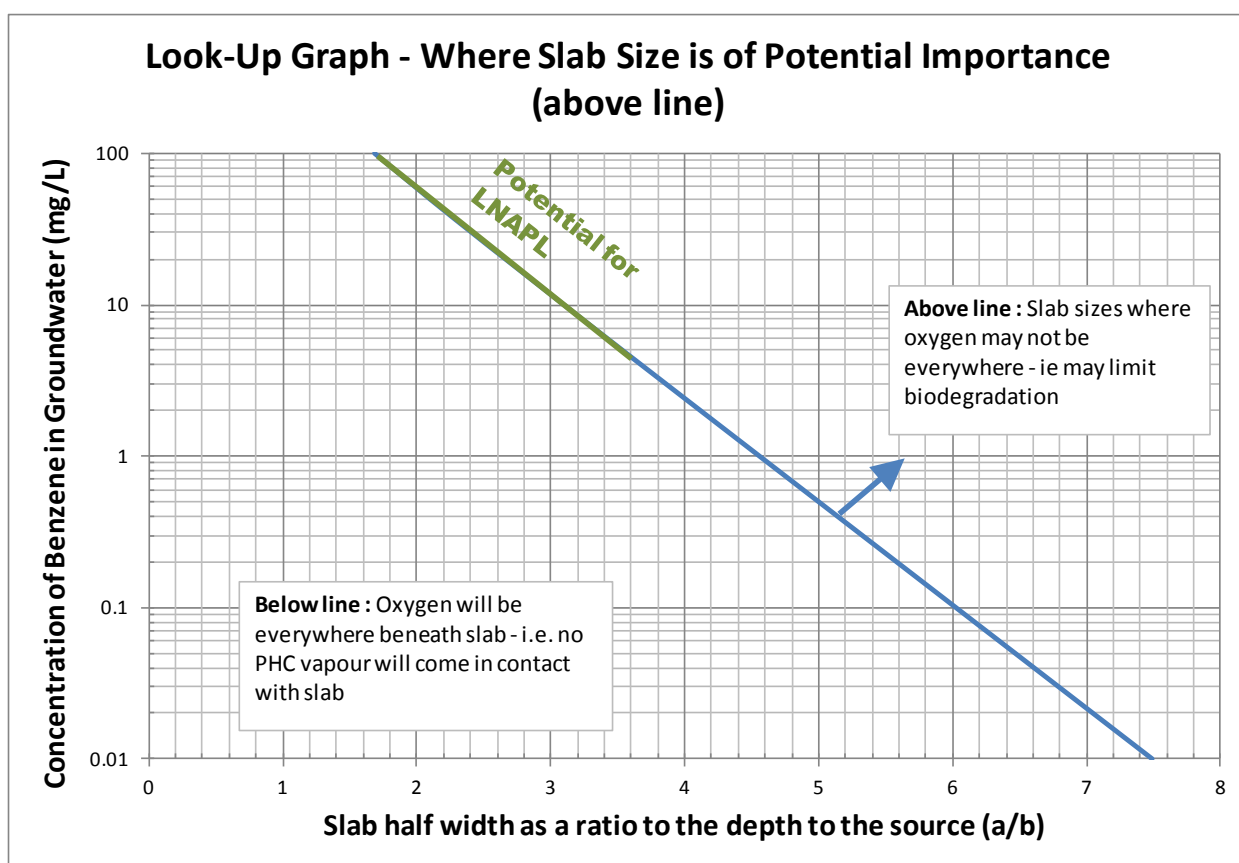


Graph B1 – Slab Size Determination vs Vapour Concentration at Source (Davis, 2013)

For such a relationship to be used in this guidance as a tool to determine when a slab may be considered sufficiently large (i.e. a “big slab”) that it may limit the potential for biodegradation to occur, the following has been undertaken:

- The source concentration (derived on the basis of a hydrocarbon vapour concentration as shown above) has been converted to a concentration in groundwater using Henry’s Law. This has been undertaken for the key compound that drives a vapour risk, namely benzene¹;
- Where source concentrations are expected to be associated with LNAPL, these have been identified to assist in determining what relationship may be relevant for sites where no concentrations are available, only LNAPL reported.

The relationship developed for benzene in groundwater is presented in the following graph that can be used as a lookup for determining when the slab size is important.



Graph B2 – Slab Size Determination vs Benzene in Groundwater (“Potential for LNAPL” occurs above a benzene concentration in groundwater of 5 mg/L)

¹ It is noted that this relationship is conservative for other aromatic PHCs. In relation to aliphatic PHCs the potential for phase partitioning is limited by the saturated vapour phase concentration which limits the significance of this relationship. As benzene is the key risk driver at PHC sites (where the vapour pathway is complete) the relationship has been established for this compound.

Based on the above, the following table provides a range of examples of the slab sizes that may be of importance, covering commonly encountered depths and concentrations.

	Slab size (minimum diameter of continuous slab) that may limit potential for biodegradation for various benzene source concentrations (m)						
Benzene source concentration (mg/L)	0.5	1	1.5	2	2.5	3	5
Depth to Groundwater (m)							
0.5	5	4.6	4.3	4.1	4	3.9	3.5
1	10	9.1	8.6	8.2	8	7.7	7
1.5	15	14	13	12	12	12	11
2	20	18	17	16	16	15	14
3	30	27	26	25	24	23	21
4	40	36	34	33	32	31	28
5	50	46	43	41	40	38	35
8	80	73	69	66	64	62	56
10	100	91	86	82	80	77	71
15	150	140	130	120	120	116	110
20	200	180	170	160	160	154	140

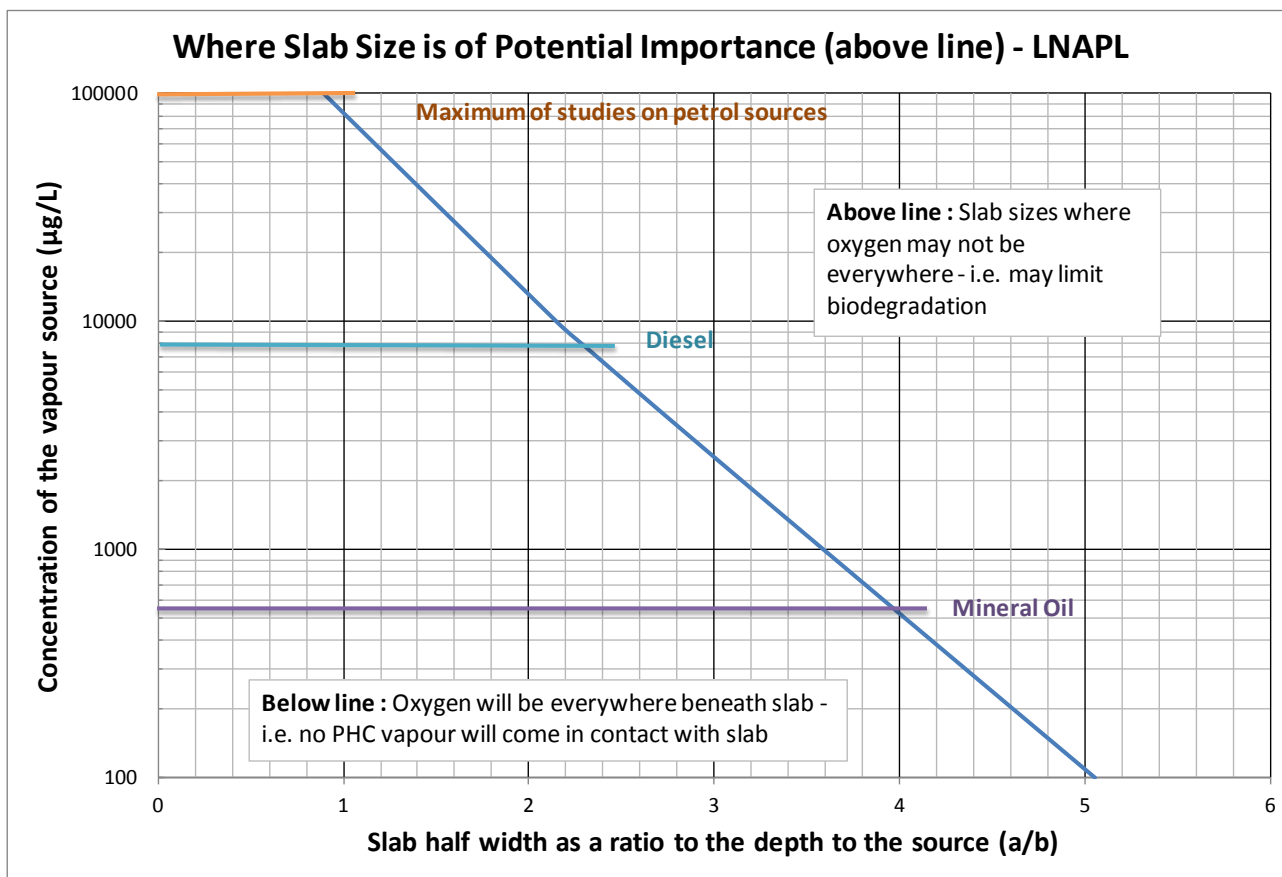
In relation to the presence of LNAPL, the determination of a slab size that is important in a PVI assessment will depend on the nature of the LNAPL present and potential concentrations of hydrocarbon vapours. When evaluating a vapour concentration from an LNAPL source, this is undertaken using Raoult's Law where the mole fraction of each key compound is considered in the calculation. For the range of products likely to be identified in a PVI assessment (mostly from various fuel product storages from current or former service stations), the total hydrocarbon vapour concentration has been considered in relation to the relationship developed by Davis (2013).

The products considered include the following:

- **Petrol:** This includes petrol sources that comprise hydrocarbons in the range C4-C12. The LNAPL calculation is based on the maximum total hydrocarbon vapours derived from fresh petrol.
- **Diesel:** This includes diesel fuel and light fuel oils comprising hydrocarbons typically in the range C10-C20.
- **Mineral oil:** These are (non-synthetic) oils comprising long hydrocarbon chains typically in the range of C15-C50 that include heavy fuel oils, automotive oils (such as engine oils) and lubricating oils.

It is expected that the assessment of PVI will need to consider a range of LNAPL sources that range from fresh to weathered. The calculations undertaken to develop the following graph and table are based on hydrocarbon vapours that may be derived from a fresh LNAPL source and will be conservative for weathered sources. A more refined assessment can be

undertaken if total hydrocarbon vapours have been measured close to the LNAPL source. These data can be directly used in conjunction with **Graph B1**.



Graph B3 – Slab Size Determination vs Vapour Concentration at Source for LNAPL Sources

Based on the above, the following table provides a range of examples of the slab sizes that may be of importance for different types of LNAPL sources, covering commonly encountered depths.

LNAPL source	Slab size (minimum diameter of continuous slab) that may limit potential for biodegradation for various LNAPL sources (m)		
	Mineral Oil	Diesel	Maximum Petrol-Type Source
Depth to Groundwater (m)			
1	8	4.6	1.8
1.5	12	7	2.7
2	16	9.2	3.6
3	24	14	5.4
4	32	18	7.2
5	40	23	9.0
8	63	37	14
10	79	46	18
15	120	69	27
20	160	92	36

The above approach is used to assist in screening out those sites where the slab-size will not be important for using screening distances and for determining appropriate depths for collecting soil gas data.

If the slab size is of potential importance, this does not mean that there is a risk to occupants in the building, only that there is the potential for biodegradation to be limited beneath some part of the building. It is then appropriate to collect more site specific data (i.e. soil gas data) to further evaluate the potential risk. It is noted that if soil gas data is collected from close to the source the potential for the slab size to be of importance can be refined using either **Graph B1 or B3**.

In determining what size slabs may be present on a particular site, where a future low-density residential development is planned, then it is reasonable to adopt the default slab size of 15m (or 7.5m from centre to the edge of the slab) to cover a wide range of building sizes and styles that may be constructed.

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APPENDIX C.

Key Chemicals and Assessment Criteria

The following presents the list of key chemicals that need to be included in PVI assessments along with relevant acute, chronic and odour air criteria and information to assist in the evaluation and interpretation of crawl space and indoor air data that may be collected from a site.

The collection of soil vapour data for the assessment of PVI risk should include the sampling and reporting of fixed gases (refer to **Appendix E** for methods), with oxygen, carbon dioxide and methane levels reported as a minimum.

Summary of Available Guidelines

In relation to the guidelines/criteria presented in **Table C1**, the following should be noted:

- Acute air guideline, in this context, is for use in assessing short-term exposure to vapours intruding from contaminated soil or groundwater but is not for use in assessing emergency releases and spills. In relation to the key chemicals assessed, there are few acute guidelines available. Where available the lowest guideline has been adopted from published peer-reviewed sources.
- Chronic air guideline, in this context, is for use in assessing long-term exposure to vapours intruding from contaminated soil or groundwater. In relation to the key chemicals assessed the chronic guidelines have been identified on the basis of guidance provided by enHealth (2012) and NEPC (1999). More specifically for BTEX, naphthalene and TPH/TRH the criteria adopted are from sources identified and considered in the derivation of the petroleum HSLs (Friebel & Nadebaum 2011a, 2011b, 2011c and 2011d), with the exception that the ethylbenzene value adopted below reflects the finalised value from ATSDR.
- Odour threshold, in this context, is for assessing when odours may be present due to vapour intrusion or if odours are likely during remediation works. Odour values have been adopted from published peer reviewed sources, with the minimum generally presented in the table below.

In the assessment of PVI risks (where there are no other sources involved) it is appropriate that analysis of relevant samples only report the analytes reported in **Table C1**.

Table C1 Summary of Key PHC to be Considered in PVI Assessment and Relevant Acute and Chronic Air Guidelines

Key Chemicals	Media in which PHC is to be evaluated in PVI Assessment			Acute Air Guideline ($\mu\text{g}/\text{m}^3$)	Averaging Time	Reference	Chronic Air Guideline ($\mu\text{g}/\text{m}^3$)	Reference	Odour Threshold ($\mu\text{g}/\text{m}^3$)	Reference
	Soil	GW	Vapour							
Key Individual PHCs										
Benzene	Y	Y	Y	29 to 170	14 days to 1 hour	26,1	1.7 (1×10^{-5} risk)	2	8 700	3
Toluene	Y	Y	Y	Note 1	--	--	5 000	4	640	5
Ethylbenzene	Y	Y	Y	22 000	14 days	6	260	6	740	7
Xylenes	Y	Y	Y	8 800	14 days	8	870	9	180	10
Naphthalene	Y	Y	Y	1 600	1-30 days	11	3	12	440	13
Hexane			Y	Note 1	--	--	700	15	5 300	16
Heptane			Y	Note 1	--	--	26 000	18	625 000	19
Cyclohexane			Y	Note 1	--	--	6000	21	87 000 – 105 000	22
Trimethylbenzenes			Y	660	30 mins	22	220	23	2 000 – 12 000	24, 22
TPH/TRH										
Aromatic C6-C10	Y	Y	Y	Assessed as BTEX (individual compounds)						
Aliphatic C6-C10			Y	Note 1	--	--	18 400	25	5 300 - 625 000	16/ 19, 20
Aromatic >C10-C16	Y	Y	Y	1 600	1-30 days	11, 17	200	25	440	13, 17
Aliphatic >C10-C16			Y	Note 1	--	--	1 000	25	Note 1	--
Key Indicators										
Oxygen			Y							
Carbon Dioxide			Y							
Methane			Y	Note 2						

Note 1: No suitable value could be found for these chemicals/categories. The other data provided in the table should enable any site to be fully assessed with regard to petroleum hydrocarbons contamination from various fuel types. If acute risk from contamination by a specific solvent (such as hexane alone) was to be assessed then a literature review to develop a suitable criteria would be required.

Note 2: A field landfill gas meter may give erroneous readings for methane at sites highly contaminated with petroleum. If this occurs take a sample that can be analysed at the laboratory and evaluate potential acute risks using explosive criteria as presented in the main PVI document.

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9. <http://www.inchem.org/documents/ehc/ehc/ehc190.htm> (last paragraph section 10.1)
10. http://www.tceq.state.tx.us/assets/public/implementation/tox/dsd/final/xylenes_all_isomers_final_2-13-09.pdf
11. <http://www.epa.gov/oppsrrd1/REDS/naphthalene-red.pdf>. The acute criteria adopted for naphthalene is based on the lowest NOAEL identified from short-term inhalation exposure studies with an application of a 10 fold uncertainty factor to address interspecies extrapolation. Note that the USEPA assessment has not considered any uncertainty factor in the application of the NOAEL.
12. <http://www.epa.gov/iris/toxreviews/0436tr.pdf>
13. <http://www.epa.gov/ttn/atw/hlthef/naphthal.html>
14. [Based on toluene as surrogate](#)
15. <http://www.epa.gov/iris/toxreviews/0486tr.pdf>
16. http://www.tceq.state.tx.us/assets/public/implementation/tox/dsd/final/hexane,n-100-54-3_final_10_15_2007.pdf
17. [Based on naphthalene as surrogate](#)
18. <http://www.epa.gov/iris/toxreviews/0486tr.pdf> and <https://netforum.avectra.com/eweb/shopping/shopping.aspx?site=aehs&webcode=shopping&cart=0&shopsearch=TPH> (heptane in TPHCWG Volume 4 is noted as being 38 times less toxic than n-hexane so this value is the IRIS value for n-hexane multiplied by 38)
19. <http://www.osha.gov/SLTC/healthguidelines/heptane/recognition.html>
20. [Based on n-hexane and heptane as surrogates](#)
21. <http://www.epa.gov/iris/toxreviews/1005tr.pdf>
22. <http://www.ontla.on.ca/library/repository/mon/20000/277838.pdf>
23. <http://www.ontla.on.ca/library/repository/mon/20000/277838.pdf>
24. http://www.epa.gov/chemfact/s_trimet.txt
25. TPHCWG (TPH Criteria Working Group) Series. <https://netforum.avectra.com/eweb/shopping/shopping.aspx?site=aehs&webcode=shopping&cart=0&shopsearch=TPH>
26. <http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=40&tid=14>

Interpretation of Crawl Space and Indoor Air Data

Due to the wide range of petroleum hydrocarbon sources, such as cigarette smoke, combustion sources and a range of products stored and used inside the home, the interpretation of crawl space and indoor air data in PVI assessments is complex. Concentrations of petroleum hydrocarbons beneath or within a home/building will be significantly affected by the use/storage of products that contain petroleum hydrocarbons (refer to **Table C3**). These will differ from home to home; hence concentrations of petroleum hydrocarbons in homes not affected by a subsurface source will vary significantly.

It is preferred that soil gas data is collected for the conduct of a PVI assessment as it avoids this additional complexity, however, there may be times when the collection of crawl-space and/or indoor air data is necessary. Whenever a crawl space or indoor air sample is collected it is important to also collect a background air sample. The background air sample should be collected outdoors, at the same time as the crawl-space/indoor air sample(s) and close to the area evaluated but not affected by the subsurface petroleum source. The collected background air sample is important for establishing concentrations in outdoor air in the same area where the PVI assessment is being undertaken. The outdoor air concentrations will be affected by local and regional petroleum sources and any measurement of crawl-space and indoor air will also reflect these concentrations. The complication in evaluating crawl-space and indoor air data is that there are other sources as well within the building itself that contribute to indoor air concentrations, and will mix with the crawl-space air.

To illustrate the complex nature of interpreting crawl space and indoor air data, in relation to background or outdoor air data, **Table C2** presents a summary of PHC data collected from 32 residential homes in Brisbane (various suburbs, not affected by subsurface PHC sources). These data show a high variability in indoor air results, and concentrations were found in the order - attached garages > indoor air > outdoor air. This reflects the range of

sources present in attached garages (which affect indoor air quality) as well as a range of indoor air sources.

Based on these data, the reporting of more elevated concentrations in indoor air compared with a background/outdoor air sample in the same area does not necessarily imply that PVI is occurring at the building evaluated.

Table C2 PHCs Reported in Residential Homes, Outdoors (at residences) and within Internal Garages

Key PHC	Concentrations Reported in Air as a mean (range) ($\mu\text{g}/\text{m}^3$)		
	Indoor Air ¹	Outdoor Air	Internal/Attached Garage
Benzene	2.4 (ND-13)	0.9 (0.4-2)	5.9 (4-8)
Toluene	10.7 (0.8-82)	2.3 (0.6-12)	25.5 (7-38)
Ethylbenzene	1.9 (ND-14)	0.3 (ND-1)	3.6 (2-5)
m&p-Xylenes	3.7 (0.3-24)	0.8 (0.21-3)	8.1 (3-12)
o-Xylene	2.6 (0.1-17)	0.4 (0.08-2)	5.4 (1-8)
Naphthalene	2.3 (ND-34)	0.1 (ND-0.4)	0.7 (0.3-1)

Ref: Connell D. and Hamidin N., 2012. Behaviour and Health Risk from Volatile Aromatic Hydrocarbons in Homes in Brisbane. ACTRA 5th Annual Scientific Meeting, Adelaide 2012.

Notes:

1 Data reported from 3 rooms in each of the 32 homes samples. Note that not all homes had internal/attached garages.

In relation to situations where PVI has occurred, review of available data indicates that concentrations indoors are significantly higher (by a factor of 5-10 fold) than ambient air. Data presented in **Table C2** indicate that a 5-10 fold increase in mean outdoor air concentrations would result in indoor air concentrations higher than the mean measured concentration. Hence, when reviewing crawl-space or indoor air data collected from a specific site, the potential for PVI to be occurring should only be considered if the measured concentrations in the crawl-space and/or indoor air are 5-10 fold higher than outdoor air. Even when this occurs, it is important that a review of indoor sources (including cigarette smoking, product storage and use) such as outlined in the questionnaire in **Appendix H** should be undertaken to further clarify if the measured concentrations are a result of PVI.

Table C3 presents a more general summary of the common sources of individual PHCs in air as well as a range of reported concentrations in indoor and outdoor air for comparison and consideration in the interpretation of data collected from a site.

Key Individual PHCs	Common background sources	Background concentrations in ambient/outdoor air ($\mu\text{g}/\text{m}^3$)	Reference	Background concentrations in indoor air (mean values) ($\mu\text{g}/\text{m}^3$)	Reference
Trimethylbenzenes	Petrol, vehicle emissions, solvents in research and industry, dyestuff intermediate, paint thinner, and as a UV oxidation stabiliser for plastics.	NSW EPA 2001 urban air: 1,2,4-TMB = 5 1,3,5-TMB = 1	6	US: Existing homes = 14 - 16 Melbourne = 3-4	8 9

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- <http://www.atsdr.cdc.gov/toxguides/toxguide-110.pdf>
- <http://www.atsdr.cdc.gov/toxprofiles/tp67-c2.pdf>
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- EPA Victoria, Environment Report: Air Monitoring in Corio 2003-07, Publication 1022.1, June 2007.
- Average 24-hour concentrations reported by Hawker D., Hawas O., Chan A., Cohen D., Christensen E., Golding G. and Vowles P., 2002. Characterisation and identification of sources of volatile organic compounds in an industrial area in Brisbane, 16th International Clean Air Conference, Christchurch, New Zealand 18-22 August.
- Mean concentrations reported by Connell D. and Hamidin N., 2012. Behaviour and Health Risk from Volatile Aromatic Hydrocarbons in Homes in Brisbane. ACTRA 5th Annual Scientific Meeting, Adelaide 2012
- Mean 24 hour average values from WA Department of Environment, http://portal.environment.wa.gov.au/pls/portal/docs/PAGE/DOE_ADMIN/TECH_REPORTS_REPOSITORY/TAB1019688/VOC_REPORT.PDF

APPENDIX D.

Installation of Soil Vapour Probes/Wells

This appendix presents the preferred methods for the installation of soil vapour probes/wells for the assessment of PVI.

The materials used for the vapour probe, tubing and sample train may differ from those presented in this appendix. However regardless of the materials used it is important that an equipment blank is conducted to demonstrate that the materials used are clean and suitable for use.

The tubing sizes outlined in the appendix are recommendations only. Different tubing sizes can be utilised provided they can be properly connected. The conduct of leak testing (including the testing of the sample train as outlined in **Appendix F**) is important to demonstrate that all such connections are tight and the installed soil vapour probe and sample train are suitable for the collection of a soil gas sample.

The quality of the installation of the wells is critical to the quality of the results. Hence, it is important that an experienced member of the team oversees the installation of the wells.

D1 Installation Techniques

Two techniques are most commonly used to install wells to allow the collection of active soil vapour samples:

1. Insertion of a hard rod (probe) driven to a target depth, collection of soil vapour through the rod while it is in the ground, and subsequent removal of the rod. This method is commonly referred to as the probe-rod method or sometimes as the temporary probe method (since the probe rods are temporarily in the ground). See **Figure D1**.



Figure D1 Probe-rod method. Sampling through a steel rod while the rod is in the ground such as with hand probes or direct push systems. Note inert tubing running down the centre of the rod

2. Burial of an inert tube (typically 1/8" to 1/4" OD) to a target depth with subsequent sampling of the soil vapour. Tubing can be buried in holes created with hand driven rods, direct-push systems, hand-augers, or drill rigs. This method is referred to by several names such as soil vapour monitoring wells, soil vapour implants, semi-permanent method (if the tubes are removed after a short period of time) or permanent probe method (if the tubes are left in the ground for a longer period of time). See **Figure D2**.

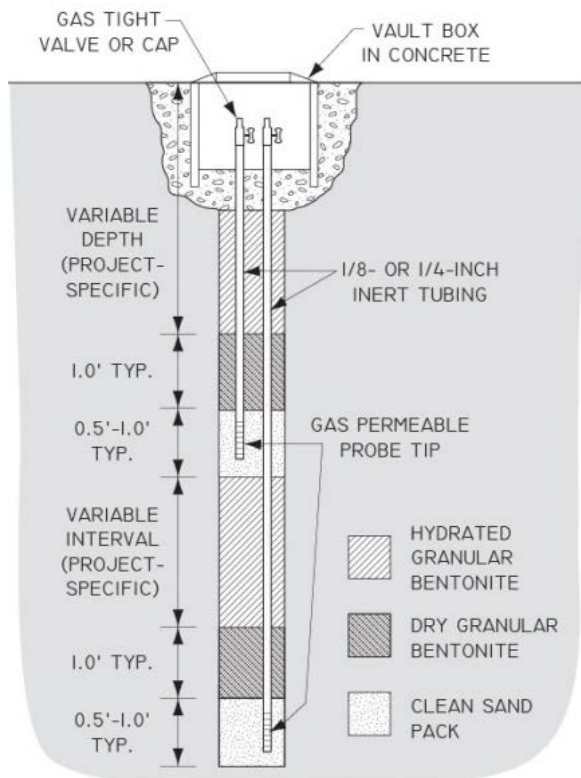


Figure D2 Cross section of soil vapour sampling points installed at various depths in the same borehole (nested well)

Both methods have been shown to give reliable, reproducible data (Di Giulio et. al., 2006a). The choice of method should depend upon the site, access, geology (texture, moisture and stratigraphy) and the project goals. For limited-access areas, a hand-probe may be all that is applicable. For deeper depths, direct-push probes are more convenient. If the probe-rod methods are used, samples should be collected through small-diameter inert tubing that runs down the probe rod so the sample does not contact the inside of the probe rod (**Figure D1**).

For repeated sampling or in low permeability soils, the second method offers advantages. Multiple tubes can be “nested” in the same borehole and are commonly referred to as nested, multi-depth vapour wells (see **Figure D3**).

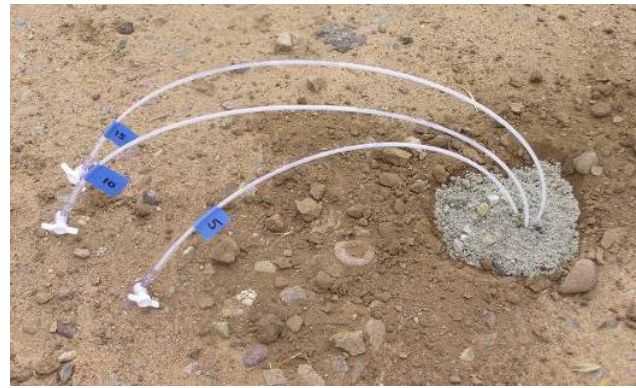


Figure D3 Nested soil gas sample points in a single well: a) Permanent probes with locking cap for repeated sampling; b) Temporary probes which will be removed after sampling

For both installation methods, a competent surface seal should be used to prevent ambient air from infiltrating into the soil vapour sample, especially at shallow sampling depths (<1m bgs or below foundation).

Note that when installing any probe into fine grained soil, care needs to be taken to ensure that shearing of the soil structure that results in the closing of soil pores on the inner surface of the well, is minimised. This issue can be more problematic with push-tube methods; however it can occur during all installations if not installed carefully.

D2 Soil Vapour Probe Materials/Construction

It is important that the correct soil vapour probe materials (**Figure D4**) are used and the probes constructed properly. Below is a list of recommended materials and construction issues for soil vapour probes. A website where these materials can be viewed is www.envservprod.com.

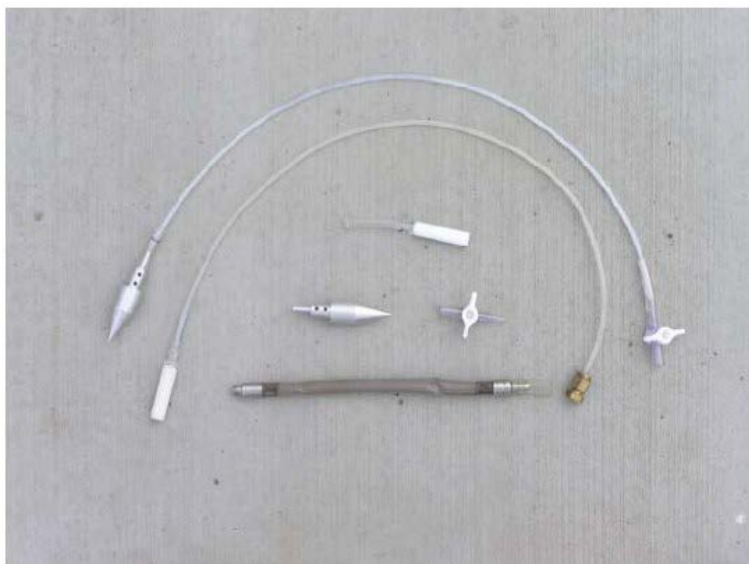


Figure D4 Soil vapour sample materials, including 1/8" OD tubing, three types of tips (ceramic, aluminium, and braided steel), and two types of surface terminations (stop cock and swage lock fitting)

Tubing

It is important to use tubing material that will not adsorb or off-gas volatile hydrocarbons. Recent studies by EPA-ORD show that nylon, Teflon, and stainless steel all gave comparative results for typical PHCs. For heavier molecular weight compounds (e.g., naphthalene or higher), stainless steel shows the least adsorption, but may be logistically impractical to use due to its inflexibility. Nylon is recommended over Teflon tubing as nylon tubing (nylaflow) is less expensive and the compression fittings are easier to seal than on teflon.

Polyethylene tubing (either LDPE or HDPE), commonly used for groundwater sampling, should not be used for soil vapour samples. It is important to check with the well installer prior to the field program to ensure they have and use the appropriate tubing. In addition, it is important where the tubing is stored and how it is handled. Any type of tubing will become contaminated and contribute to false positives if it is stored in the back of a truck unsealed or near the truck exhaust.

Tubing Diameter

Nominally 1/8" outer diameter (OD) or 1/4" OD. 1/8" OD tubing is easier to drop down a bore hole than 1/4" OD tubing.

Probe Tip

Stainless steel, ceramic, plastic (choice depends upon project specifications).

Surface termination on tubing

Swagelok fittings or plastic valves (2-way inert plastic valves or stop cocks) are best for sealing the tubing that will remain in the ground for an extended time. An end-cap can also be used. If a valve is used, it is important to secure it tightly to tubing, as the valve is a permanent component of the soil vapour collection system.

Surface termination on ground

Options include flush mounts on floor/surface, below ground level with or without locking cover, variable above ground-level completions.

Equipment Blanks

Collection of an equipment blank is recommended for all vapour intrusion investigations. Clean air or nitrogen should be drawn through the probe tubing, probe tip, and the sampling train at the start of the field program. The collected sample should be analysed for the same compounds as the soil vapour samples. Only materials that can provide a clean blank should be used in the construction of the soil vapour well.

D3 Soil Vapour Probe Installation Protocol

At some sites, such as active service stations, ground disturbance protocols require special probe installation protocols. For example, soil vapour points are generally installed by burying tubing into an open borehole (method 2) as opposed to driving a steel rod into the ground (method 1) to avoid the possibility of striking an underground utility. However at some sites, the probe-rod method may be suitable and often is faster than burying tubing. Hand probes are also an optional method, especially when sampling in places with limited access. In this appendix, discussion is limited to installation of tubing into open bore holes (method 2). Detailed protocols for collecting through probe rods (method 1) can be found in Cal EPA (2012), Di Giulio et. al. (2006) and API (2005).

Equilibration Time

When probes are installed, the in-situ soil vapour can be displaced and a period of time is required for the soil vapour to re-equilibrate. A recent USEPA study (USEPA 2011) showed the following equilibration times were required to achieve 80% of the final value:

- Sampling through probe rod installed by hand: 15 minutes
- Sampling through probe rod installed with direct push methods: 30 minutes
- For probes where tubing is buried in a sandpack in the ground: 8 hours

This study was done in fine-grained soil. Equilibration times can be expected to be less in coarse grained soils.

The time between probe installation and sampling will depend on the investigation objectives and the data quality requirements. For example, if a soil vapour survey is conducted using temporary points to map the extent of a vapour plume, and the sample data are not intended for use in risk assessment or site closure decisions, then sampling sooner after installation would be acceptable.

While the above indicates that the time for equilibrium to be established following installation may be lower, to obtain data for risk-decision making in Australia, it is preferred that soil vapour probes consisting of tubing buried in a sand pack be allowed to equilibrate for at least 24 hours before sampling. However if sample timing is more constrained it is acceptable to sample after a shorter period of time (e.g. 8 hours) provided the wells were installed during dry weather conditions (i.e. not in the rain where the installation allowed for the movement of rainfall down to the probe sample depth) and stabilised parameters (oxygen, carbon dioxide and PID levels) can be demonstrated prior to sampling.

If rotary drilling or percussion methods are used to emplace the tubes, or if air knives are used to clear the sample locations, longer periods of time are required for the sand pack to equilibrate with the soil vapour. The use of air knives is not recommended. To determine the equilibration time, a test of concentration vs. time can be used to determine when values stabilise. Another method is to purge the soil vapour and monitor the soil vapour concentration with a portable meter. When the concentrations stabilise, equilibrium is assumed and a sample can be collected for analysis.

Probe Surface Seals:

For collection systems with large purge volumes or designed to collect large sample volumes, it is often necessary to seal the probe at the surface. Seals may also be necessary for small volume systems if the soils are porous and the sampling depth is close to the surface (i.e. less than 1m). Most common sealing techniques are to pack the surface contact

of the probe with the soil with grout or bentonite. If any other materials are used to seal the probe, they should be tested to ensure they are free any chemicals of concern.

Standard Operating Procedure for Installing Soil Vapour Wells

Soil vapour sampling points can be installed down a variety of boreholes ranging in diameter from 2.5 to 20 cm. Boreholes may be created with hand equipment (hand-auger), by direct-push methods, or rotary drill-rigs. A good understanding of the geology of the location where the borehole is to be installed is useful to ensure the probe is appropriately placed without clogging. Hand augering will likely be the most common method used to create a bore hole if ground disturbance protocols exist or subsurface utilities exist. Installation of vapour sampling points in the same borehole at varying depths (nested vapour wells) are easier in boreholes >4 cm ID. It is not recommended to construct nested wells with less than 0.75m separation between sample ports, to minimise the potential for interconnections (leaks) between sample ports.

In the following procedure, it is assumed that utilities have been cleared and an open borehole exists.

1. Measure depth to the bottom of borehole, and cut the probe tubing to appropriate length to have enough for the required type of surface termination (flush, recessed, protruding).
2. Add enough sand to create a 15 cm layer in the bottom of borehole (calculate volume based upon borehole ID).
3. Drop soil vapour point and tubing down borehole. If the hole is deep and borehole narrow, adding a small weight (e.g., nut) can facilitate the probe extending to the bottom of borehole. Cover probe tip with 15 cm of sand. Cover the sand with a 8-10 cm layer of dry bentonite to prevent water seeping into the sand pack from possible over hydrating of bentonite above.
4. If a single vapour sampling point is used in a boring then grout to near surface using bentonite that is hydrated with sufficient water to ensure a tight seal, and then complete with cement. Be sure not to pinch off tubing at terminus if concrete is used to complete well to the surface.
5. For nested wells, add bentonite grout (hydrating periodically throughout the installation) until reaching 15 cm below the next sample depth. Add 15 cm of sand then insert the next vapour sampling point (be sure to label the tubing at surface before you install in the borehole) and fill with 15 cm of sand, followed by 8-10 cm of dry bentonite then hydrate bentonite until next depth sample is reached. Use this procedure until all sample depths are completed (**Figure D5**). For nested wells, cut the protruding lengths of tubing at different lengths, so that the deepest sample tube is the longest and the others progressively shorter. Having different lengths of tubing is helpful for identification if the labels on each tube are lost or become illegible.

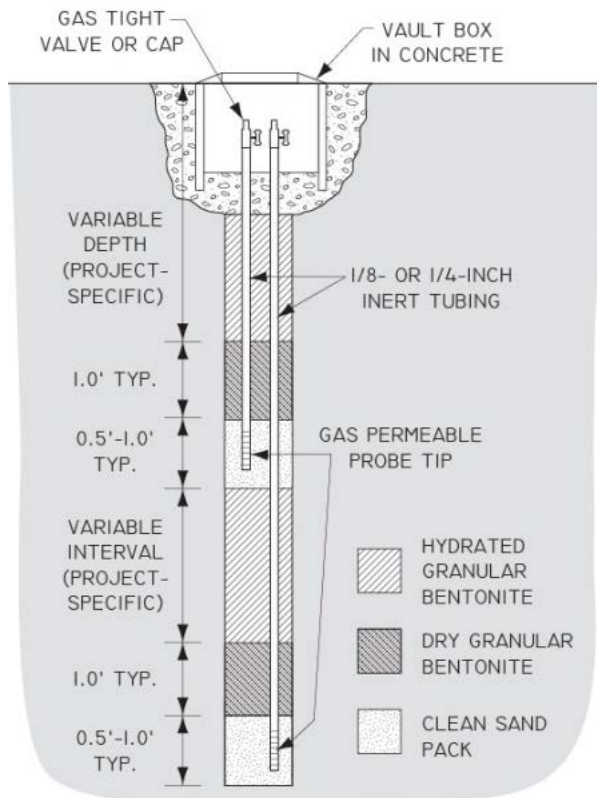


Figure D5 Cross section of nested soil vapour sampling points installed at various depths.

6. Terminate surface ends of tubing with 2-way plastic valves (Figure D6), Swagelok nuts & caps or other appropriate end-caps.

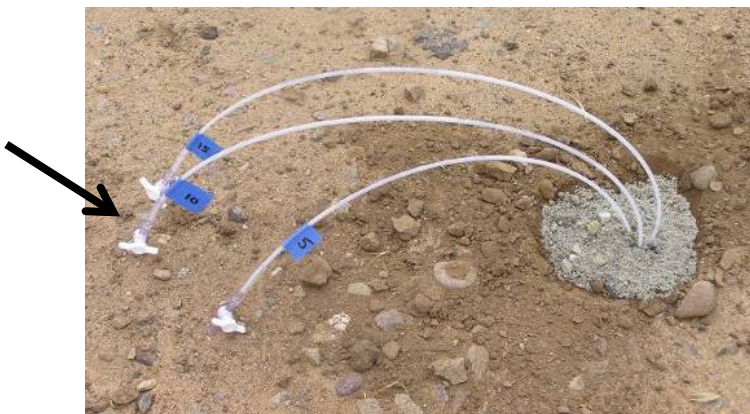


Figure D6 Nested soil gas sample points in a single borehole

7. If sampled the same day as installation, purge at least one volume of soil vapour equivalent to the volume of tubing and sand pack around probe tip. Estimate tubing volume at 0.3 mL/m for 1/8" tubing and 1.5 mL/m for 1/4" tubing. If sampled on a different day from installation, only purge the volume of the tubing. For moist, clay-rich soils, a longer time frame may be needed to allow soil vapour to migrate into the sand pack.

Standard Operating Procedure for Installing Sub-Slab Probes

Sub-slab probes are installed similarly to permanent probes. The probe typically consists of 1/8- to 1/4 inch OD inert tubing with or without a probe tip (**Figure D7**). Using a rotary hammer drill, a ~1 inch diameter hole is drilled approximately 1½ inches (4 cm) into the slab to make room for the Swagelok fitting. A 3/4 inch diameter hole is then drilled through the remaining slab thickness and 0 to 5 cm into the underlying sub-slab base material (typically engineered aggregate). The inside of the hole should be cleaned out and wiped with a damp towel to remove the drilling dust and ensure an airtight seal. The probe assembly is then inserted into the hole so that the probe tip is just below the slab.

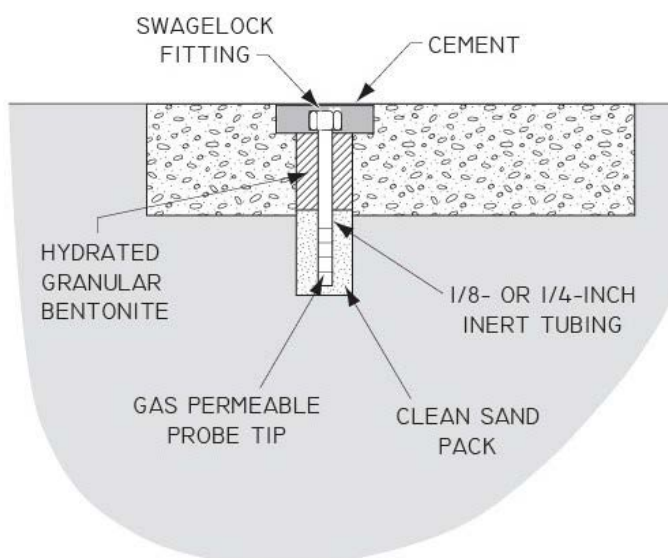


Figure D7 Sub-slab soil vapour probe schematic

If the probe is to be removed following sampling (temporary installations), the probe tubing can be inserted to the base of the hole with 15 to 60 cm of tubing extending above the surface with a 2-way valve to seal it. Clean sand is then poured into the hole until the probe tip is covered to form a filter pack. Granular bentonite is poured to the surface and hydrated (preferably prior to being poured into the well). Care should be taken not to allow water to leak into the filter pack sand.

If the probe is to be left in place for repeated sampling (permanent installation), the surface termination should be a fitting with a threaded plug to seal the probe (Figure D8) or equivalent. The tubing should be cut to the appropriate length so that the probe tip is just below the slab and the surface termination is flush with the slab surface.

Clean sand is then poured into the hole until the probe tip is covered to form a filter pack. Granular bentonite is poured to the top of the 3/4 inch OD hole and hydrated (preferably prior to being poured into the well). Care should be taken not to allow water to leak into the filter pack sand.

Finally, the Swagelok fitting is sealed in place with a small amount of quick-drying cement. To avoid cementing the probe closed, the cement should be poured no higher than flush with the top of the compression fitting. Cement should not be allowed to flow around the threaded plug.

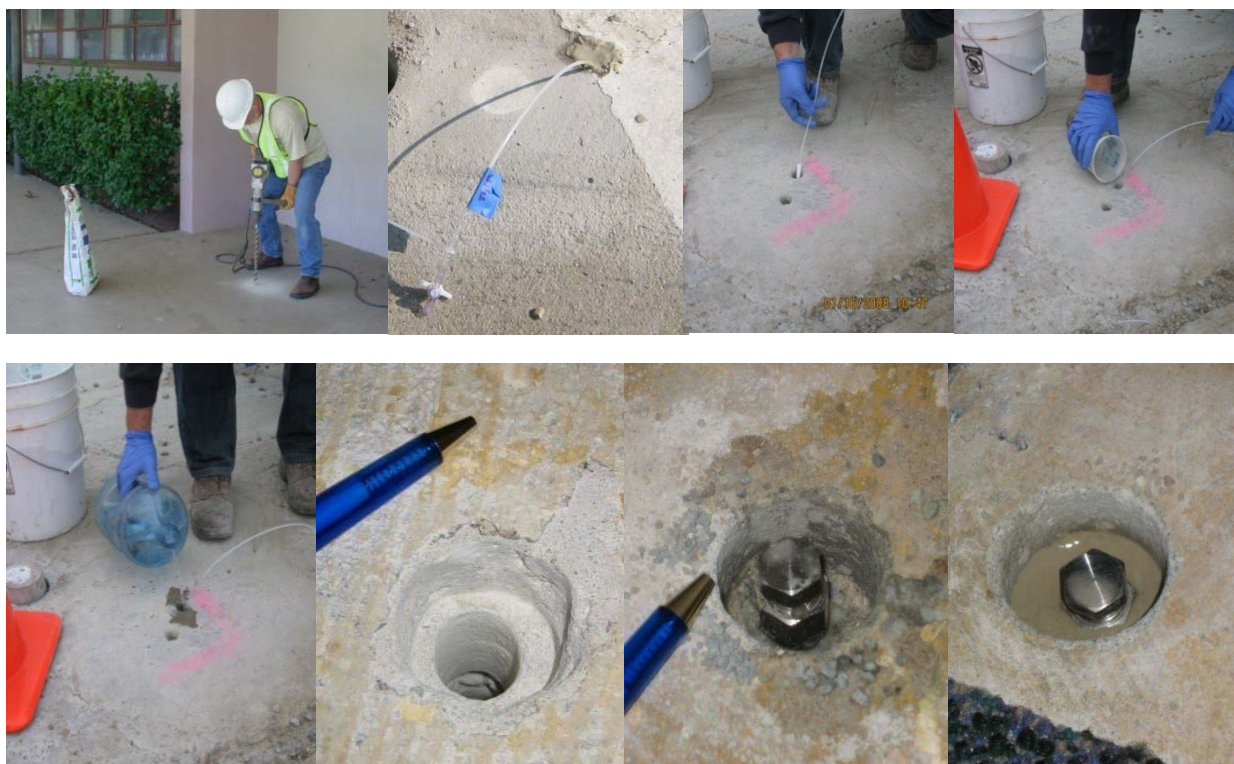


Figure D8. Photos showing installation of permanent sub-slab vapour sampling probe.

When sampling permanent probes, the surface cement can crack during sampling increasing the chance for leaks. This can be minimised by using a short length of tubing to connect from the probe tip to the sample container. Typically, sub-slab probes are not sampled for at least 30 to 60 minutes after installation.

References

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APPENDIX E.

Factors to Consider in PVI Assessments

This appendix presents a number of common errors and areas where additional clarification is required. This appendix does not address every error or issue that may be experienced at a site and hence it is important that the sampling and evaluation of PHC vapours is conducted by experienced personnel.

Vapours and vapour intrusion are unfamiliar territory for many practitioners in this field (regulators, stakeholders, consultants, subcontractors). The following outlines a number of common errors and issues that arise in the collection and assessment of data for the assessment of PVI.

1. Confusion with Units

A very common error in looking at concentrations in air is thinking ppbv is equivalent to µg/L or ppmv is equivalent to mg/L. For concentrations in air (unlike for concentrations in water) the units are not equivalent, and the conversion depends primarily upon the molecular weight of the compound. Converting between units (e.g., µg/L to µg/m³, percent to ppmv) is also a common source of error.

It is recommended that prior to scoping a field program and conducting field work:

- Instruct the laboratory as to which units and detection levels the data are to be reported.
- Locate an easy-to-use unit conversion spreadsheet available at many web sites (e.g., www.handpmg.com or <http://www.airtoxics.com/cclasses/unitcalc.html>).

Most often, errors involve not converting air concentrations reported in ppmv to mg/m³ (and vice versa). The ideal gas equation is the basis of the conversion:

$$PV=nRT$$

where

P = ambient pressure (atm)

V = gas volume (L)

n = moles of gas

R = universal gas constant (0.08206 L atm K⁻¹ mol⁻¹)

T = temperature (K)

Converting soil gas concentrations from mg/m³ to ppmv

Assuming a soil gas pressure of 1 atm, the ideal gas equation can be modified to convert soil gas concentrations from mg/m³ to ppmv according to:

$$\text{Concentration in ppmv} = \frac{\text{Concentration in mg/m}^3 \times (273.15 + ^\circ\text{C}) \times 0.08206}{\text{MW}}$$

where

ppmv = ppm by volume (i.e., volume of gaseous concentration per 10⁶ volumes of soil gas)

mg/m³ = milligrams of gaseous concentration per cubic metre of soil gas

MW = molecular weight of the chemical (g/mol)

°C = soil gas temperature in degrees Celsius

Example Calculation

For a gas sample containing benzene (MW = 78.1 g/mol), convert 20 mg/m³ to ppmv at 25 °C.

$$\text{Concentration of benzene in ppmv} = \frac{20 \times (273.15 + 25) \times 0.08206}{78.1} = 6.27$$

Converting Soil Gas Concentrations from ppmv to mg/m³

Assuming a soil gas pressure of 1 atm, the ideal gas equation can be modified to convert soil gas concentrations from ppmv to mg/m³.

$$\text{Concentration in mg/m}^3 = \frac{\text{Concentration in ppmv} \times \text{MW}}{(273.15 + ^\circ\text{C}) \times 0.08206}$$

where

ppmv = ppm by volume (i.e., volume of gaseous concentration per 10⁶ volumes of soil gas)

mg/m³ = milligrams of gaseous concentration per cubic metre of soil gas

MW = molecular weight of the chemical (g/mol)

°C = soil gas temperature in degrees Celsius

Example Calculation

For a gas sample containing benzene (MW = 78.1 g/mol), convert 20 ppmv to mg/m³ at 25 °C.

$$\text{Concentration of benzene in mg/m}^3 = \frac{20 \times 78.1}{(273.15 + 25) \times 0.08206} = 63.8$$

2. TPH/TRH

Analytical methods for TPH/TRH in soil gas can only reliably report to C12 for volatile components. This is out of step with the HSL fractions for soil gas that include the group >C10-C16. However it is appropriate to use the laboratory reported >C10-C12 value when comparing with the HSLs for >C10-C16.

In some cases, TPH/TRH results are reported by the laboratory in ppmv or ppbv. The conversion of TPH/TRH data from ppmv into mg/m³ is a little more complicated as the TPH/TRH measurements apply to a range of compounds with varying molecular weights. Often a surrogate is specified by the laboratory and the molecular weight of that surrogate compound should be used when converting units. Depending on the analytical method used or the reporting format, the surrogate may not have been reported by the laboratory (it is useful to request this information be reported by the laboratory). In such situations, it is recommended that the molecular weight of an appropriate surrogate for each TPH/TRH group reported, as specified by the TPH Criteria Working Group or TPHCWG (1997), are used to do the conversions. Some examples of suitable surrogates are as follows:

TPH/TRH grouping (most common volatile fractions reported by laboratories)	Examples of Suitable Molecular Weights and Surrogates (g/mol)
C ₆ -C ₈ aliphatic	100 (n-heptane)
C ₆ -C ₈ aromatic*	92 (toluene)
>C ₈ -C ₁₀ aliphatic	128 (n-nonane)
>C ₈ -C ₁₀ aromatic	120 (1,3,5-trimethylbenzene/propylbenzene)
>C ₁₀ -C ₁₂ aliphatic	170 (n-dodecane)
>C ₁₀ -C ₁₂ aromatic	134 (1,2,4,5-tetramethylbenzene)

* Note that in the application of the HSLs individual aromatic C₆-C₈ compounds, namely benzene, toluene, ethylbenzene and xylenes (BTEX), are subtracted prior to consideration.

3. Required Screening/Target Levels

Another common error is using incorrect screening levels. Residential values are erroneously applied at commercial sites, incorrect attenuation factors are used to determine screening values, or values determined from predictive models are incorrect.

Occupational guideline values (workplace exposure standards), are typically derived on the basis of a methodology that is comparable to the determination of public health standards for the whole community and are based on the protection of workers (who are on average healthier than the whole community). However they use different standards of protection and safety factors than used for the general community, such as tolerating relatively minor adverse effects. It is unusual for occupational guideline values to be used in environmental health risk assessments. The Guidance Note on the Interpretation of Exposure Standards for Atmospheric Contaminants in the Occupational Environment NOHSC 3008(1995) 3rd Edition – states that the occupational guideline values should not be used for assessing community air pollution or to assess long term non-occupational exposures.

In addition, in some jurisdictions it is not normally considered appropriate to use occupational guidance values for assessing a contaminated site if the contaminants being assessed are not used in the workplace affected by the contamination.

The screening level ultimately determines the required analytical method and the need for additional assessment so it is critical that the appropriate guidelines are chosen. These issues are further addressed in **Sections 3, 4 and 5** of the PVI guidance.

4. Calculation of Air Concentration following Analysis of Sorbent Tubes

When collecting an air sample using a sorbent tube the analytical laboratory will report the mass detected on the tube (in ng/tube or µg/tube). In some cases the analytical laboratory will utilise supplied field information on the sampled air volume to calculate an air concentration. However in some cases this is not undertaken and hence it is important that the air concentration is calculated from the mass detected on the tube and the field information on the volume of air sampled through the tube. The following equation can be used to calculate the air concentration:

$$\text{Concentration } (\mu\text{g}/\text{m}^3) = \frac{\text{mass detected on tube } (\mu\text{g})}{\text{volume air drawn through tube } (\text{m}^3)} = \frac{\text{mass detected on tube}(\text{ng})}{\text{sample flow rate}(\text{L}/\text{min}) \times \text{sample time}(\text{min})}$$

It is important to determine the sample flow rate for every individual tube. It is also important to consider the limitations imposed by the methodology in determining flow rates and sampling times. If too much air is moved through the tube then it is possible to get breakthrough which will impact on the robustness of the result. If too little air is moved through the tube then it may not be possible to get a sufficiently low limit of reporting. These issues must be considered when preparing to undertake such sampling.

5. Measurement of PHCs in Soil Headspace using PID

There are a number of factors to consider in order to obtain consistent headspace readings using a PID:

- The use of a consistent methodology.
- The impact of container materials on sample integrity.
- Awareness of variations in PID response at high humidity.
- The impact of soil type on headspace formation.

Headspace concentrations are affected by the size of container, amount of sample and the size of the available headspace. Temperature, development time, hold time and analysis time should all be considered as should the permeability of the container and any contamination by the container. There is evidence that some sample containers are not impervious to hydrocarbon vapour migration, which would lead to artificially low results (reported to be as much as a factor of two). Hence it is important that the methodology used is consistent².

The issue of variable PID response from different equipment and at high humidity was documented in a study reported by Maine DEP³. This study reported variations in PID response by equipment brand. Petroleum hydrocarbon response over a wide range of humidity varied from unit to unit by up to 4 times. Units that were tested were assigned correction factors or “Set Points” to adjust the field readings to match the laboratory readings. Note that the standard calibration on 100 ppm isobutylene does not correct for these issues since it is a dry gas mixture and so fails to compensate for moisture content, always present in headspace samples. In addition the calibration does not correct for differences in readings between different brand PIDs.

If a PID is being used as the only line of evidence for decision making on a PVI site then these issues need to be adequately accounted for in the assessment. It is recommended that the field PID readings are not used as the only line of evidence in PVI assessments.

6. Effect of Barometric Pressure on Soil Gas Measurements

The collection of soil gas data is often perceived to be significantly affected by changes in barometric pressure. The available data (for non-landfill affected sites) do not indicate that this is the case (as discussed further below) and hence the timing of soil gas data collection should not be determined by barometric pressure conditions.

² An example headspace analysis screening procedure is provided in the following document: <http://www.mass.gov/dep/cleanup/laws/94-400.pdf>

³ <http://www.neiwppcc.org/tanks2009/presentations/Whittier%20PID%20Presentation%20-%20Full%20Set.pdf>

At landfill sites (not addressed in this guidance) soil gas is generated and the difference in soil gas pressure and the barometric pressure will affect the lateral and vertical movement of landfill gas, depending on the pressure gradient. In these situations barometric pressure changes are important.

In relation to the sampling of soil gas for the assessment of VI, a number of international guidance documents, and published studies, have indicated the potential for barometric pressure to affect the migration (i.e. mass flux) of vapours from the subsurface to indoor air. The changes in mass flux (or the soil vapour flow rate) from subsurface to indoor air is of importance when estimating concentrations in indoor air based on subsurface measurements. Hence it is often referenced that barometric pressure has an effect on vapour intrusion.

The measurement of a soil vapour concentration however is not a measure of mass flux (or soil vapour flow rate). While less data, which address variability in soil vapour concentrations (compared with soil vapour flow rates) over time are available, the available data do show that soil gas concentrations do not vary significantly (i.e. by a factor of >5-10 fold) with changes in barometric pressure. This is expected as soil gas concentrations in the subsurface are dependent on the source concentration, characteristics of the chemicals and volume of air in the soil pores which does not change significantly with barometric pressure changes.

The available studies include the following:

- A review of the influence of temporal variability (in particular temperature and pressure [barometric and subsurface soil gas pressure]) on soil gas concentrations was conducted by the USEPA (2007). This involved the collection of 9500 soil gas samples from 12 soil gas probes over a 6 week period from a site in California. The study concluded that none of the temporal variables, including barometric pressure changes, had a discernible effect on the measured soil gas concentrations.
- A study conducted at a duplex (2 adjacent residential homes) in the US (Hartman et al 2012) over a number of months (and various meteorological conditions) using continuous GC monitoring, where half the property was heated and the other half was unheated, indicated the following:
 - sub-slab and soil gas concentrations are relatively stable with the concentrations reported to vary by a factor of <2 fold;
 - indoor air concentrations were more variable reflecting a range of factors that affect the migration (mass flux) of soil gas to indoor air.
- A study of sub-slab data collected beneath 2 residential homes in New York (Folkes et al. 2009) involved the collection of discrete samples on a monthly basis over a period of approximately 18 months. The data varied by less than an order of magnitude with no seasonal (including barometric pressure) trend identified in the variability reported. It is noted that some data quality issues (with the seals of the sub-slab ports) were noted and may be responsible for the variability reported.

References

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APPENDIX F.

Soil Vapour Sample Collection

This appendix presents the preferred methods for the collection of soil vapour samples for the assessment of PVI. Other methods can be used provided they meet the data quality objectives for the project and are adequately documented and justified.

Different types of connectors and fittings may be used in the sampling of soil vapour. It is important that the materials used for connectors and fittings have been tested and can provide a clean blank, and that they are leak tested to ensure that all the connections are tight are suitable for the collection of a soil gas sample.

The approach adopted for the sampling of soil vapour is critical to the quality of your results. Hence it is important that you or an experienced member of your team oversees the sampling.

F1 Active Soil Vapour Methods

Collection of soil vapour samples using active methods consists of the following steps:

- Leak detection prior to sampling
- Purging the probe and sample train
- Collection of the soil vapour sample into a suitable container, such as passivated canisters, adsorbant tubes or tedlar bags⁴. It is noted that other sampling media may also be used where adequately justified. Refer to CRC CARE Technical Report 13 (Davis, Wright & Patterson 2009) for further details on the advantages and disadvantages of sample collection methods.

It is generally considered to be good practice to only use dedicated connectors and tubing (from the soil gas well to the sampling media) for each location and to order the sampling of soil gas from areas where lower concentrations are expected to areas where higher concentrations are expected (where possible). This minimises the potential for cross-contamination and interference/bias/drift in field instruments that may be used.

F1.1 Leak Detection (prior to sampling)

When quantitative soil vapour data are desired, for example for risk assessments, leak testing the system as a quality assurance measure is strongly recommended. Leaks in the sampling train or leaks of ambient air into the probe tubing can result in diluting the soil vapour samples with ambient air and will result in underestimating actual contaminant concentrations. Excessive vacuum conditions resulting from low porosity soils or high moisture content soils may exacerbate the potential for ambient air leakage.

Two methods of leak detection are recommended: (1) Performing a “shut-in” test of the sampling train and applying a leak detection compound to the vapour probe at the surface or (2) Applying a tracer gas over the probe and over the entire sampling apparatus.

⁴ Note that the use of tedlar bags is not preferred for PVI assessments as the holding time is very short and naphthalene recovery is poor.

Leak Test Method 1 – Shut-in Test and Leak Detection Compound at Surface

The shut-in test is performed by sealing the sampling train from the vapour probe tubing termination to the sample container (e.g., canister, Tedlar bag) and applying a vacuum to the sampling train. The applied vacuum should hold steady (not decrease) for at least 30 seconds. The start and end vacuum should be recorded and reported.

Figure F1 is an example of a simple sampling train arrangement for a shut-in test. The system consists of a 2-way valve at the vapour probe termination, a vacuum gauge, and a 3-way valve on a gas-tight syringe. The 2-way valve is closed. A vacuum is then applied by drawing back the syringe plunger and the 3-way valve turned to shut off the syringe. The vacuum in the sampling train is then monitored for at least 30 seconds. If the sampling train does not hold the vacuum, then all connections should be rechecked for the leak and the shut-in test repeated.



Figure F1. Simple sampling train arrangement for a shut-in test.

Once the shut-in test has been successfully completed, a leak check compound is applied to the surface completion of the probe. The leak check compound can be applied by wetting a towel with a liquid compound⁵ (e.g., isopropanol) and placing it around the probe tubing at the ground surface (**Figure F2**), or by placing a small shroud over the surface completion and filling the shroud with a tracer gas (e.g. helium) (**Figure F3**).

⁵ If this method is adopted care must be taken to ensure that cross contamination does not occur.

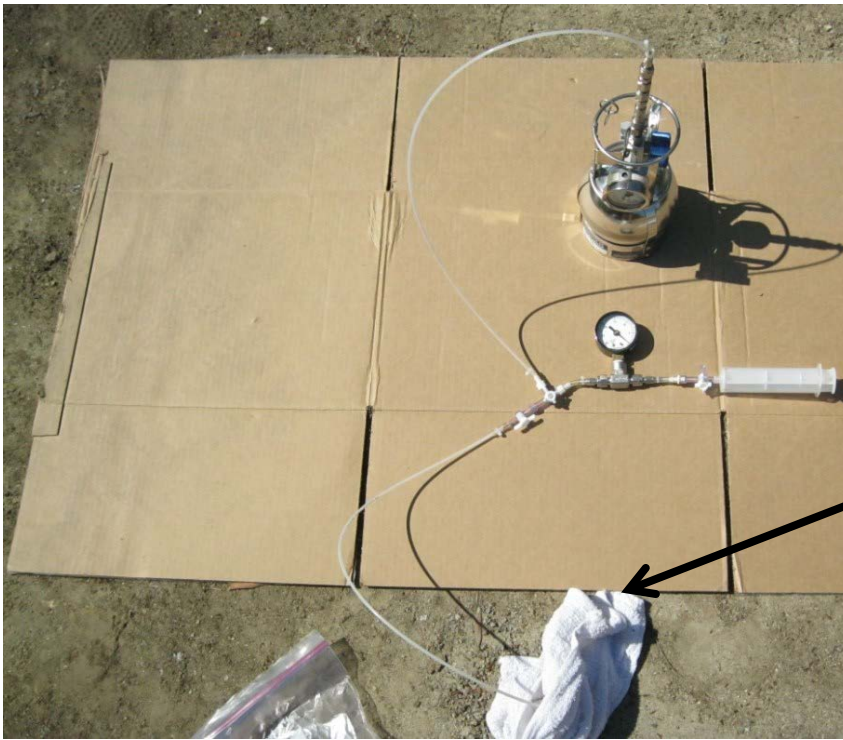


Figure F2. Sampling arrangement showing vapour probe surface seal covered with a liquid leak check compound on towel (bottom of photo)



Figure F3. Gas shroud method. Shroud (blue) covering the vapour probe surface seal with line in from helium cylinder, field helium detector, and syringe with vacuum gauge for purging the probe tubing exiting from the shroud.

Leak Test Method 2 – Covering Sampling Train & Probe with Gaseous Tracer

The second method involves enclosing the entire sampling apparatus, including the sample container, all tubing and connections, and the vapour probe surface completion in a shroud, which is filled with a tracer (**Figure F4**). This method is operationally more cumbersome as it requires a source of the gaseous tracer on site and it is difficult to

turn on, turn off, and adjust the collection device once under the shroud but it provides a real time indication of whether there is a leak or not.



Figure F4. Covering the entire sampling system & probe with a shroud

Testing the Soil Vapour Sample For Leaks

For the two leak test methods described above, it is advantageous to measure both the concentration of tracer compound in the shroud and the concentration of tracer compound in the soil vapour sample in the field using a hand held field meter. If canisters are being used, it is advisable to measure the tracer in the probe tubing after purging and prior to opening the canister. If the tracer concentration⁶ in the probe tubing is greater than the allowable amount (10% of the concentration in the shroud), the leak should be found and corrected before opening the canister. After the canister has filled, the probe tubing should be tested again. If the tracer concentration in the probe tubing is greater than the allowable amount, then the sample in the canister may be compromised. Depending on the methodology adopted, the soil vapour sample in the canister can also be tested for the tracer at the laboratory. Fully document in the sampling log sheets, both the shroud and probe tracer concentrations. This procedure is more difficult to employ if the entire sampling train is under the shroud (leak test method 2).

An alternative procedure is to first collect the sample in a gas-tight bag and then test the bag for the tracer compound. If the tracer concentration in the bag is less than the allowable amount, the sample is leak-free and can be shipped to the laboratory or transferred on-site (or at the laboratory) into a canister (see following section on sampling into gas-tight bags). If the tracer concentration in the bag exceeds the allowable amount, the sample is considered compromised, the leak should be found

⁶ Note that when using field meters for tracer tests (e.g. helium meter) the tracer concentration measured should be taken as an indicative concentration (i.e. order of magnitude) rather than a precise measurement as it is common for field meters to drift (typically higher) during the sampling event (primarily due to the repeated measurement of elevated concentrations in the shroud).

and corrected, and the sampling procedure repeated (the same gas-tight bag can be reused).

Selection of Leak Detection Compound

The selection of leak detection compounds is site and analysis specific. Considerations include whether it is a known or suspected contaminant at the site, or included in the laboratory's list of target analytes for the method being used, and whether it can be monitored with portable measurement devices. Common leak detection compounds are isopropanol and helium. Each of the compounds has several advantages and disadvantages (see following table).

Isopropanol is readily available, inexpensive, and flammable and does not require the use of a shroud, as it can be applied to a towel placed around the vapour probe, although it can also be used with a shroud by placing the towel inside the shroud. A further advantage of isopropanol is that it can be detected using methods TO-14/15/17 and with a portable PID. However, because it is handled at extremely high concentrations, it is possible to introduce high concentrations into the sample, which can render the sample useless by raising analytical reporting levels. When using liquid tracer compounds, extreme care needs to be taken to not contaminate the sampling train parts with tracer compound. Gloves should always be worn when handling the tracer compound and a different pair of gloves should be worn when handling/assembling sampling train components. Although isopropanol can be detected by a portable PID, the PID might be reading actual compounds of interest in the soil vapour (such as BTEX) and give a false positive as far as leak detection is concerned. On this basis the use of isopropanol as a tracer compound for the conduct of PVI assessments is not preferred, however it can be used provided the above issues are addressed and the test is conducted by experienced personnel.

Helium concentrations can be readily measured in the field using a selective hand-held meter. However, most helium meters also respond to methane, so if methane is suspected at the site, false positives on the helium meter are possible but this can be checked with the landfill gas meter to confirm. A further advantage of helium is that its presence in a sample, even at high concentrations, will not interfere with TO-14/15/17 analysis for VOCs. However, if the sample collected into the canister is required to be analysed for helium, the laboratory must run a separate analytical method to analyse for helium.

Table F1 Comparison of Common Leak Check Compounds

Compound	Advantages	Disadvantages
Isopropanol	<ul style="list-style-type: none"> • Inexpensive and readily available • Detected using method TO-14/15 and SW8260 • Can be used without a shroud 	<ul style="list-style-type: none"> • Cannot be selectively measured in the field with a portable meter. • High concentrations can interfere with laboratory analysis • Potential for cross contamination • Flammable
Helium	<ul style="list-style-type: none"> • Can be selectively measured in the field with a portable meter giving real time information about leaks • Will not interfere with TO-14/15 and SW8260 analysis 	<ul style="list-style-type: none"> • Can be more expensive • Requires valves and fittings for cylinder • False positives on meters may be caused by methane

F1.2 Purging the Probe & Sampling Train

Purge Volume: The sample collection equipment used for soil vapour sampling has an internal volume that is filled with air or some other inert gas prior to insertion into the ground. This internal volume, often called the dead volume, must be completely purged and filled with soil vapour to ensure that a representative soil vapour sample is collected. If vapour wells (tubing) are installed and sampled the same day as installation (not recommended), the air volume of the sand pack should also be included in the total system volume. Probe purging is typically accomplished using a pump or a syringe equipped with a 3-way valve (**Figure F5**). Syringes are an inexpensive and simple approach for purging small volumes up to 1 litre. For larger purge volumes, a pump with variable flow rates and a flow meter is more efficient. Purging may also be conducted using a portable PID or landfill gas meter where the reporting of stabilised parameters can be used to demonstrate that purging is complete and soil gas can be reliably sampled. Care should be taken if the well has the potential to be wet.



Figure F5. Left: purging with a plastic syringe. Right: purging with a low-flow pump

At a minimum, enough vapour should be withdrawn prior to sample collection to purge the probe and collection system of all ambient air or purge gas (1 purge volume).

While it is important to collect enough vapour to purge the system, collecting too much vapour can also have drawbacks. The larger the quantity of soil vapour withdrawn, the greater the potential that atmospheric air might be drawn into the probe, especially when sampling at shallow depths (<1 metre). If larger sample volumes are attempted, the potential for leaks around fittings increases and the samples can be less representative. Thus, sampling equipment with small internal dead volumes offers advantages over systems with larger dead volumes because the former systems require significantly less vapour to be withdrawn when purging the system.

Since soil vapour data are often interpreted by comparing across the whole site, it is important that the purge volume be consistent for all samples collected at the same depth from the same site.

Sample Flow Rate: The USEPA (2007) measured soil-vapour concentrations over different flow rates ranging from 100 mL/min to 5000 mL/min in soil vapour probes and found no significant difference in measured soil vapour concentration. This suggests that flow rate does not appear to be an important variable on soil-vapour concentrations. However for the purpose of collecting reliable soil gas samples in all soil types in Australia a flow rate that is <500 mL/min is recommended.

When sampling using canisters of 1-1.5 litres, a sampling time of a few minutes to 2 hours is appropriate.

It is noted that when sorbent tubes are proposed to be used for the collection of samples, the sample volume (and flow rate) needs to be determined with consideration of the desired detection limits and vapour concentrations likely to be present (to ensure that the tube is not saturated during sampling). The flow rate through the sorbent tubes should be monitored and recorded throughout the sampling period as this measure is important in the calculation of the concentration (refer to **Appendix E**).

Applied Vacuum During Sampling: Some guidance documents require applied vacuums at the probe to be less than 100 inches of water (~8 inches of Hg⁷). However, for high permeability soils, a qualitative method is typically all that is necessary to estimate if there is little permeability and if too much vacuum is likely to be created during sampling. Connect a 20-50 mL gas-tight, syringe to the probe and pull on the plunger. If the plunger can be pulled easily, there is high permeability and the applied vacuum will likely be small. If the plunger is hard to pull (compared to pulling outside air) or if the plunger retracts towards the probe after being released, then there is likely to be too little permeability to get an uncompromised sample.

For low permeability soils, a quantitative method is preferable using a vacuum gauge placed between the probe and sample container (**Figure F6**). If canisters are being used to collect the soil vapour sample, be aware that a gauge on the summa canister measures the vacuum in the canister, not the vacuum applied to the soil vapour probe, so an additional gauge must be placed in the sampling train between the flow regulator on the canister and the probe (**Figure F7**). For gauges located on the flow restrictors, check with the supplying laboratory to determine if they measure the vacuum in the canister or vacuum at the probe tip.



Figure F6 Vacuum gauge in sampling train

⁷ Units most commonly used in vacuum gauges. If other gauges are used where different units are reported please convert these values.

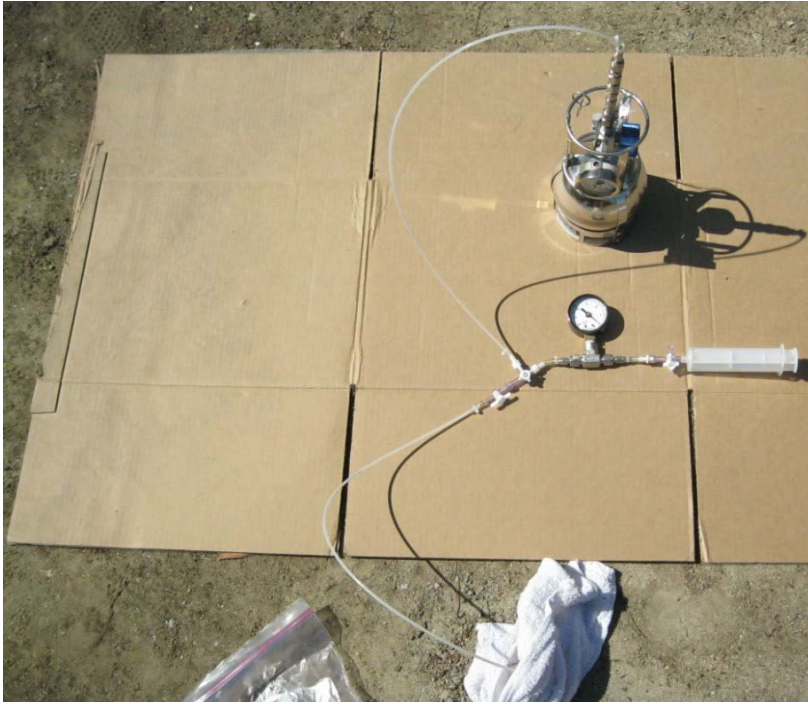


Figure F7 Vacuum gauge between flow regulator on the canister and the soil vapour well

F1.3 Sample Collection into Passivated (Summa) Canisters

For the sampling of soil vapour it is only necessary to collect a small volume of sample. Hence, a 1 to 1.5 litre canister is suitable. Sampling of soil vapour is not recommended using large volume canisters (such as 6 litre canisters).

Passivated canisters should be certified clean by the laboratory prior to sampling. This certification can be done either as a batch or on an individual canister basis. Both are suitable for the sampling of soil gas.

Prior to sampling, the canister shall be checked to ensure that a vacuum of approximately -26 to -30" Hg is present (note vacuum gauges on canisters typically have an accuracy of +/-5" Hg although digital gauge can have an accuracy of +/-0.25" Hg). The canister should be connected to the probe tubing. The canister should be connected to the probe tubing, but not opened, before leak testing has been completed (or a tracer compound is applied) and the well has been purged.

Once the leak detection compound is applied, an aliquot of the soil vapour should be tested for the tracer compound before opening the canister. This is typically done by having a sampling port next to the canister connection (using a Swagelok tee connection or a 3-way plastic valve). If the leak detection compound is below acceptable levels, the well can be purged and canister can then safely be opened. If the leak detection compound is above acceptable levels the sampling should not be conducted. Instead, the canister should be disconnected, and the source of the leak found and corrected. By following this procedure, you will avoid filling canisters with soil vapour samples that fail the leak detection test.

If a large volume canister is being used (>1000 mL) or if the sample depth is very close to the surface (e.g., sub-slab samples), the soil vapour probe should be retested for the leak detection compound after the canister is filled. This is necessary because the canister cannot be tested for the leak detection compound in the field, so if the soil

vapour is leak-free after the canister is filled, it is reasonable to conclude the sample in the canister is leak free also.

To ensure that a sufficiently low flow rate is achieved, flow regulators, available from the laboratory, should be used. At the completion of sampling a slight negative vacuum should be left in the canister. Canisters should not be cooled nor left in the direct sunlight during storage or transport for analysis.

A more specific sampling procedure relevant for the use of passivated canisters is attached to this appendix.

F1.4 Sample Collection onto Adsorbents (Thermal Desorption Tubes)

Soil vapour can easily be transferred from the soil vapour probe onto an adsorbent using the same syringe and 3-way plastic valve (**Figure F8a**). The adsorbent tube is connected between the probe and the syringe so that the syringe pulls the soil vapour through the adsorbent. Other devices such as a low-flow pump can also be used to pass soil vapour over the adsorbent (**Figure F8b**), but pumps upstream of the adsorbent should not be used as cross-contamination between samples will occur. Pumps should be calibrated before use to ensure correct measurement of volumetric flow and a flow meter is used to monitor and report the flow rate during the sample period. Also, the pump flow rate might change if the soil permeability changes. Sample flow rate may be up to 50 mL/min for sampling in tight (e.g. clay) formations, and up to a maximum of 500 mL/min for sampling in permeable formations.

It is important to determine the sample flow rate for every individual tube used in a monitoring round. It is also important to consider the limitations imposed by the methodology in determining flow rates and sampling times. If too much air is moved through the tube then it is possible to get breakthrough which will impact on the robustness of the result. If too little air is moved through the tube then it may not be possible to get a sufficiently low limit of reporting. These issues must be considered when preparing to undertake such sampling.

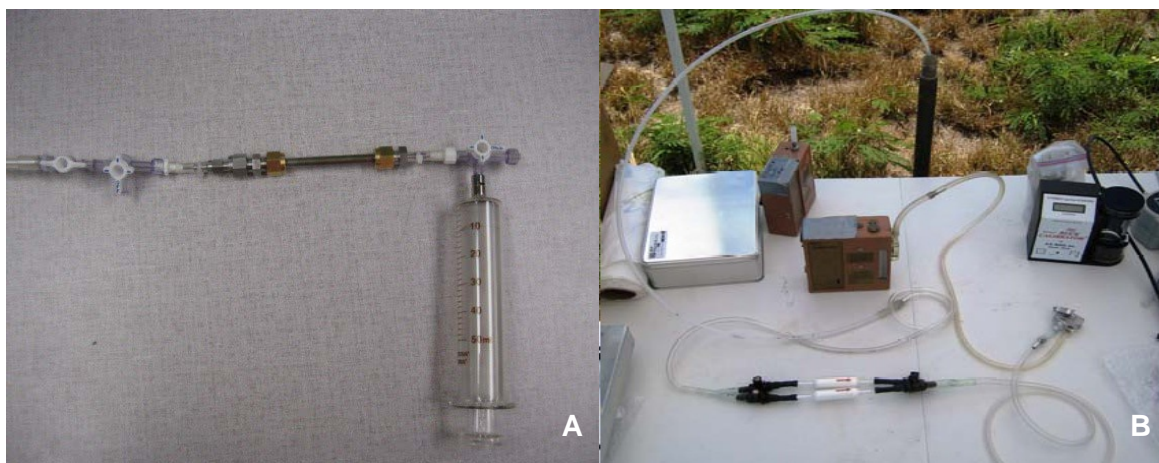


Figure F8 Sampling arrangement for adsorbent tubes: A - with a gas-tight syringe; B - With a low-flow pump

The laboratory should provide guidance on the type of adsorbent for the VOCs of interest and on required sampling volumes based on their detection limits. Often, two tubes are placed in series in case there is any breakthrough of the VOCs from the first

tube. An alternative approach is to collect two tubes at each sampling location: one sample at the laboratory recommended sample volume to reach the detection limits and a second sample collected at 10% of the laboratory recommended sample volume. The lower volume sample is then available for analysis if the higher volume sample is saturated by hydrocarbons. The sample volumes might be adjusted downward if high concentrations are expected or detected at the sampling location.

Leak detection is best performed using the shut-in test procedure for the sampling train and a shroud or towel over the surface of the probe (leak test method #1).

After sampling, the tubes shall be sealed, transferred to the laboratory supplied sample container, and stored with ice/freezer packs within a cool box.

A more specific sampling procedure relevant for the use of sorbent tubes is attached to this appendix.

F1.5 Sample Collection into Gas-Tight (Tedlar) Bags

After purging and application of the leak detection compound over the probe, soil vapour can easily be transferred from the soil vapour probe into a gas-tight bag using a certified clean glass or Teflon syringe (**Figure F9a**). Other devices such as a vacuum chamber (available from SKC, Inc.) can also be used to fill gas-tight bags (**Figure F9b**), but pumps upstream of the bag should not be used as cross-contamination between samples will occur. The bag should be filled, while being careful not to over-inflate and potentially compromise the bag seals.

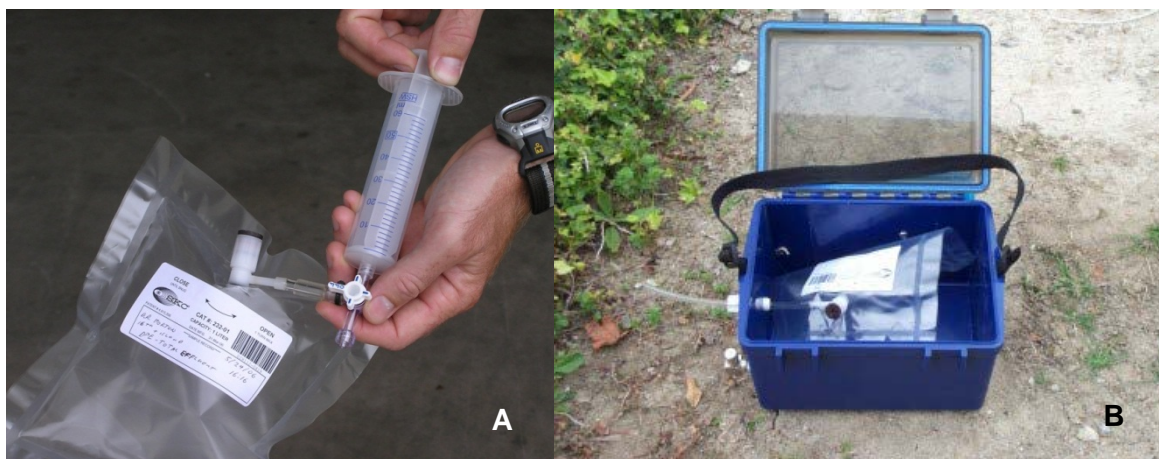


Figure F9. A - Filling a gas-tight bag using a syringe and 3-way valve. Top of the valve is connected to the probe tubing. B - A vacuum chamber (sometimes called a lung-box) to inflate gas-tight bags

Using gas-tight bags offers the advantage of testing the actual soil vapour sample that will be later analysed for the VOCs for the leak detection compound (this is not possible with canisters as described previously). Connect the portable meter directly to the gas-tight bag and measure the tracer compound (it may also be useful to measure O_2 , CO_2 , and PID at this time). If it is below acceptable levels, then the soil vapour sample is valid and the remaining amount in the bag can be sent off for analysis. If it is above acceptable levels, the gas-tight bag is easily emptied and can be reused for the same soil vapour sample location once the leak is found and corrected.

Storage time in gas-tight bags for petroleum hydrocarbons is approximately 48 hours, meaning the samples must reach the laboratory and be analysed within 48 hours of sampling. This can be difficult to achieve in Australia. Also, naphthalene and other heavier compounds can adsorb to the surface of the bags and the longer the sample is in the bag the more this occurs. Also, not all gas-tight bags are the same, so pick a bag that has been shown by the manufacturer or your laboratory to be stable for the compounds of interest. Care must be taken to not puncture or compress the bag during storage. It is best, but not necessary, to store the sample in the dark. The bags should never be chilled. They can be shipped by air provided they are not completely filled (to allow for pressure changes during the flight). If storage times longer than 48 hours are anticipated, or if a more durable storage container is desired, the sample in the tedlar bag can be transferred into a passivated canister (**Figure F10**). When undertaking such a transfer, care must be taken to ensure the transfer line is leak free and that the potential for cross contamination is minimised. It is also possible that some of the higher boiling point VOCs can adsorb to the internal surface of the bag and be lost to the sample on transfer.



Figure F10 Transferring soil vapour sample from a gas-tight bag into a 400mL canister

F2 Passive Soil Vapour Methods

Passive soil vapour methods consist of the burial of an adsorbent in the ground with subsequent retrieval and measurement of the contaminants found adsorbed to the adsorbent (**Figure F11**). Compounds, during migration through the media (adsorbent), contact the passive sampler and diffuse into the sampler. These methods give a time-integrated measurement, and therefore reduce the uncertainty due to temporal variations. However, passive soil vapour methods only yield soil vapour data in terms of mass (e.g., micrograms [μg] or in some other form of relative units), not concentration, because the amount of vapour (soil gas) that comes into contact with the adsorbent while it is buried is unknown. Calculation of concentration from the mass units is sometimes attempted by estimating the volume of vapour that passes by the buried adsorbent during the burial time period from a vapour diffusion model. Another method is to determine an uptake rate for the passive collector. At present, comparative studies show the agreement between passive results to actual measured

soil vapour results to be within an order of magnitude. Hence, due to this uncertainty, passive soil vapour data are considered to give qualitative, not quantitative results, and hence the method is considered a screening tool for soil vapour in vapour intrusion assessments.

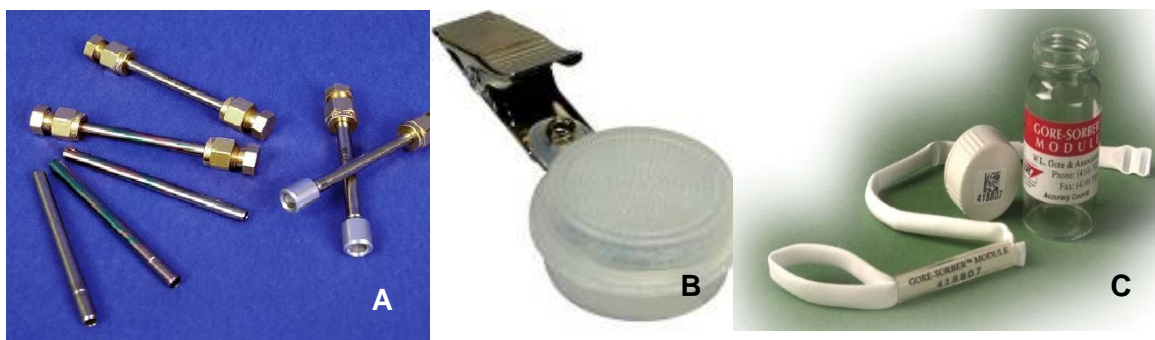


Figure F11 Examples of passive collectors: A - Adsorbent inside tube open on one end; B - Adsorbent inside badge; and C - Adsorbent inside vapour permeable, waterproof membrane

Although qualitative, passive soil vapour sampling can provide useful information when investigating the vapour intrusion pathway. Samplers are generally easy to deploy and retrieve, therefore allowing for cost effective placement of a large number of samplers offering good coverage. The composition of subsurface soil gases can be determined from passive soil samples and the location of subsurface plumes can be mapped, particularly edges of plumes to determine if contamination is near current or future buildings. Passive methods offer a quick and relatively inexpensive method to find preferential pathways into a structure or around a structure, such as utility corridors. Passive soil vapour sampling methods can also be useful in situations where active methods may not be applicable, e.g., areas of low-permeability and high-moisture settings. Further, they are capable of detecting and reporting compounds present in very low concentrations.

Additional information on use, benefits, and limitations of passive soil vapour sampling in the context of vapour intrusion, can be found in ASTM (2011), ITRC (2007) and Hodny, Whetzel & Anderson (2007).

Installation and Retrieval of Passive Samplers

For exterior soil vapour and sub-slab soil vapour sampling, a narrow diameter hole (e.g., 2.5 cm) is advanced to the desired sampling depth (e.g., 15cm to 2 metres; **Figure F12**). Hole depth and diameter depend on the passive sampler design and sampling objectives. Sampler depths of 1.5 metres or less can be accomplished using hand tools (e.g., slide hammer and tile probe, rotary hammer drill and carbide-tipped bit). Deeper soil vapour sampler installations, or deployment into larger diameter holes, may require more invasive drilling equipment, and may require casing the hole similar to the requirements for a permanent active sampling well. The sampler is lowered into the hole to the desired sample depth using a wire or string, which is then anchored at the soil surface. Materials are then used to seal the hole just above the sampler and at the surface (e.g., natural, impermeable cork) preventing down hole vapour infiltration of ambient air. Therefore, no sampling equipment remains on the surface after sampler installation, minimising or eliminating the potential for equipment damage or vandalism, and allowing occupants to continue their activities unimpeded. Retrieval of the sampler

occurs by removing the hole seal, pulling the sampler from the subsurface, and securing it in an appropriate container for transport back to the laboratory.



Figure F12. Passive soil vapour module installation. Photos A to E: Exterior soil vapour sample using slide hammer and rotary hammer drill, insertion of a passive soil gas sampler, and sealing hole. Photos F to H: Subslab soil vapour sample.

Exposure periods depend on passive sampler design and the target reporting levels. Generally finer grained soils, higher soil moisture, less volatile compounds, greater depths to contaminant source, and lower reporting levels, extend the sampling period. The exposure period should be long enough to achieve detectable reporting levels, but not so long that the adsorbent saturates with the target compound(s). Additional information can be found in the ASTM standard on passive soil vapour sampling (ASTM 2012).

Passive Soil Vapour Survey Design

Because the installation and retrieval of passive soil vapour samplers are relatively inexpensive and quick, a large number of samplers can be deployed conveniently and economically at a site, yielding a high resolution image of the subsurface impact. Sample spacing should be a function of project budget and sampling objectives. In a review of the published literature, there appears to be no firm guidance on sample spacing. Sample intervals of 15 to 30 metres are common, with closer spacing when site information is lacking. Survey design should attempt to limit oversampling (collect too many samples and reporting redundant data), but avoid under sampling (collecting too few samples to resolve the feature(s) of interest). A well-designed passive soil vapour survey will identify areas of the site no longer requiring further investigation, while focusing subsequent sampling in areas now known to be impacted.

Attachments

SOP for canister sampling

SOP for sorbent tube sampling

References

ASTM 2011, '*D7758 - 11 Standard Practice for Passive Soil Gas Sampling in the Vadose Zone for Source Identification, Spatial Variability Assessment, Monitoring, and Vapor Intrusion Evaluations*', American Society for Testing and Materials.

ASTM 2012, '*D7648 - 12 Standard Practice for Active Soil Gas Sampling for Direct Push or Manual-Driven Hand-Sampling Equipment*', American Society for Testing and Materials.

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Schumacher, BA & Zimmerman, JH 2008, '*Effects of the Variation of Select Sampling Parameters on Soil Vapor Concentrations*', presented at Remediation of Chlorinated and Recalcitrant Compounds: The Sixth International Conference, Monterey, CA, May 19 - 22, 2008.

Schumacher, BA, Hartman, B, Zimmerman, JH, Springer, D, Elliot, J & Rigby, M 2007, '*Results from EPA Funded Research Programs on The Importance of Purge Volume, Sample Volume, Sample Flow Rate and Temporal Variations on Soil Gas Concentrations*', presented at Air & Waste Management Association Conference, Vapor Intrusion: Learning from the Challenges, Providence, RI, September 26 - 28, 2007.

APPENDIX G.

Indoor Air and Crawl-Space Sampling

The descriptions of indoor air sample collection procedures in this section are general in nature and reflect commonly accepted designs and methods followed by the USEPA. The goal of the indoor air sample collection procedures is to collect a representative indoor air sample for the purpose of assessing the risk posed by contaminants present within a building. However, many commonly used consumer products contain some of the same target compounds of concern that are measured in indoor air samples (e.g. benzene from petroleum based products used in garages and PCE from dry-cleaned clothes).

When conducting indoor air sampling as part of a vapour intrusion study, outdoor ambient air samples should also be collected. Ambient air samples are important to characterise site-specific outdoor air contaminants. Ambient air typically contains numerous VOCs such as benzene and TCE that can often exceed indoor air risk based screening levels (USEPA 2011). For residential structures, outdoor air samples should be collected from a representative upwind location away from wind obstructions. For commercial structures, outdoor air samples should be collected in locations upwind of the intakes of the building HVAC systems.

Outdoor air samples should be collected at locations to minimise bias toward obvious sources of volatile chemicals (e.g. vehicles, lawn mowers, oil storage tanks, service stations, industrial facilities). Outdoor air samples should be collected and analysed by the same method as indoor air samples and generally for the same time periods as the indoor air samples.

Indoor air samples are typically collected under conditions representative of the normal use of the structure (i.e. doors open or closed depending on their typical condition and the type and condition of the air conditioning/ventilation systems in use in the building). It may be useful to collect a sample directly from a point of suspected vapour entry, such as a sump or other enclosed space, to better understand the site specific conditions. If collecting a combination of indoor air samples, outdoor air samples, and sub-slab soil vapour samples for a project, it is better if the indoor and outdoor air samples are collected first followed by collection of the sub-slab soil vapour samples. It is not recommended that sub-slab samples be collected simultaneously with the indoor air samples, because the installation and purging of the probes may introduce site chemicals of concern into the indoor air.

Initial Building Survey

An important first step in any indoor air sampling program is a building survey to assess potential indoor and background sources of VOCs. It is recommended that a survey checklist (refer to **Appendix H**) be used to document information on the building conditions, products/chemicals used or stored in the building, and other potential sources of indoor air contamination.

As part of the building survey, potential preferential vapour intrusion pathways should also be identified. Utility corridors can act as contaminant migration pathways allowing VOCs to travel long distances. Any foundation penetrations such as water, sewer, gas, electric and telecommunication lines, as well as sumps should be documented during

the survey. To be active these pathways need to provide a direct connection between the contaminated vapours and the building being investigated.

Depending on the target compounds, screening for VOCs using direct reading instruments, such as a high sensitivity PID (e.g. RAE brand PID that reads ppb) or combustible gas meter may be useful. Depending on the situation and availability of equipment this may include instruments that have detection limits in the parts per billion (ppb) range. These may be used for locating potential points of vapour entry, locating indoor VOC sources, or identifying acute exposure or potentially explosive situations.

Indoor Air Sample Locations

The number of indoor air samples collected is dependent upon the size, layout, and use of the building, however, for most properties it is recommended that indoor air samples are collected from a minimum of two locations, and crawl-space samples are collected from one location. However where samples are collected from a small apartment/home one indoor air sample may be sufficient (and should be justified prior to sampling).

A typical single family residential dwelling (approximately 140 m²) should have one indoor air sample collected from the ground floor and one from the basement or crawl space (if present). Larger dwellings may require additional samples. Multi-family residential units and commercial or retail buildings will require a more careful review of the building features and typically warrant multiple sample locations. The sampling plan should take into account the different exposure scenarios (e.g., day care, medical facilities) that exist within the building and any sensitive populations that may be exposed to the contaminated vapours. In structures with basements, both the occupied living areas and basement areas should be sampled from a risk management perspective. For multi-storied residential buildings, initial samples are typically collected on the lowest occupied floor as they are likely to be most prone to vapour intrusion.

For samples collected in the breathing zone of the primary living or working area, the sample inlet port is typically placed in the breathing zone, approximately 1-1.5m from the floor. Samples should be collected away from windows, doors and heater/AC vents.

Indoor Air Sample Duration

The duration of indoor air sampling is typically matched to the type of building. In general, sampling duration is typically 24 hours for residential buildings and 8 hours for commercial/industrial building samples. Longer duration samples may be appropriate if significant variability in VOC concentrations is suspected. Passivated canisters are available with flow controllers for up to 7-day collection periods. For longer durations, passive samplers are available.

Indoor Air Sample Frequency

Sampling frequency is determined by the site, objectives of the study and the nature of the contaminants. A single sampling event is unlikely to yield data that are representative of exposure concentrations over a chronic or long term exposure period of time, however where there is a significant margin of safety and multiple lines of evidence can be provided to support the conclusion, one round of data may be sufficient. Typically, a minimum of two sampling rounds are recommended, one in cooler weather conditions when structures are closed up and one in warmer weather

conditions when structures are more open. However, many studies have shown indoor air temporal variations to be less than a factor of 10, so if initial results are 10 times below applicable screening levels, a second sampling round may not be necessary. Refer to the PVI guidance (**Box 5.8**) for further detail.

Indoor Air Sampling Methods

The most common methods for collecting indoor air samples are:

1. Collection in a passivated canister.
2. Active collection on adsorbents using a flow pump.
3. Passive collection on adsorbents.

Refer to CRC CARE Technical Report 13 (Davis, Wright & Patterson 2009) for further details on the advantages and disadvantages of these sample collection methods.

Collection in an Evacuated Canister

The sampling canister is a passivated or specially lined inert container (**Figure G1**) that is sent to the field under vacuum and is certified clean and leak free. The canister fills with air at a fixed flow rate over a pre-set period of time with use of a flow controller that is calibrated and set in the laboratory. Initial and final vacuums are recorded for each canister. The main advantages of canister sample collection are the capability of analysing multiple samples from the same canister and the ease of deployment and retrieval. To ensure the canisters are filling at the proper rate, it is advisable that the rate at which the vacuum is decreasing is checked during deployment to see that it is line with the flow expected through the flow controller.



Figure G1 Examples of evacuated passivated canisters and flow controllers.

Passivated canisters should be certified clean by the laboratory prior to sampling. This certification can be done either as a batch or on an individual canister basis; however where only a few samples are collected from an individual home/building it is recommended that individual canister certification is obtained.

Canisters with dedicated vacuum gauges facilitate this effort and are strongly recommended. The canister must be retrieved prior to being completely filled (with some residual vacuum remaining) to ensure proper collection period.

A typical indoor air sampling arrangement using canisters is depicted in **Figure G2** and includes the following major elements:

- Canister (nominally 1 litre to 6 litre, noting that the collection of samples for 8 hours or longer will require the use of the larger 6 litre canister)
- Flow controller (nominally 8 to 24 hours)
- Pressure gauge (on canister or on flow controller)
- Gas-tight fittings (typically swagelok or equivalent).

The gas-tight fittings are closed at all times, except when actively collecting an air sample, to prevent ambient air from entering the system.

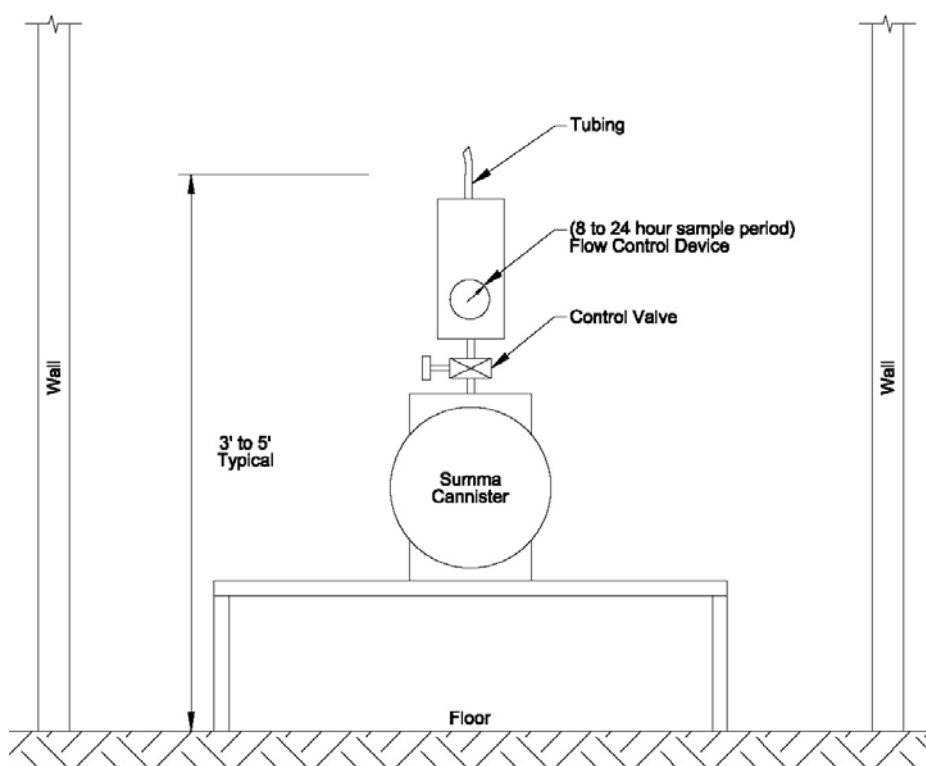


Figure G2 Schematic showing arrangement for collecting indoor air using evacuated canisters

Collection on Adsorbents Using Flow-Pumps

Sample collection on an adsorbent is an option for VOCs and a requirement for SVOCs and can be done actively or passively. Active sampling requires drawing air at a calibrated flow rate through a tube containing adsorbent media over a specified time period. The flow rate and sampling volume used are determined based on the adsorbent used, the chemicals of concern and the amount (mass) of adsorbent contained in the tube. The samples are taken to the laboratory for thermal or chemical desorption and subsequent analysis. Reporting limits are based upon the amount of air that is passed through the tube. It is important to utilise a sorbent that is certified clean and that can be reliably used for the collection and analysis of the chemicals of concern. Low flow pumps are available allowing collection periods of up to 24 hours.

It is important to determine the sample flow rate for every individual tube used in a monitoring round. It is also important to consider the limitations imposed by the methodology in determining flow rates and sampling times. If too much air is moved through the tube then it is possible to get breakthrough which will impact on the robustness of the result. If too little air is moved through the tube then it may not be possible to get a sufficiently low limit of reporting. These issues must be considered when preparing to undertake such sampling.

Passive Collection on Adsorbents

For longer term sampling (days to weeks), passive adsorbent samplers can be used (**Figure G3**). Such devices may be considered less intrusive than canisters so may be preferred for sampling in houses. For the sampling of indoor/ambient air (where there is air movement past the sampler) passive samplers have been shown to provide reliable quantitative results. The collection of compounds is based on the diffusion of the compound onto the adsorbent and does not rely on pumps. The passive sampler is simply hung in the indoor air space to be sampled and left for a predetermined period of time. Exposure times must be determined based on estimated sample concentrations such that the sampler does not reach a state of equilibrium (or saturation) with the environment, a common source of low bias. Check with the laboratory as to the best type of adsorbent to use for the compounds of concern. Diffusion coefficients for these samples are model and target compound specific. Check with supplier (or laboratory) to confirm availability of diffusion coefficients for the compounds of interest at the site.



Figure G3 Examples of passive collectors

Sampling of Crawl-Spaces

There are several options for sampling air from the crawl space. Crawl spaces can be sampled by collecting soil vapour samples (active or passive) or crawl space air samples (with canisters or adsorbents). Most commonly, crawl space air samples will be collected following protocols similar to indoor air samples. A sampling tube is inserted horizontally through the crawl space access ports or vertically through the overlying floor typically for the same duration as indoor air samples. If instantaneous samples are proposed, they should be collected during the period of the expected highest concentrations, for example when the structure's heater is on.

Crawl spaces are known to readily communicate with the overlying structure, so crawl-space air is likely to contain VOCs from household products. An alternative is to collect

soil vapour samples to avoid the complications introduced by household products that might have moved into the crawl space air.

References

Davis, GB, Wright, J & Patterson, BM 2009, '*Field assessment of vapours*', CRC CARE Technical Report no. 13, CRC for Contamination Assessment and Remediation of the Environment, Adelaide, Australia.

USEPA. 2011, '*Petroleum Hydrocarbons and Chlorinated Hydrocarbons Differ In Their Potential for VI*'. United States Environmental Protection Agency, Washington, D.C., September, 2011: pp. 13.

APPENDIX H.

Field Records

The following present example field record sheets and indoor air survey forms that may be used in the sampling of vapour.

Example Indoor Air Building Survey & Sampling Form

Preparer's name: _____ Date: _____

Preparer's affiliation: _____ Phone #: _____

Site Name: _____ Job #: _____

Part I - Occupants

Building Address:

Property Contact: _____ Owner / Renter / other: _____

Contact's Phone: home () _____ work () _____

mobile () _____

of Building occupants: Children under age 5 _____ Children age 6-15 _____
Adults _____

Part II – Building Characteristics

Building type: residential / multi-family residential / office / retail / commercial / industrial

Describe building: _____ Year constructed: _____

Sensitive population: day care / nursing home / hospital / school / other (specify):

Number of floors below grade: _____ (full basement / crawl space / slab on grade)

Number of floors at or above grade: _____

Building dimensions (sketch if complex): _____ m (width) _____ m (length)

Depth of basement below grade surface: _____ m Basement size: _____ m²

Basement floor construction: concrete / dirt / floating / stone / other (specify): _____

Foundation walls: poured concrete / concrete blocks / stone / other (specify) _____

Basement sump present? Yes / No

Sump pump? Yes / No

Water in sump? Yes / No

Type of heating system (circle all that apply):

electric radiator wood (including slow combustion) gas heating (flued and unflued)

reverse cycle air conditioning (including ducted) evaporative cooling system

oil heater electric column heater

other (specify): _____

Type of ventilation system (circle all that apply):

central air conditioning (including ducted) mechanical fans bathroom ventilation

fans individual air conditioning units kitchen range hood fan outside air intake

other (specify): _____

Type of fuel utilised (circle all that apply):

Natural gas / electric / fuel oil / wood / solar / other

(specify): _____

Are the basement walls or floor sealed with waterproof paint or epoxy coatings? Yes /
No

Septic system? Yes / Yes (but not used) / No

Other underground services that connect to building

(specify): _____

Type of ground cover outside of building: grass / concrete / asphalt / paving / other

(specify) _____

Sub-slab vapour/moisture barrier in place? Yes / No

Type of barrier: _____

Part III - Outside Contaminant Sources

Known contaminated site in vicinity (specify, including distance): _____ -

Other stationary sources nearby (service stations, emission stacks, etc.):

Heavy vehicular traffic nearby (or other mobile sources):

Part IV – Indoor Contaminant Sources

Identify all potential indoor sources found in the building (including attached garages), the location of the source (floor and room), and whether the item was removed from the building 48 hours prior to indoor air sampling event. Any ventilation implemented after removal of the items should be completed at least 24 hours prior to the commencement of the indoor air sampling event.

Potential Sources	Description/Location(s)	Removed (Yes / No / NA)
Petrol storage cans		
Petrol-powered equipment		
Kerosene storage cans		
Paints / thinners / strippers		
Cleaning solvents		
Oven cleaners		
Carpet / upholstery cleaners		
Other house cleaning products		
Moth balls		
Polishes / waxes		
Insecticides		
Furniture / floor polish		
Nail polish / polish remover		
Hairspray		
Cologne / perfume		
Air fresheners		
Fuel tank (inside building)		NA
Wood stove or fireplace		NA
New furniture / upholstery		
New carpeting / flooring		NA
Hobbies - glues, paints, etc.		

Part V – Miscellaneous Items

Do any occupants of the building smoke? Yes / No How often? _____

Last time someone smoked in the building? _____ hours / days ago

Does the building have an attached garage directly connected to living space?

Yes / No

If so, is a car usually parked in the garage? Yes / No

Are petrol-powered equipment or cans of petrol/fuels stored in the garage? Yes / No

Do the occupants of the building have their clothes dry cleaned? Yes / No

If yes, how often? weekly / monthly / 3-4 times a year

Do any of the occupants use solvents in work? Yes / No

If yes, what types of solvents are used? _____

If yes, are their clothes washed at work? Yes / No

Have any pesticides/herbicides been applied around the building or in the yard?

Yes / No

If so, when and which chemicals? _____

Has there ever been a fire in the building? Yes / No If yes, when? _____

Has painting or staining been done in the building in the last 6 months? Yes / No

If yes, when _____ and where? _____

Part VI – Sampling Information

Sample Technician: _____ Phone number: () _____

Company: _____

Sample Source: Indoor Air / Sub-Slab / Near Slab Soil Gas / Exterior Soil Gas

Were "Instructions for Occupants" followed? Yes / No

If not, describe modifications: _____

Sample locations (floor, room):

Sampling Data

Sample #	Location	Analytical Method	Sample Volume	Sample Time	Sample Date	Sampler Type	Relative Humidity (%)	Ambient Temp (°C)

Type of field instrument used (include summary of results):

Sketch of Sample Location(s) in Building



Part VII - Meteorological Conditions

Was there significant precipitation within 12 hours prior to (or during) the sampling event? *Yes / No*

Describe the general weather conditions: _____

Part VIII – General Observations

Provide any information that may be pertinent to the sampling event and may assist in the data interpretation process.

Example Indoor air Sampling Logsheet

Crawl Space or Indoor Air Sampling Field Notes

Location ID:

--

Site	
Client and Project Number	
Date	
Sampler	
Laboratory Used	
Location (description)	

Environmental Conditions

Temperature	
Barometric pressure	
Windspeed and direction	
Relative humidity	
Rainfall (in past 24 hours)	

Crawl-Space or Indoor Air Sampling

Sample ID (canister/tube number)	
Flow Controller ID	
Equipment Blank ID	
Start Time	
Start pressure	
Flow rate	mL/min
Finish Time	
Finish pressure	
Flow rate	mL/min
Volume collected	

Field Readings:

	PID	ppm	ppm
	LEL	%	%
Field observations			

Note: Include instrument models and calibration details when reporting field results

Example Soil Vapour Sampling Logsheet

Soil Gas Sampling Field Notes

Location ID:

--

Site	
Client and Project Number	
Date	
Sampler	
Laboratory Used	

Environmental Conditions

Temperature	
Barometric pressure	
Windspeed and direction	
Relative humidity	
Rainfall (in past 24 hours)	

Helium tracer test:

Time	
Helium in headspace	%
Helium reading - ambient air	ppm
Stabilised helium in sampling line	ppm
Stabilised helium in sampling train	ppm (includes check of all fittings and canisters)
Conformance	yes/no (conformance where <10% of He in headspace)

Soil Gas Sampling:

Purge method and flow rate	
Purge time	
Pressure test (pass/fail)	
Sample ID (canister/tube number)	
Start Time	
Start pressure	
Flow rate	mL/min
Finish Time	
Finish pressure	
Flow rate	mL/min
Volume collected	

Stabilised Field Readings:

	Before Sampling	After Sampling
PID	ppm	ppm
LEL	%	%
O ₂	%	%
CO ₂	%	%
CH ₄	%	%
Field observations		

Note: Include instrument models and calibration details when reporting field results

APPENDIX I.

Analytical Methods for PVI Assessments

A list of analytical methods available and commonly used in Australia for soil vapour and indoor air samples are summarised in Table I-1:

Table I-1 Summary of Analytical Methods for Soil Gas, Indoor and Ambient Air Samples at Petroleum Hydrocarbon Affected Sites¹

Parameter	Method	Sample Media/ Storage	Description	Method Holding Time	Reporting Limit ²	Available in Australia?
VOCs						
Polar and Non-polar VOCs	USEPA TO-15	Canister Ambient Temperature	GC/MS	30 days for canister	1-3 µg/m ³	Generally available in Australia
Trace Level VOCs	USEPA TO-15 SIM	Canister Ambient Temperature	GC/MS	30 days for canister	0.03-0.5 µg/m ³	Some laboratories in Australia are accredited for this method. Usually have to let lab know prior to pickup so canister verification is suited to lower detection limits
Polar and Non-polar VOCs	USEPA TO-17 ³	Sorbent Tube Chilled (<4oC)	GC/MS	30 days for sorbent tube	2-4 ng/tube	Generally available in Australia
Polar and Non-polar VOCs	USEPA TO-17 ³ SIM	Sorbent Tube Chilled (<4oC)	GC/MS	30 days for sorbent tube	0.1-0.5 µg/m ³	Some laboratories offer this method in Australia
VOCs	USEPA 8260B modified	Syringe, Tedlar Bag, Glass Vial Ambient Temperature	GC/PID	On site analysis or 2 days for Tedlar bag or 30 days for vial	50-100 µg/m ³	Some laboratories can offer this method on request
VOCs	USEPA 8021B modified	Tedlar Bag Ambient Temperature	GC/PID	On site analysis or 3 days for tedlar bag	10-60 µg/m ³	Not offered in Australia
Fixed Gases						
Fixed Gases (methane, nitrogen, oxygen, carbon dioxide, carbon monoxide)	ASTM D-1946	Canister or Tedlar Bag Ambient Temperature	GC/TCD/FID	30 days for canister 3 days for tedlar bag	0.1-0.0001%	Generally available in Australia although tedlar bags are not always acceptable
Natural Gases	ASTM D-1945	Canister or Tedlar Bag Ambient Temperature	GC/FID	30 days for canister 3 days for tedlar bag	0.1-0.0001%	Generally available in Australia although tedlar bags are not always acceptable
TPH/TRH – Alkanes						
C4-C12	USEPA TO-15	Canister or Tedlar Bag	GC/FID	30 days for	100 µg/m ³	Some laboratories in Australia offer this

Parameter	Method	Sample Media/ Storage	Description	Method Holding Time	Reporting Limit ²	Available in Australia?
		Ambient Temperature		Canister 3 days for Tedlar Bag		method
C5-C16+	USEPA TO-17	Sorbent Tube Chilled (<4oC)	GC/MS	30 days for sorbent tube	2-4 ng/tube	Some laboratories in Australia offer this method
C5-C12	Mass DEP APH ⁴	Canister or Tedlar Bag Ambient Temperature	GC/MS	30 days for Canister	2-4 µg/m ³	Some laboratories in Australia offer this method

Notes for Table I-1

¹This is not an exhaustive list. Some methods (other than those listed above) may be more applicable in certain instances and their use should be justified on each occasion.

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

³The indicated methods utilise a sorbent based sampling technique. The detection limits will be dependent upon the amount of air passed through the media.

⁴Mass DEP-APH method – Massachusetts Department of Environmental Protection Method for the Determination of Air-Phase Petroleum Hydrocarbons (APH)

GC/MS = Gas chromatography/mass spectrometry

GC/FID = Gas chromatography/flame ionization
detector

GC/TCD = Gas chromatography/thermal conductivity
detector

VOC = Volatile organic compounds

PAH = Polycyclic aromatic
hydrocarbons

SVOC = Semi-volatile organic
compounds

The weblinks for these analytical methods are summarised in Table I-2:

Table I-2. Weblinks for Analytical Methods for Petroleum Hydrocarbon VOCs in Vapour Samples

Analyte	Analytical Method	Reference
TPH/TRH	USEPA TO-15 USEPA TO-17 MA-APH	http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-15r.pdf http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-17r.pdf http://www.mass.gov/dep/cleanup/laws/aphsop09.pdf
BTEX, naphthalene	TO-15 TO-17	http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-15r.pdf http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-17r.pdf
VOCs	TO-15 TO-17 MA-APH	http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-15r.pdf http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-17r.pdf http://www.mass.gov/dep/cleanup/laws/aphsop09.pdf
Oxygen, Carbon Dioxide, Nitrogen, Methane	ASTM D-1946 ASTM D-1945 portable meters	http://www.astm.org/Standards/D1946.htm http://www.astm.org/Standards/D1945.htm

Choosing the Analytical Method

The primary criteria for choosing the appropriate method are:

- Compounds of concern;
- Required detection level and other data quality objectives (DQOs);
- Sampling logistics; and
- Cost.

US EPA toxic organic (TO) methods are best to use when low detection limits of VOCs are required ($< 50 \mu\text{g}/\text{m}^3$). If high concentrations are expected, less sensitive (and less costly) methods may be sufficient.

The American Petroleum Institute publication titled *Collecting and Interpreting Soil Gas Samples from the Vadose Zone* (API, 2005) recommends that prior to the selection of analytical methods, the following questions should be answered:

- What are the specific chemicals of concern or other analytes (e.g., natural attenuation parameters) that need to be identified by the analysis? The key specific analytes (e.g., benzene, naphthalene) for the subsurface-vapour-to-indoor-air exposure pathway should be identified. Generally, these will be the volatile and semi-volatile chemicals of concern identified during the overall site investigation. Many regulatory agencies have identified specific chemicals of concern that should be included in the analyte list. However, if specific chemicals of concern are not identified, an analytical method should be selected based on its ability to detect the range of analytes (e.g., VOC, SVOCs) that may be present at a site.
- What analytical method reporting limits are required to adequately assess the potential exposures? It is important to determine the smallest concentrations of chemicals of concern in soil vapour or other analytes that are expected to be required for purposes of evaluating the subsurface-vapour-to-indoor-air exposure pathway. To evaluate this exposure pathway, indoor air target levels for chemicals of concern or other analytes should be identified. These indoor air target levels can be used to identify the necessary detection limits for the soil vapour analyses.
- Do soil or groundwater analytical results, or other field data, indicate that concentrations of chemicals of concern in soil vapour will be high? If concentrations of chemicals of concern or other analytes in soil vapour are anticipated to be high, then the analytical method selected should address high concentrations. In cases where high concentrations are anticipated, USEPA OSWER methods may be appropriate. Comparison studies have shown that the 8000 series methods give equivalent results to the TO methods in this higher concentration range.
- How are the samples to be collected? The analytical method selected, in many cases, will define the collection method (e.g., canister or absorbent tube) that should be used and typically the sample preparation that is required to analyse a sample. Tedlar bags are not generally supported by Australian laboratories.
- Do the regulatory agencies/auditors require accreditation of the laboratory or that specific analytical methods be used? Some regulatory agencies/auditors require that samples be analysed by specific methods. They may also require the laboratory that is conducting the analysis to be NATA accredited (or equivalent). In some cases, this may limit the use of field analytical methods.

- *Are there short turnaround times required for analytical results?* Turnaround times will be influenced by shipping requirements, holding times, laboratory backlog, and analytical methods. Depending on the priorities of the subsurface-vapour-to-indoor-air exposure pathway evaluation, field analysis (likely to be limited to PID in Australia) may be preferable to shipment to a laboratory. Field analysis can provide nearly real time results.
- *Are the analytical methods appropriate for the soil vapour samples?* The analytical methods often are updated with newer techniques. It is suggested that the user consult with the regulatory agency/auditor and a qualified analytical laboratory to identify analytical methods appropriate for the specific site.

Additional Analyses Specific to Petroleum Hydrocarbon Compounds

Methane Analysis

There are a number of options available when analysing for methane. Field analysers are available (LFG monitors, etc.) and there are also several lab methods. Note that the reporting of methane using a LFG monitor can be erroneous (biased high) where elevated petroleum hydrocarbon vapours are present. The more commonly used methods for higher level methane concentrations are ASTM D-1945 and ASTM D-1946. These methods typically utilise a thermal conductivity detector for % levels of methane, or an FID to detect levels near the atmospheric background concentration range of 5 ppmv. If source determination of methane is desired (landfill gas, thermogenic, or biogenic), isotopic techniques are available that examine carbon and hydrogen isotope ratios that will distinguish one potential source from another.

Naphthalene

Methods TO-13, TO-15 and TO-17 have often been used for naphthalene. TO-13 and TO-17 are absorbent methods which minimise the potential losses of naphthalene in a canister during storage and transport.

Fixed Gas Analysis: (Oxygen, Carbon Dioxide, Methane)

Fixed gases, typically defined as oxygen, nitrogen, methane, carbon dioxide, and carbon monoxide, are readily analysed via laboratory-based methods that utilise a thermal conductivity detector (TCD) for detection. ASTM D-1945 and ASTM D-1946 are two of the more common methods, and can typically detect concentrations as low as 0.01%. These same methods can also be used to analyse for helium, which is typically employed as a tracer gas during leak check procedures. Sorbent tube methods (i.e. TO-17, TO-13) are not suitable for fixed gas analysis since the sorbents will not readily adsorb fixed gases.

These compounds can also be measured in the field using hand-held analysers, such as a Landtech GA-90/GEM-2000 or RKI-brand Eagle. The fixed gas analyser can be connected directly to the 2-way valve on the tubing to the vapour sampling point. The gas analyser has an internal pump that can be used to extract soil vapour and purge the system before the fixed gas analysis. Purging is considered complete when the gas measurements on the analyser are stabilised. After stabilisation, the oxygen, carbon dioxide and methane concentrations are recorded in the field log. Note that the reporting of methane using hand-held analysers can be significantly biased by the presence of elevated petroleum hydrocarbon vapours. Where elevated methane levels are reported in the field, the vapour sample collected (or a specific sample collected) should be analysed for fixed gases by the laboratory.

Field Methods

On-site screening can be extremely beneficial for vapour intrusion assessments as real-time data enable detection of preferential vapour migration sources or pathways and allows additional sampling locations to be added (spatially or vertically). Field screening with hand-held PIDs enable rapid identification of vapour migration routes around and into structures; although most field screening instruments are limited to the ppmv range for VOCs, which may not provide sufficient sensitivity for quantitative vapour intrusion investigations.

References

API 2005, '*Collecting and Interpreting Soil Gas Samples from the Vadose Zone, A Practical Strategy for assessing the subsurface vapour to indoor air migration pathway at petroleum hydrocarbon sites*', American Petroleum Institute, Publication Number 4741, November 2005.

APPENDIX J.

Quality Assurance Considerations

Quality Assurance and Quality Control (QA/QC) procedures should be implemented in every step of the assessment process to ensure the collection of data of acceptable quality. This section will cover some general QA/QC considerations for field and laboratory activities.

QA/QC for Active Vapour Sampling:

The majority of the soil vapour and indoor air sampling conducted for the investigation of the vapour intrusion pathway is for VOCs. The focus of this active sampling QA/QC section is on USEPA Methods TO-15 and TO-17.

Below are examples of QA/QC procedures that should be considered. This list is not meant to be exhaustive:

- Sample storage was appropriate for the media (ambient for canisters and <math><4^{\circ}\text{C}</math> for sorbent tubes) and samples were analysed within the required holding time?
- Required field QC samples: field duplicates to be collected at a frequency of 1 per 10 samples; equipment blanks and field blank (1 per sampling day)
- Analyte list and reporting limits: discuss your site specific compound list and reporting limits with the laboratory to ensure they can be met.
- Determine whether the laboratory refers to a method detection limit (MDL), practical quantitation limit (PQL), or some other reporting limit when they refer to their reporting limit
 - MDL = Method Detection Limit - 99% confidence that data is distinguishable from background noise
 - PQL = Practical Quantitation Limit - An estimated value usually 3-5 times the MDL
 - RL = Reporting Limit - Concentration \geq the lowest calibration standard $>$ MDL
- Required laboratory QC samples: Instrument Tuning, Initial Calibration, Continuing Calibration Verification, Laboratory Control Spike and Method Blank (at the frequency specified in the laboratory's procedures).
- Laboratory accreditation: does the laboratory hold accreditation for the analysis method?
- Certified canisters: did the canister test non-detect below the reporting limit for the VOCs of concern.
- Certification of flow controllers: did the controller test clean.
- Flow controllers: specify the collection period to the laboratory
- Standard operating procedures (SOPs): ensure that the sampling crew follow documented, reproducible field procedures
- System leak checks for soil vapour samples: utilise a tracer gas to check for leakage around the sampling probe and analytical sampling train
- Initial & final vacuum readings: the sampler should take the canister vacuum reading before and after sampling to ensure that the canister was leak free upon receipt in the field and that the flow controller collected the sample over the specified amount of time.

- Precautions should be taken to avoid sample interference such as avoiding fuelling vehicles prior to sampling or the use of permanent marking pens in the field
- Additional QC samples
- Trip blanks refer to canisters sent out with the canister batch to test for the presence of contaminants introduced during transit and storage
- Equipment blanks refer to purified gas (air, nitrogen) samples collected through the sampling system to test for the presence of contaminants introduced by the sampling methods
- Analytical holding time per USEPA TO-15: analysis of canister samples for VOCs must be completed within 30 days from collection; check with state or region to verify their holding time requirements. For tedlar bags the holding time is 48 hours, for a syringe the holding time is minutes while for some passive samplers it can be months as long as they are stored correctly.

QA/QC for Passive Vapour Sampling:

Modified USEPA methods 8270 may be used for analysis of passive samplers in addition to USEPA TO-17. QA/QC requirements are based more on data quality objectives than on prescriptive procedures. Specific QA/QC procedures will vary depending on the manufacturer of the sampler and on the analytical laboratory. Therefore, it is important to understand what procedures will be used and to determine if they are adequate to meet the data quality objectives.

At a minimum QA/QC procedures should consider the following:

- Passive sampler installation, retrieval, and handling – to ensure consistency of deployment and sample integrity prior to analysis.
- Units of measure – concentration or mass (or some other relative) units. If concentration data are to be provided is there sufficient data to verify sampling rates, indifference to changing air flow, and sampler capacity?
- Detection limit – are the sampler and analytical method of sufficient sensitivity?
- Deployment time – is it long enough to get the required detection limit?
- Cleanliness of sampler - are procedures in place to verify cleanliness of sampler? Sampler background must be sufficiently less than reporting limits.
- Instrument calibration – are target compounds used for calibration and concentration ranges adequate to cover chemicals of concern and suspected sample levels?
- Sample storage was appropriate for the media (<4°C for sorbent materials) and samples were analysed within the required holding time?
- Control samples – method, trip, and field blanks to verify integrity of samples during shipment and potential levels of background.
 - Method Blanks are clean adsorbent material analysed by the applicable analytical method to determine any potential background levels of target compounds contributed by the analytical method.
 - Trip Blanks are unexposed passive samplers, which accompany samplers during transport to the field and then to the laboratory. Trip blanks are intended to determine any potential background levels of target compounds that may have been contributed during transport.
 - Field Blanks (for soil vapour sampling only) are passive samplers exposed to ambient conditions for the same amount of time field

exposed samplers are exposed to ambient conditions prior to installation in the subsurface. Field blanks are intended to determine potential contribution of background levels of target compounds contributed by ambient air and not soil vapour.

- Replicate analyses - if replicate analysis is required, does sampler allow for multiple analyses or do multiple samplers need to be co-located.

Other QA/ QC considerations:

- Passive samplers should be transported in a sealable container to preserve cleanliness prior to use, and to prevent additional adsorption during return shipment to the analytical laboratory.
- For subsurface applications, the samplers should also have a design that keeps soil, microbes, liquid water, and other contaminants from coming in direct contact with the adsorbent.
- The adsorbent material should be hydrophobic to minimise water vapour uptake.
- Accurate time recording is essential for comparison of results, and all samplers in a given medium should be deployed for a consistent amount of time unless some locations have very high concentrations which would warrant a shorter sampling period. The time may vary for different media, for example, if soil vapour concentrations are expected to be higher than indoor air concentrations, the soil vapour samplers may approach saturation before the indoor air samplers have sufficient mass to reach analytical detection limits, in which case, the indoor air samplers should be deployed for a longer period than the subsurface samplers.

APPENDIX K.

Checklist for Reviewing Soil Vapour Data

Sample Collection

Active Soil Vapour Data

- Did the probe rod have an internal inert tube (SS, Teflon, nylon)?
- Was the probe reused? If so was it adequately decontaminated between samples?
- Were at least 3 dead volumes of the probe purged?
 - ⇒ *Avoid excessive purging, unless field screening (O₂, CO₂, PID or FID and tracer gas) conducted to demonstrate absence of atmospheric air intrusion.*
- Did the field screening of PID, O₂ and CO₂ provide results consistent with those expected based on sample location (in relation to contamination), depth and soil type? Are the results consistent with the CSM (in particular parameters that relate to and support biodegradation processes)?
- Were samples collected deep enough to minimise air infiltration?
- Did it rain shortly before the sampling event?
 - ⇒ *Soil vapour sampling should be avoided following significant precipitation*
 - ⇒ *Generally there is no consensus on how much rain can fall or how much time should elapse before taking samples. It depends on soil type, ground surface cover, amount of rain and previous soil moisture content. As a general guide sampling from wells in open ground (not beneath buildings or concrete pavement) should occur 3-7 days after 25mm rainfall has occurred within an approximate 24 hour time period.*
- Was a reliable method used to ensure the absence of atmospheric air leakage?
 - ⇒ *Tracer compound used to demonstrate no leakage down or around probe and at all sample train fittings.*
- Were samples collected in appropriate containers for the chemicals of concern?
- If canisters were used, was each canister certified clean or batch tested?
- Were dedicated flow controllers & sample trains used for each sample?
 - ⇒ *It is not recommended that flow controllers and sample trains are re-used. Cleaning of these components in the field has been shown to be ineffective and the re-use of such equipment can result in cross-contamination.*
- Were vacuum pumps used in the sample collection? If so, did the flow rate decrease because of resistance to flow?
- Were excessive vacuums required to obtain a sample?
 - ⇒ *>100 inches of H₂O (~8 inches of Hg) should be avoided*
- Were samples collected upstream of the vacuum pump (where used)?
- Was the sample flow rate through the sorbent tubes monitored and reported throughout the sampling period?
- For canisters, were samples stored at ambient air temperature?
- For sorbent tubes, were these stored and shipped at <4°C
- Were samples analysed within recommended holding times?

Passive Soil Vapour Programs

- Were method and trip blanks analysed?
 - ⇒ *Needed to show absence of contaminants from lab or transportation back and forth to site*

- Were samplers left in the ground for consistent and sufficient time?
 - ⇒ Generally a few days to 2 weeks (unless in an area with very high levels being sampled).
 - ⇒ Collected in same sequence as deployed
- Were duplicate samples collected and how do they compare?
- Are data used appropriately?
 - ⇒ For what purpose?
 - ⇒ Were active soil vapour samples collected for comparison?
 - ⇒ How well do passive and active samples compare?
- Could measured values be from infiltration of contaminated atmospheric air or from volatiles emitted from an overlying surface (e.g., asphalt, dirty soil)? (i.e. is there a chance of cross contamination from the environment?)
- Are relative concentrations of compounds detected consistent with expectations from other media (soil vapour, groundwater, bulk soil)?
- Were the passive samplers stored and shipped at <4°C
- Were samples analysed within recommended holding times?

Sample Analysis

The following questions should be asked when examining the analysis of any type of soil vapour sample: active or passive.

Active and Passive Soil Vapour Samples

- What methods are being used? Can they detect the target compounds at the required levels of sensitivity?
- Have the method required calibration standards been analysed?
- Are the reported values within the documented calibration range of the instrument?
- Are any compounds co-eluting?
- Have the method required QA/QC samples been analysed (blanks, duplicates, etc.)
- Are the calibration standards within method required holding times and traceable to a certified source?
- In what units are the data reported ($\mu\text{g/l}$, $\mu\text{g/m}^3$, ppbv, ppmv)?
- For high concentrations, have large dilutions been performed and do these affect the interpretation of the results? (i.e. are the detection limits above the adopted screening values for the PHCs evaluated?)

Passive Soil Vapour Samples

In addition to the analytical issues summarised above, the following issues should be examined with passive soil vapour samples:

- How are the samples desorbed from the collector?
- Is the desorption process quantitative and does it fractionate?
- What units are the data reported in (mass etc.)?

APPENDIX L.

Checklist for Reporting Critical Aspects and Assessments Steps in PVI Assessment

Critical Issue and Assessment Steps	Relevant at Site (y/n)	Addressed in Report Section
Objectives of PVI assessment		
Determination of whether there is contamination present		
LNAPL		
Contaminated groundwater (dissolved phase)		
Contaminated soil		
Site ruled out from needing further assessment as no relevant contamination present at site		
Development of Sufficient CSM (meets minimum requirements from Table 1 of PVI guidance)		
Source of Contamination identified		
Nature and extent of contamination identified		
Geology described		
Hydrogeology described		
Zone of influence established		
Buildings and uses present		
Buildings and uses proposed		
Evaluation of whether short-term/acute risks are present		
Auditor/regulator notified of short-term/acute risks and rectification actions developed		
Contamination in direct contact with existing or proposed building foundations		
Review and use of HSLs – where applicable, are concentrations above HSLs?		
Review and use of screening distances – where applicable is the distance between contamination and receptors/building foundation greater than screening distances?		
Site ruled out from needing further assessment as vapour intrusion is not of significance as determined through appropriate use of HSLs or screening distances (unless preferential pathways present)		
Preferential pathways present		
Where contamination is in contact with foundations, modelling of indoor air concentrations from seepage indicates a potential risk		
Where contamination is not in contact with foundations, modelling of indoor air concentrations from groundwater using J&E (or equivalent) indicates a potential risk		
Collection of Vapour Data		
Soil gas samples taken to provide evidence of level of risk		
Soil gas samples collected from appropriate locations and depths		
Soil gas samples collected from representative conditions		
Soil gas samples collected in accordance with Box 5.4 of PVI guidance (also refer to Appendix K)		
Crawl space samples taken to provide evidence of level of risk		
Air samples collected from appropriate locations and over appropriate period of time		
Air samples collected in accordance with Box 5.5 of PVI guidance		
Indoor air samples taken to provide evidence of level of risk		
Air samples collected from appropriate locations and over appropriate period of time		

Critical Issue and Assessment Steps	Relevant at Site (y/n)	Addressed in Report Section
Air samples collected in accordance with Box 5.5 of PVI guidance		
<i>Evaluation of vapour data</i>		
Is the data of suitable quality to use in the assessment (QA/QC evaluation)		
Is there sufficient data for making robust conclusions		
<i>Conclusions of PVI Assessment</i>		

APPENDIX M.

Case Studies

The following presents three case studies that outline how the PVI guidance can be used to assess PVI risks at sites. The case studies presented are very brief and are intended to only show how the PVI guidance can be used in these situations. It would be expected that when these sites are reported that more detail (including providing a detailed conceptual site model) is presented (as required in the PVI guidance).

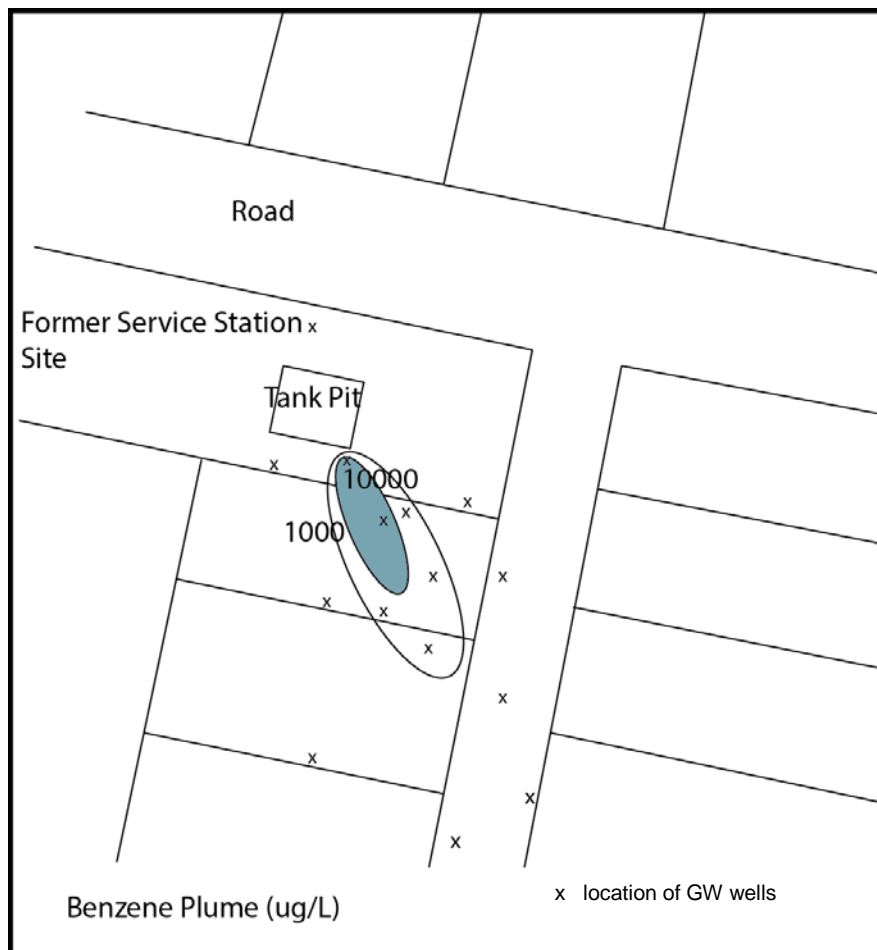
Case Study 1

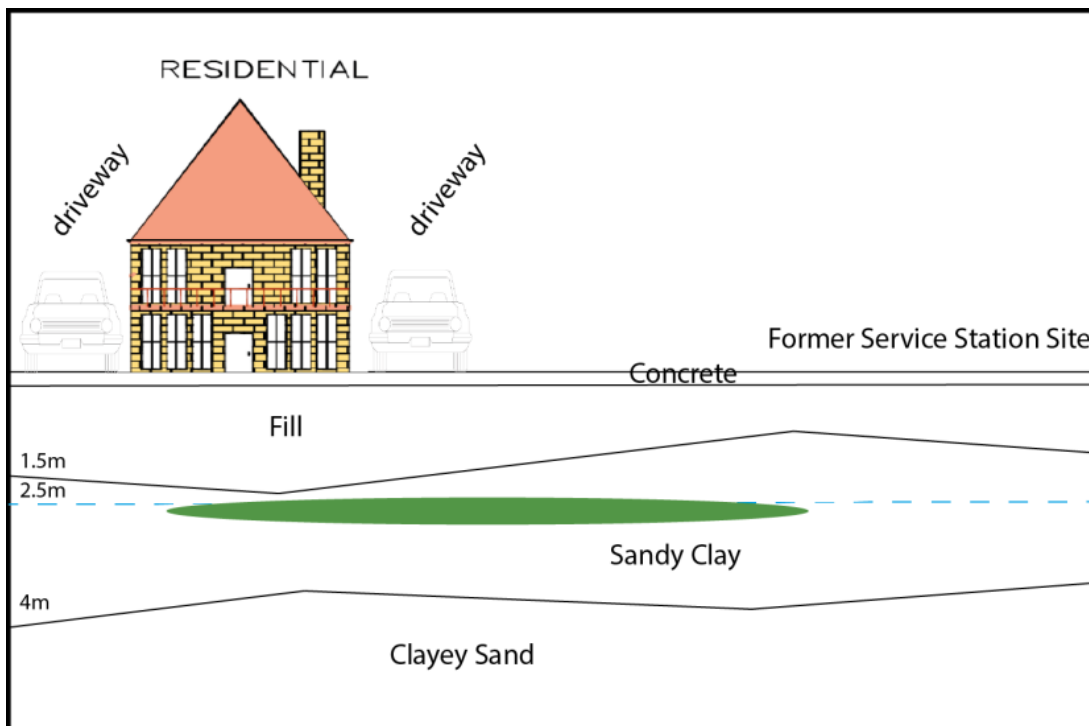
Introduction

A former service station, that closed 5 years ago, is being investigated and remediated. The properties on the down gradient boundary are residential with very little open ground due to the size of the houses constructed and a long driveway down one side to a townhouse at the back of the block.

Conceptual Site Model

The following figure shows the extent of the groundwater plume, which has been delineated and shown to be stable.





A brief description of the site conditions has been provided in the above diagrams just to set the scene for the case study. A PVI assessment should include a more detailed description of the conceptual site model as outlined in the guidance.

Preliminary PVI Assessment (Section 3 of PVI Guidance)

Following Decision Diagram 1, the following is determined:

LNAPL

The guidance asks whether LNAPL is present at the site. There was no LNAPL observed to be present at the site but the plume had concentrations of benzene above 20 mg/L and BTEX concentrations above 50 mg/L which indicates LNAPL is present using the definition outlined in **Box 2.1**. This requires movement to the next step.

Zone of Influence

The next step in the preliminary PVI assessment is to identify the zone of influence. At this site the zone of influence is limited to the two houses immediately downgradient of the former service station site. The groundwater assessment indicates that the plume is stable and quite contained and so other properties are outside the zone and do not require consideration in this assessment.

Short-term risks

The normal/simplest approach to assessing the potential for short term risks (next step in the preliminary PVI assessment) is to model the vapour intrusion using the J&E model as outlined in the CRC Care Technical Report 10 Volume 1. Also PID data from the groundwater wells or other locations can be used as indicated in the table in **Box 3.1**.

In this case, soil gas wells were installed at this site and in a number of relevant off-site locations around the adjacent house located above the plume. This will not always be the case and it is not expected that soil gas data will be available for this part of the assessment.

The PID results for the soil gas wells when they were installed were 100-3200 ppm which indicated that significant levels of contaminants were present throughout the soil profile. **Box 3.1 (Table 2)** indicates that 500-2500 ppm should trigger an odour flag in an assessment. Levels above 1400 ppm at the surface indicate the potential for short-term issues in confined spaces while levels above 3500 ppm in the soil gas indicate the potential for short-term issues in the building.

The soil gas showed levels of in excess of 10 000 000 $\mu\text{g}/\text{m}^3$ for benzene and toluene and levels in excess of 1 000 $\mu\text{g}/\text{m}^3$ for ethylbenzene and xylenes at a 2 metre depth.

It is noted that at this site, preliminary modelling of vapour risks from groundwater indicated a potential for chronic risks (both non-threshold (6×10^{-5}) and threshold (3)) However the collected soil gas data suggested higher vapour risks than predicted using the modelling. Further evaluation of the data for the site indicated that soil contamination was also present in the unsaturated zone at the site boundary with the residential property (where the soil gas samples were collected). This contamination (that met the definition for contaminated soil in **Box 2.1**) was also contributing to the soil gas levels and also limiting the potential for effective biodegradation.

To evaluate the potential for short-term risks, the speciated soil gas data available for this site can be compared with the action levels listed in **Box 3.1 (Table 2)**. The benzene result (10 000 000 $\mu\text{g}/\text{m}^3$) is well above 17 000 $\mu\text{g}/\text{m}^3$ which is the trigger for short-term risks to be considered in soil gas.

In this example there are a number of lines of evidence here indicating that short-term risks are likely – PID close to trigger for subsurface, modelling results indicating an elevated risk (where quite elevated when risks from groundwater and soil are summed) and the soil gas results being above the short-term action levels.

Consequently, the next step for this project should be to consult with the auditor or the regulator to determine what actions are required. These actions should be undertaken promptly.

Screening PVI Assessment

Potentially not required – cannot be decided until acute/short-term risk is addressed.

Detailed PVI Assessment

Potentially not required – cannot be decided until acute/short-term risk is addressed.

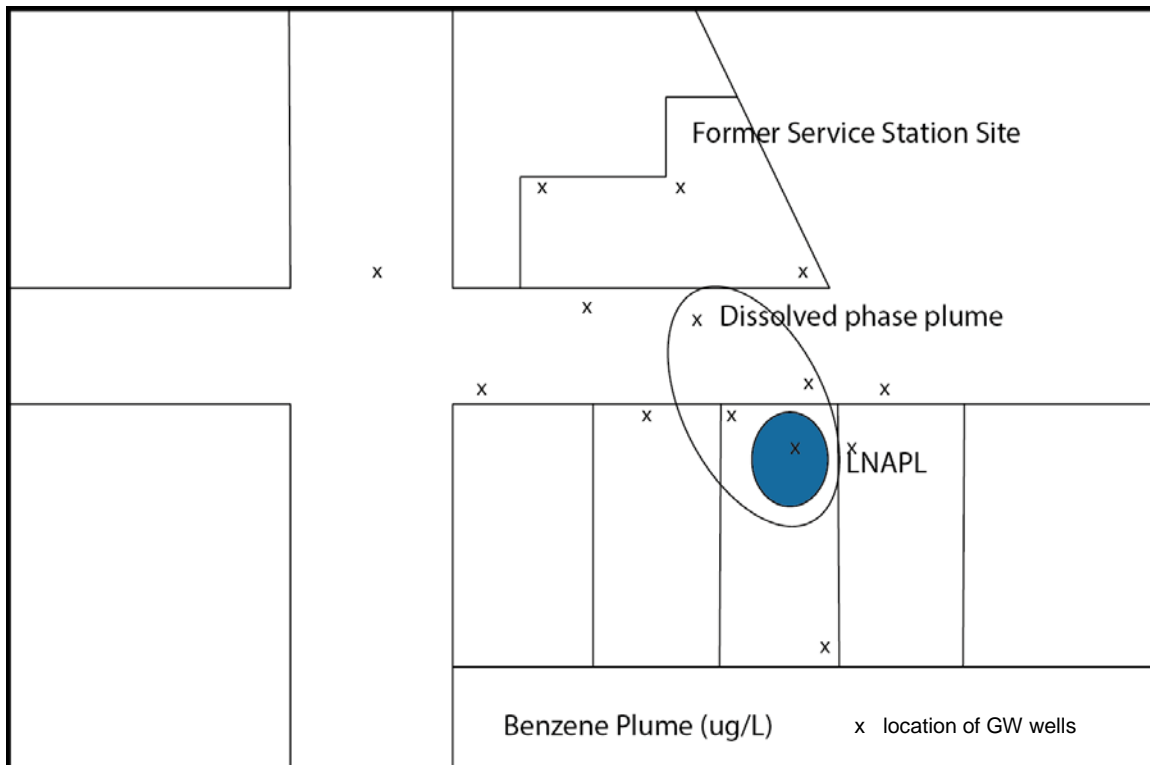
Case Study 2

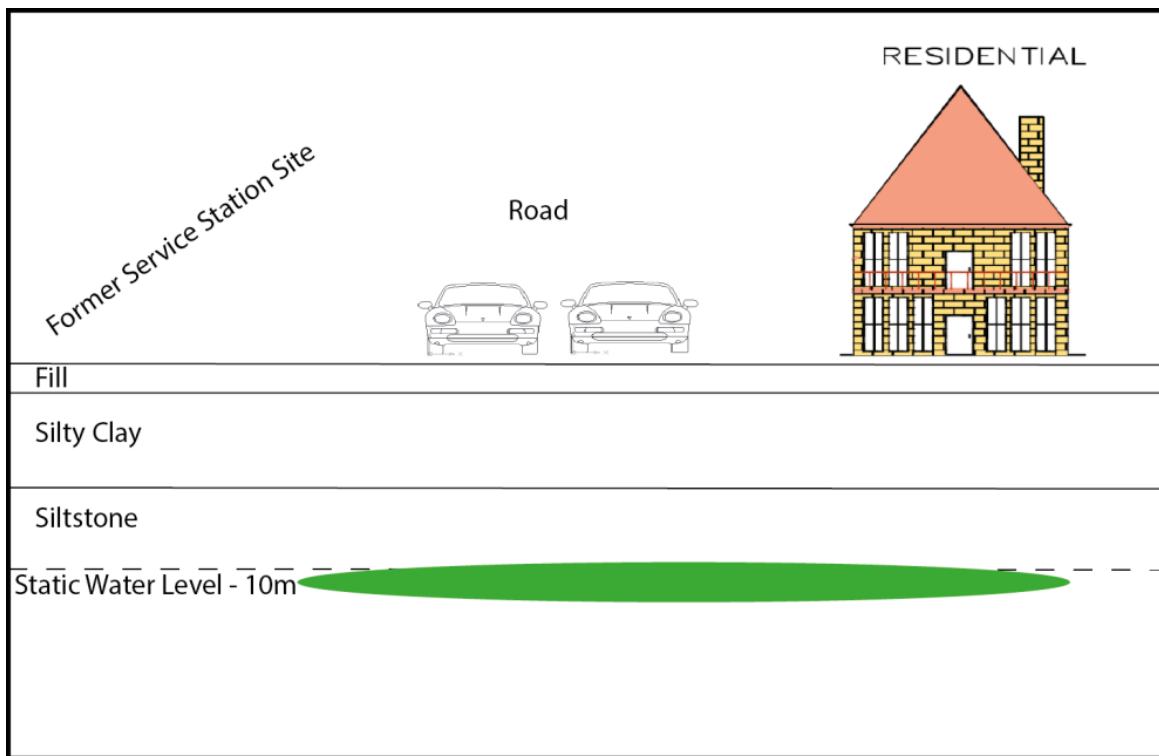
Introduction

A former service station site has been remediated. The final step in the project is to look at the remaining off-site issues. The groundwater has been contaminated with petroleum hydrocarbons and the contaminated groundwater has moved off site. A small amount of LNAPL has been found to be present under the houses on the other side of the road from the former site.

Conceptual Site Model

The following figure show the extent of the groundwater plume, which has been delineated and shown to be stable.





A brief description of the site conditions has been provided here in these diagrams just to set the scene for the case study. A PVI assessment should include a more detailed description of the conceptual site model as outlined in the guidance.

Preliminary PVI Assessment (Section 3 of PVI Guidance)

LNAPL has been noted to be present beneath the off-site areas being evaluated.

The zone of influence includes the road and the 2 houses overlying the LNAPL. The dissolved phase plume surrounding the LNAPL has been evaluated and shown to be stable and well contained. Hence only those 2 houses are considered to be receptors.

None of the triggers listed in the **Table in Box 3.1** have been exceeded so no short-term risks are expected. In addition the depth to groundwater is 10.2 m, hence the LNAPL is not in direct contact with the existing building foundations.

The assessment then moves to the screening PVI phase.

Screening PVI Assessment (Section 4 of the PVI Guidance)

Due to the presence of LNAPL in the areas being investigated, the HSLs cannot be used for the purpose of screening PVI risks at this site.

The guidance directs us to look next at the distances between the receptors and the contamination – **Box 4.2** in the guidance. The **Table in Box 4.2** indicates that if the LNAPL and the receptors are separated by 8 m or more vertically and the soil separating them is uncontaminated then there is unlikely to be a PVI risk at the site.

For this site the depth to groundwater is 10.2 m. The soil between the LNAPL and ground surface is expected to be uncontaminated (for the purposes of the PVI assessment) in this location as it is off-site and was not affected by the infrastructure at

the former service station site or any other petroleum hydrocarbon sources. The size of the residential homes considered is also less than 15 m in diameter. In addition, the size of the blocks will preclude the future construction of homes that are more than 15 m in diameter. Hence the size of the residential building slabs (current or future) does not affect the application of screening distances at these sites.

Consequently, the assessment indicates that this site does not pose a PVI risk and no further investigation is required in terms of PVI.

Detailed PVI Assessment

Not required.

Case Study 3

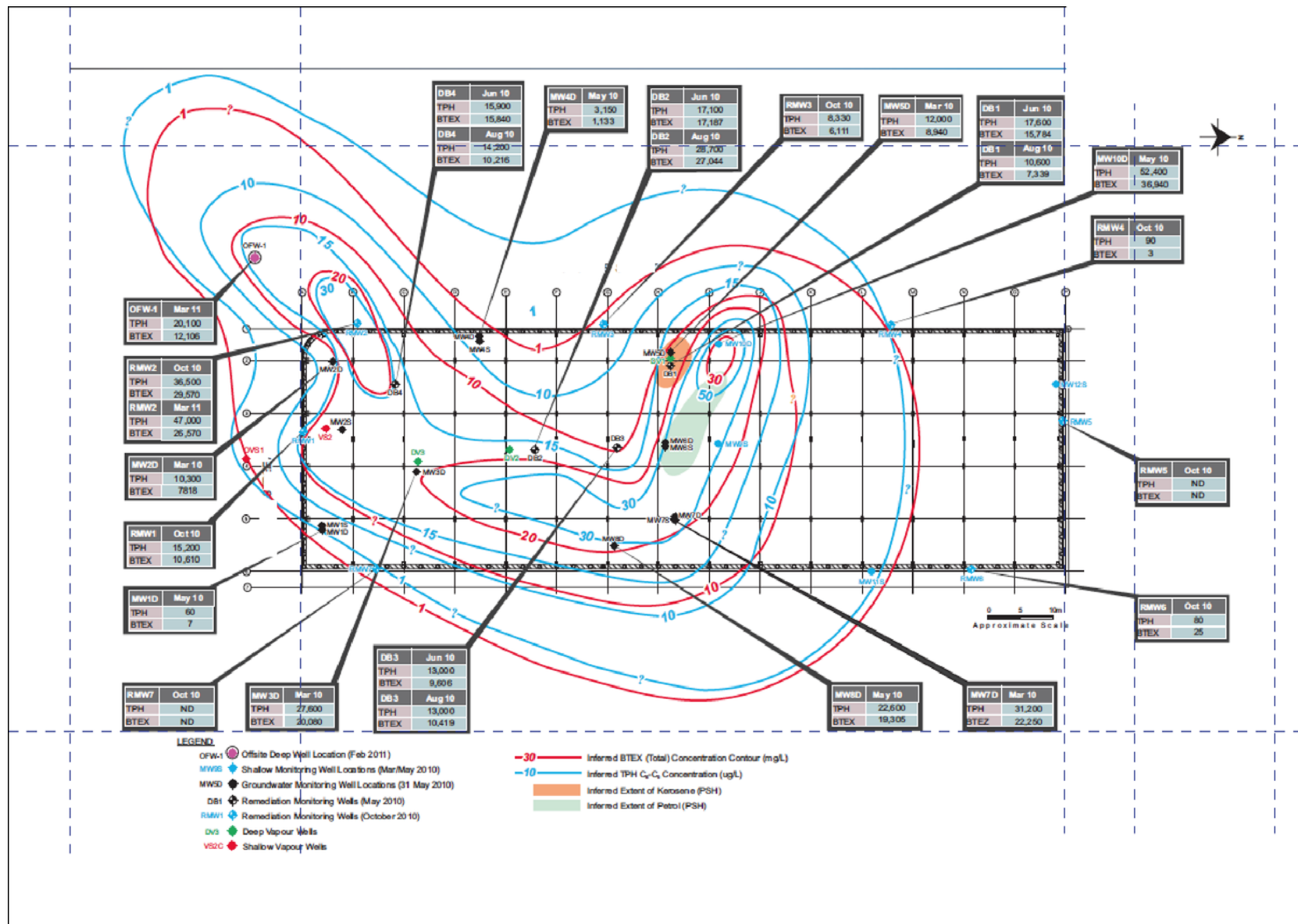
Introduction

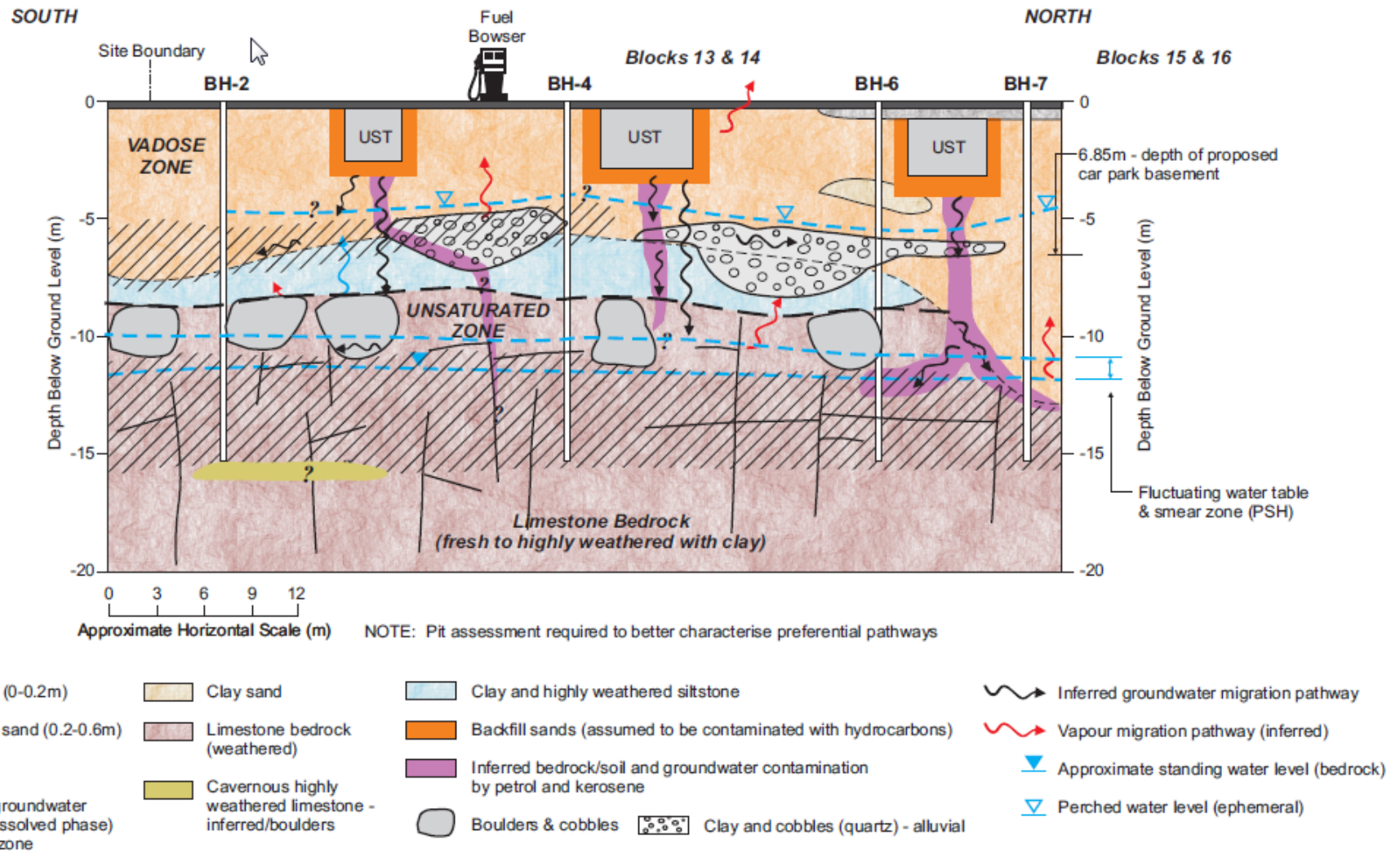
A former service station closed 10 years ago and was subsequently redeveloped as a car dealership. The redevelopment did not include removal of former USTs. Some of the USTs remained in use at the dealership for the supply of fuel. The dealership closed 2 years ago and the site was purchased by a developer with the aim of constructing a mixed high density retail and residential building above 3 levels of underground basement parking, extending to approximately 6 to 8 m depth. LNAPL and dissolved phase contamination was identified at approximately 10 to 12 m depth beneath the majority of the site. In addition residual contamination remained in soil and perched groundwater located in isolated locations at 3 to 4 m depth.

Conceptual Site Model

The following diagrams show:

- the extent of groundwater contamination on the site, including locations of observed LNAPL and concentrations of TPH/TRH and BTEX;
- a cross-sectional CSM for the site based on the former use of the site.





Preliminary PVI Assessment (Section 3 of PVI Document)

The available data support the presence of petroleum hydrocarbon contamination as LNAPL, dissolved phase and in soil.

The PVI assessment being conducted is limited to the on-site area which is the zone of influence that needs to be considered. It is noted that off-site impacts and the larger zone of influence will also need to be addressed at some stage.

None of the conditions outlined in **Box 3.1**, for the existing site, identify the presence of any short-term/acute risks. LNAPL and dissolved phase impacts are not currently, nor are likely to (in the proposed development) be in direct contact with the building foundations. It is noted that the contaminated perched groundwater and most of the contaminated soil will be excavated during construction of the proposed building.

Move on to the screening PVI assessment.

Screening PVI Assessment (Section 4 of the PVI Document)

Due to the presence of LNAPL at the site the HSLs cannot be applied (as per **Box 4.1** in the guidance).

The guidance directs us to look next at the distances between the receptors and the contamination – **Box 4.2** in the guidance.

To apply the screening distances in this box, the soil between the contamination source and receptor needs to be uncontaminated (as per the definition for PVI assessments – **Box 2.1**). This is not the case at this site and hence screening distances should not be used for the existing site.

For the future development the contaminated soil is to be remediated, however the size of the proposed building is significantly larger than 15 m in diameter (and LNAPL is present). Hence the screening distances should not be applied for the assessment of the proposed building.

Move onto the detailed PVI assessment.

Detailed PVI Assessment (Section 5 of the PVI Document)

For this site, the process outlined in **Section 5.3, Decision Diagram 4** should be used. On the basis of this decision process the following was conducted:

- Modelling was undertaken to evaluate the potential for PVI risks in the proposed building. This was undertaken in accordance with **Box 5.2**, with building-specific parameters adopted as building plans were provided. The modelling identified the potential for PVI risk. The calculated risks (non-threshold risk of 5×10^{-5} and HI of 2) were high enough to suggest that further assessment should be undertaken (and/or the assessment could jump straight to implementing mitigation). Hence soil gas data was collected.
- Soil gas samples were collected in accordance with **Box 5.4**, where the following decisions were made:
 - Based on **Table 4** in the guidance, the assessment is for a future building, where samples can be collected in the site and there is a basement proposed to a depth of 6-8 m depth. On this basis a minimum

- of 3 locations would need to be sampled above the LNAPL extending to at least 6-8 m (the depth of the proposed basement). Following this guidance soil gas wells were initially installed (in accordance with the PVI guidance) at 3 locations above LNAPL to 8 m depth.
- No soil gas wells were required where the contaminated soil remained as this was to be removed during remediation and excavation for the building.
 - The soil gas wells were sampled 14 days after installation so the minimum 7 days between installation and sampling was met. No rainfall was recorded in the suburb for 10 days prior to sampling so the conditions were suitable for sampling.
 - Leak testing was undertaken and all wells passed the integrity test (for the well and sample train).
 - A simple vacuum test was conducted and the wells sampled passed.
 - A minimum of 1 volume was purged using a PID and LFG meter to obtain and reported stabilised parameters confirming purging was adequate and soil gas was sampled.
 - Samples were collected using an active method (canisters) at a rate of 10 mL/minute, which was suitable for the clay materials present at 8 m depth.
 - Samples were analysed for petroleum hydrocarbons (speciated and as TPH/TRH). In addition oxygen, carbon dioxide and methane were reported by the laboratory as the readings on the field LFG meter were erroneous due to interference from elevated PHC vapours.
 - The soil gas data were evaluated in accordance with **Box 5.6**, where the following decisions were made:
 - The data quality was evaluated and the data were suitable for evaluation.
 - The soil gas data was evaluated for the proposed building, which had a large slab and basement, and where the data from 8 m depth was appropriate for use.
 - The PHC vapours at 8m depth were evaluated using a model (based on **Box 5.2** and site-specific building parameters) where the calculated risks (non-threshold risk of 3×10^{-5} and HI of 1) were calculated.
 - **Box 5.8** was used to determine if sufficient data was available to make PVI conclusions. The MOS was between 1 and 0.1. Based on this evaluation (as per **Step 6 in Box 5.6**), either mitigation measures could be implemented or additional data collected to provide more certainty in the risk calculations. In this case the decision was made to collect additional data, but identify the potential that mitigation may be required.
 - The building was not constructed hence no indoor air data could be collected. In addition site works had already begun and the original soil gas wells were lost. Hence new soil gas wells were installed on the site boundary, above LNAPL, maximum dissolved phase contamination and above the northern end of the building where no contamination was present. The wells were installed to 8 m (the depth of the basement) as well as more shallow depths of 4 m and 2 m to assist in evaluating off-site areas where biodegradation of PHC to the ground surface is of importance.

- Additional soil gas data were collected in accordance with **Box 5.4**. The data were evaluated in accordance with **Box 5.6** where the potential for unacceptable PVI risks was confirmed and mitigation measures were recommended for the proposed building.
- It is noted that the collection of additional soil gas data identified the presence of a preferential vapour pathway in the underlying geology. The presence of boulders and gravel provided a pathway for significantly elevated PHC vapours to move from the contaminated area (directly above LNAPL) to the uncontaminated northern portion of the site, adding weight to the requirement for mitigation measures to be implemented.

It is noted that in this case example the decision to implement vapour mitigation measures within the proposed building could have been made earlier, based on the initial vapour modelling or the first round of soil gas data. The cost associated with the installation of the mitigation measures meant that additional certainty in relation to the PVI conclusions was required to inform these decisions.



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Established and supported
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