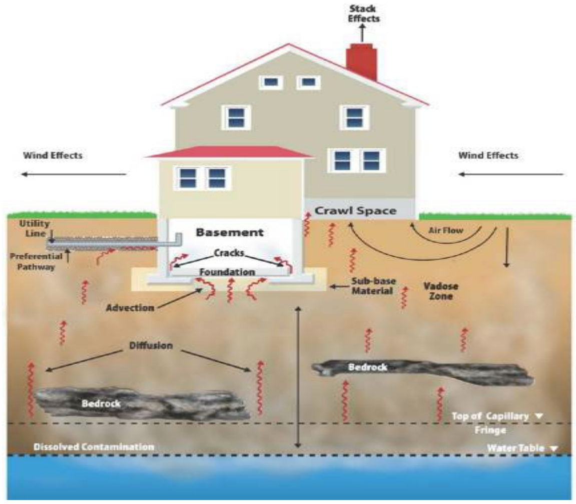
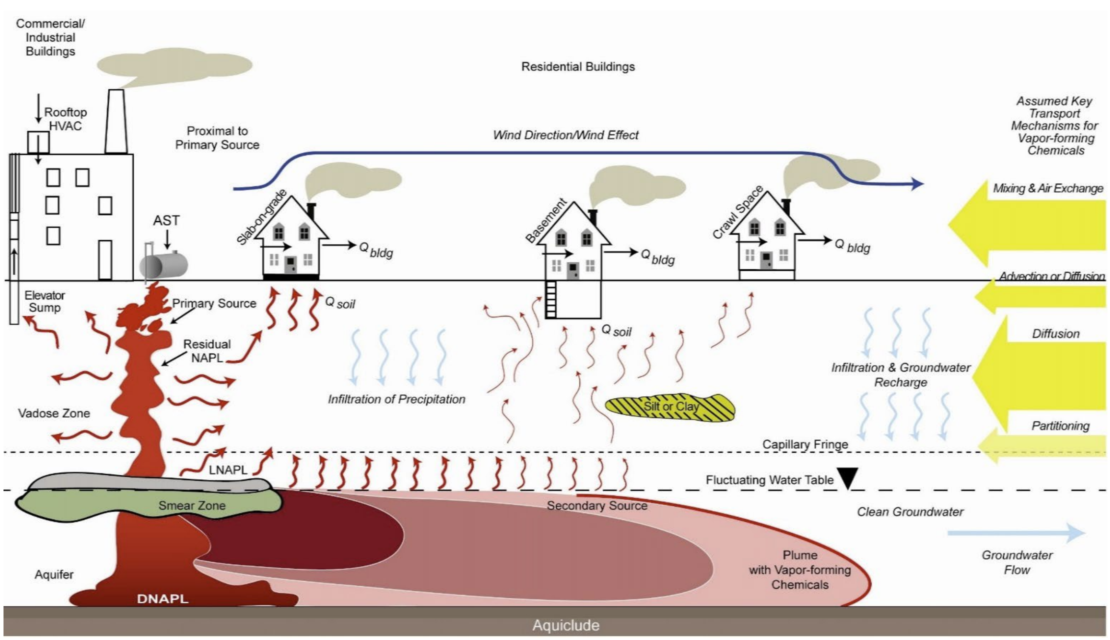


Vapour intrusions – hazardous ground gases

Review and guidance based on current scientific consensus



Footnotes: Top image from Burk and Zarus (2013) J Environ Health. May; 75(9): 36–41; Bottom image from US EPA (2015a)

OFFICIAL DOCUMENT SUMMARY

"Vapour intrusion" is the migration of chemical vapours and gases from sub-surface sources of volatile substances or gases through soils and into the indoor air spaces of overlying buildings. These vapours and gases may pose acute hazards in terms of fire and explosion while also presenting potential health effects to occupants of affected buildings, both based on short-term and long-term exposure.

In 2016 the Australian Government Department of Health commissioned a report describing the literature and consensus science on vapour intrusion risks, sampling and assessment methodologies, site conceptual model development, vapour intrusion modelling considerations, inclusive of limitations, risk management/control options and other relevant issues.

This report titled "*Vapour intrusions – hazardous ground gases. Review and guidance based on current scientific consensus*" explores the selection processes for chemicals of potential concern, examines the site settings, and reviews issues of concern across toxicology, epidemiology, and exposure assessment. Regulatory agency vapour intrusion guidance is presented for Australia and State and Territory jurisdictions and those in Canada, Europe (particularly the Netherlands and UK), New Zealand and the United States.

The international literature and international regulatory guidance in this area is rapidly evolving and requires regular review and consideration of new information to update national regulatory guidance. "*Vapour intrusions – hazardous ground gases. Review and guidance based on current scientific consensus*" is a point-in-time standalone technical resource to improve assessment of vapour intrusion sites by government agencies, site contamination auditors and practitioners.

AUDIENCE

This enHealth document is primarily intended for use by environmental health and regulatory agencies reviewing risk assessments and people preparing risk assessments for environmental health agencies. It is also intended to be of assistance to environmental scientists seeking information on vapour intrusion.

ACKNOWLEDGEMENTS

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Glossary of abbreviations	
α	Attenuation Factor in the JEM
L/hr	Litres per hour
$\mu g/m^3$	Microgram per cubic metre
%	Percentage
% v/v	Percentage volume/volume
% w/w	Percentage weight/weight
2D	Two-dimensional
3D	Three-dimensional
Air Toxics NEPM	National Environment Protection (Air Toxics) Measure
Atm m^3 mol^{-1}	Atmosphere-metre cubed per mole
ABS	Australian Bureau of Statistics
ADIs	Acceptable Daily Intakes
ASC NEPM	National Environment Protection
ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
BC	British Columbia
BPRISC	BP's Risk-Integrated Software for Cleanups
BRAC	Base Re-alignment and Closure Act
BSI	British Standards Institute
CARACAS	Concerted Action on Risk Assessment for Contaminated Sites in the European Union
CARB	Californian Air Resources Board
CAS	Chemical Abstracts System
CCME	Canadian Council for Ministers for the Environment
CHCs	Chlorinated Hydrocarbons
CI	Confidence Interval
CIRIA	Construction Industry Research and Information Association
CL:AIRE	Contaminated Land: Applications in Real Environments
CLEA	Contaminated Land Exposure Assessment model
CLM Act	Contaminated Land Management Act
CLU-IN	Clean-Up Information
COC	Chemical of Concern
COI	Chemicals of Interest
COPC	Chemicals of Potential Concern
CQA	Construction Quality Assurance
CRCCARE	Co-operative Research Centre for Contamination and Remediation of the Environment
CS	Characteristic Gas Situation
CSM	Conceptual Site Model
CSOIL	Dutch Contaminated Land Soil Exposure Assessment Model
DEFRA	Department for Environment, Food and Rural Affairs
DER	Department of Environment Regulation
DHHS	Department of Health and Human Services
DNAPL	Dense Non-Aqueous Phase Liquid
DQOs	Data Quality Objectives
DQRAchem	Detailed Quantitative Risk Assessment of Chemicals
DTSC	Department of Toxic Substances
EA	Environment Agency
EC	European Commission/Electrochemical cells

EEA	European Environment Agency
enHealth	enHealth Council
EPA	Environmental Protection Agency or Authority
ERT	Electronic Reporting Tool system
FID	Flame Ionisation Detection
FUDS	Formerly Used Defence Sites
GC	Gas Chromatograph
GC-FID	Gas Chromatograph-Flame Ionisation Detection
GC-MS	Gas Chromatograph-Mass Spectroscopy
GPLC	Guiding Principles of Land Contamination
GSI	Groundwater Services Incorporated
GSVs	Gas Soil Values
HILs	Health Investigation Levels
HSLs	Health Screening Levels
HQ	Hazard Quotient
HVAC	Heating, Ventilation and Air Conditioning system
IARC	International Agency for Research on Cancer
ICs	Institutional Controls
IPCS	International Programme on Chemical Safety
IR	Infra-red
IRIS	Integrated Risk Information System
ISAs	Integrated Science Assessments
ITRC	Interstate Technology and Regulatory Council
JEM	Johnson and Ettinger model
JRC	Joint Research Centre
LNAPL	Light Non-Aqueous Phase Liquid
MfE	Ministry for the Environment
MILs	Monitoring Investigation Levels
mmHg	millimetres of mercury
MS	Mass Spectroscopy
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NES	National Environment Standard
NHMRC	National Health and Medical Research Council
NRC	National Research Council
NSW DECCW	New South Wales Department of Environment, Climate Change and Water
NSW EPA	New South Wales Environment Protection Agency
O_2	Oxygen
OECD	Organization for Economic Co-operation and Development.
OEH	Office of Environment and Heritage
OSWER	Office of Solid Waste and Emergency Response
PCE	Tetrachloroethylene
PID	Photo-Ionisation detection
RBCR	Risk-Based Corrective Action
RCRA	Resource Conservation and Recovery Act
RISC	Risk-Integrated Software for Cleanups
RIVM	Dutch National Institute for Public Health and the Environment
SA EPA	South Australian Environment Protection Authority
SAQP	Sampling and Analysis Quality Plan
SGVs	Soil Guidance Values
STP	Standard Temperature and Pressure
$SVQG_{IAQ}$	Soil Vapour Quality Guidelines for Indoor Air Quality

TCE	Trichloroethylene
™	Trademark
TRVs	Toxicological Reference Values
UPSS	Underground Petroleum Storage Systems
UK	United Kingdom
US DoD	United States Department of Defence
US EPA	United States Environment Protection Agency
VISL	Vapour Intrusion Screening Levels
VOC	Volatile Organic Compound
VOLASOIL	Dutch Volatiles in Soil Exposure Assessment Model
WHO	World Health Organisation

1 EXECUTIVE SUMMARY

"Vapour intrusion" is the migration of chemical vapours and gases from sub-surface sources of volatile substances or gases through soils and into the indoor air spaces of overlying buildings. These vapours and gases may pose acute hazards in terms of fire and explosion while also presenting potential health effects to occupants of affected buildings, both on the basis of short-term and long-term exposure. Vapour intrusion is a significant environmental health issue resulting from pollution across former farming, agricultural or industrialised areas in urban and rural regions of Australia.

There are significant gaps in the Australian public health assessment and management of exposures arising from hazardous ground gases (associated with landfills or waste dumps) and volatile chlorinated hydrocarbons (associated with groundwater or land contamination) across residential areas. While traditionally, hazardous ground gases from landfills are considered distinct from vapour intrusion due to sub-surface volatile hydrocarbons, their evaluation in terms of acute or chronic inhalation exposures in confined environments is similar. The gaps in assessment are due to a limited focus on assessment of such inhalation exposures including their population health impacts. The evolving nature of these complex assessments across the international literature and regulatory guidance requires regular review and consideration of new information to ensure that assessments are robust and include the most recent methodologies.

The aim of the report is to develop public health guidance for the assessment and management of sites affected by vapour intrusion in Australia that is structured towards the human health risk assessment process and includes the most recent information. It is designed to support comprehensive consideration of human exposure and avoid potential adverse outcomes with an overall theme of "*How to undertake a vapour intrusion risk assessment*".

This report explores the selection processes for chemicals of potential concern, examines the site settings, and reviews issues of concern across toxicology, epidemiology and exposure assessment. Regulatory agency vapour intrusion guidance is presented for Australia and State and Territory jurisdictions and those in Canada, Europe (particularly the Netherlands and UK), New Zealand and the United States.

Current risk assessment methods and paradigms are explored with commentary on biological monitoring and environmental epidemiology. Vapour intrusion assessment methods are considered and current frameworks presented with the differences between site contamination and landfill hazardous gases and vapours identified.

Vapour intrusion modelling is reviewed and the use of a current common industry model clarified in terms of understanding and use. Measurement methods are presented across sampling and analytical requirements with assessment methods summarized. Multiple lines of evidence factors representing the current method of overall assessment are discussed. The report concludes with a review of risk management measures and how risk communication is managed across the plethora of technical information that comprise this field of public health.

In order to provide guidance through critical thinking, the following questions and sources of information/guidance have been structured to aid practitioners in ensuring they complete comprehensive and robust vapour intrusion risk assessments:

Question	Source of information/Guidance
Preliminaries	
The primary vapour intrusion questions posed are: • *"Is there a potential for sub-surface migration and would reactivity of the volatile in the sub-surface mitigate such a process?"* • *"Would its atmospheric concentration present a health risk over short or longer periods of exposure?"*	Review site history data and available site data. US EPA (2002**)** [Now superseded by OSWER 2015]. Toxicological data based on enHealth hierarchy of sources.
What is the overall purpose of the risk assessment and general scope?	Requires preliminary understanding of site-specific exposure potential and impacted population – see enHealth (2012a); NEPM Schedule B4.
Are there current implications which require immediate actions (e.g. potentially exposed community, fire and explosion risks)?	Refer enHealth (2012a); US EPA (2015a); internet databases on physico-chemical and toxicological properties; site history.
Are there sensitive populations – children or the aged and infirm?	Local evaluations of community demographics or published health survey data.
What factors (population, sub-surface or built environment will change with time?	Review of future planning laws; local council programs, COPCs and fate/transport/toxicological properties.
Are there legal implications or other legal considerations involved?	Consult legal practitioners as required.
Have the objectives been clearly defined?	Discussions with all stakeholders and consideration of site history and site-specific data.
Are there socio-economic-political considerations and how will these be managed to meet the risk assessment objectives?	Identification of all stakeholders and chairpersons. Community and regulatory agency engagement and discussions. Risk communication advice to be sought from professional independent facilitators.
Who are the stakeholders involved (industry, developers, government, community)?	
If the community is involved how will they be engaged?	
What is the complexity of the assessment that is required?	See enHealth (2012a); Burk and Zarus (2013); US EPA (2015b).
Is a multi-disciplinary team of experts necessary to meet the objectives?	Review discipline areas and level of complexity/knowledge required to meet objectives.

Question	Source of information/Guidance
Preliminaries (cont.)	
What is required to be achieved for decision-making? *Qualitative risk assessment?* *Quantitative risk assessment* *Practical risk mitigation measures?*	Review site history, planned development, COPC and the CSM. See NEPC (1999, as amended 2013); ASTM E1739-95 (2015); enHealth (2102a); US EPA (2015a); ITRC, (2014); ATSDR, WHO, RIVM and US EPA databases and reports. Review available data and discuss timeframes with key stakeholders.
Which decision-making process will provide the greatest confidence in the assessment?	
What is the history of the site and surrounds?	
What substances are associated with this history?	
What are their physico-chemical properties and pathway-specific toxicity?	
Is there sufficient data for the substances involved?	
What are the time frames for completion?	
Hazard assessment	
Has there been a thorough review of the latest toxicological information?	Review currency of toxicological data against on-line data sources, e.g. WHO, ATSDR, RIVM, EA, US EPA.
Has the review used data consistent with the enHealth hierarchy of literature sources?	See enHealth, (2012a).
If regulatory agency TRVs are used, how old is the toxicological data that have been used to derive that TRV?	Review currency of guidelines against on-line data sources. e.g. WHO, ATSDR, RIVM, EA, US EPA.
Has the toxicological data been considered relevant to the population of interest?	
Is there a population or sub-population region-specific sensitivity that needs to be considered?	Review on-line local demographic data from Australian Bureau of Statistics (ABS) or related publications and/or state health agency survey data. Review COPC toxicology from current on-line data sources, e.g. WHO, ATSDR, RIVM, EA, US EPA.
Are the exposure estimations or measurements aligned with the toxicological dose response time frames?	Review current toxicological data from on-line data sources, e.g. WHO, ATSDR, RIVM, EA, US EPA. Review local population health data and behaviours relevant to these populations including local environmental health conditions. Refer enHealth (2012b) and ABS on-line data on population residence times. Literature search on Web of Science or equivalent.
What is the best approach to data interpolation or extrapolation for exposure durations?	
Are peak exposures important?	
Are exposure assessment durations aligned with the residence time of the affected individual or population?	
Are there population behaviours that may potentiate the exposure due to co-exposures?	

Question	Source of information/Guidance
Exposure assessment	
Have the physico-chemical and concurrent toxicological properties been evaluated for exposure assessment?	Refer on-line physico-chemical databases, e.g. US EPA sources. Literature search on Web of Science or equivalent. Review site-specific analytical data and trend analyses.
Is the substance subject to degradation and how?	
What are the breakdown products of degradation in soil, air or water?	
Will measurement or modelling (fate and transport/inhalation exposure model) approaches be used?	See Baker, (2009); DHHS, (2008b); DTSC, (2015); Grassman et al., (1998); ITRC, (2014) NEPC (1999, as amended 2013); NSW DECCW (2010); NSW EPA (2012; 2014); US DoD (2009); US EPA (2015 a, b, c). Consider multiple line of evidence. Review site-specific- and region-specific factors. Literature search on Web of Science or equivalent.
What is the justification for the method employed?	
If measurement, can the sampling methodology (in space and time) be justified?	
Have the data quality objectives in measurement been detailed and met?	
If modelling, has the uncertainty and variability been considered in input parameters – both for environmental data and exposure data?	
Has a worst case scenario (WCS) been considered in the evaluation? Is this a plausible setting? Has a best case scenario (BCS) been considered? What is the variability?	
If WCS has been evaluated, how does the exposure setting compare with reality, should calculated exposures be deemed unacceptable? What refinement is required?	
Has a conceptual site model of exposure been considered and the relevant conduits to indoor or confined environments been evaluated?	
What are the changes in exposure over time – diurnal, seasonal?	
Are there spatial changes in exposure that need to be accounted for?	
Are there differences between individual personal exposures and those from static monitoring that need to be accounted for?	Review site-specific and local environmental health data. Literature search on Web of Science or equivalent.
How long will the population of interest reside on the contaminated site or surrounds?	Refer local Council/Planning data; ABS on-line data; local health agency survey data.
Will biological monitoring (as a measure of internal dose) be undertaken?	See enHealth, (2012a); ATSDR on-line data; literature search on Web of Science or equivalent. Review risk communication protocols (see Covello and Allen, 1988)
If biological monitoring is undertaken, how will this occur, under what time constraints and under what community engagement protocols?	

Question	Source of information/Guidance
Exposure assessment (cont.)	
Have the environmental parameters used been obtained from a reliable source?	Review and see US EPA (2015a).
Have the COPC characteristics been obtained from a credible source?	See enHealth (2012a).
Are the environmental factors representative of the site setting and/or surrounds?	Review site-specific data. See US EPA (2015a); ITRC (2014); enHealth (2012a).
Is there confidence in the site-specific data for the CSM?	Review and see NEPC (1999 as amended 2013) and US EPA (2015a).
Has the population been characterized and sensitive sub-groups been determined?	ABS on-line data; local health agency survey data. See enHealth (2012a); US EPA (2014b)
Have the most suitable exposure factors for the relevant population of interest been used?	Examine variability to assess outcome ranges and margin of safety, see enHealth (2012b).
Has uncertainty and variability been evaluated?	See enHealth (2012a).
Has sensitivity analysis been undertaken and have the most sensitive variables been confirmed as representative of the site setting?	See enHealth 2012a; Tillman and Weaver (2005)
Risk characterization	
What confidence is there in the assessment outcomes?	Refer enHealth 2012a; US EPA (2014b). Seek peer-review if required.
How will the assessment outcomes and uncertainties be explained to affected parties?	Review and see Covello and Allen (1988); enHealth (2012a); US EPA (2014b, 2015b). Clarify uncertainties and limitations and seek discussions with all stakeholders.
What residual issues exist that may change the risk assessment outcomes?	
What additional information is required to establish confidence in the risk assessment?	
Is the information sufficient for decision-making and communication to risk managers?	
Modelling	
What vapour intrusion model is to be used and does it represent the site-specific exposure scenario?	See Provoost et al., (2009; 2010; 2010; 2013); Evans et al., (2002; US EPA (2015a).
Is the vapour intrusion model peer-reviewed?	
Does the vapour intrusion model used align with the understanding of the CSM?	
Have all inputs and outputs been documented and in the case of the former, substantiated?	Review site-specific data and local CSIRO/BOM and on-line environmental databases.
Are the inputs realistic parameters?	
Have critical parameters been identified and a sensitivity analysis conducted for the most critical (qualitative or quantitative)?	See Tillman and Weaver (2005; 2007), Johnson (2005) and Moradi et al., (2015)
Has the appropriate modelling approach been determined and documented (e.g. calibration, uncertainty analysis, bounding case analysis)?	See US EPA (2015a); ITRC (2014); enHealth 2012a).

Question	Source of information/Guidance
Modelling (cont.)	
Has the presentation of data been considered in order to ensure the recipient of the information can readily understand the information in a short time period. For example, 2D and 3D visualisation for the CSM?	Review graphic presentation formats.
What predictive variability is known regarding the vapour intrusion model used and how should this be considered in the assessment outcomes?	See Turczynowicz and Robinson, (2007b); Provoost et al., 2010.
Should new individual measurements (i.e. field sampling) be undertaken to confirm one or more of the results from modelling?	Review outcomes. variability analysis, margin of safety, multiple lines of evidence. See NEPC, (1999, as amended); US EPA, (2015a); ITRC, (2014)
Measurement methods and assessment	
Are the objectives of the sampling and analyses clearly understood?	See NEPC, (1999, as amended); US EPA, (2015a); NSW DECCW, (2010); NSW EPA, (2012).
What data quality objectives (DQOs) will be used?	
If DQOs are not met how will this be addressed?	
Is historical information sufficient to establish COPCs?	Review site history, see enHealth, (2012a); NEPC, (1999, as amended).
Is there a preliminary conceptual site model to guide nature and extent investigations?	Review site data, previous reports, see; US EPA, (2015a).
What sampling will be undertaken; how, using which techniques; when, for how long; and across what areas?	See NEPC, (1999, as amended) Davis et al., (2009); DTSC, (2015); ITRC, (2014); US EPA, (2015a); ASTM (2012a, b).
What analytical methods will be employed?	
What methods of drilling and installations are required?	
What equilibration times will be used?	
What field instrumentation may be used and is it fit for purpose?	
Are pre-sampling surveys required?	
Is concurrent testing across transport compartments required?	See ITRC (2014); Johnston and Gibson (2013); Turczynowicz et al., (2012); US EPA (2015a); ITRC, (2014).
How will diurnal and seasonal variability be addressed?	
How will spatial variability be addressed?	
How will worst case scenarios be evaluated?	
Would alternative delineation methods be appropriate?	See Davis et al., (2009); ITRC (2014).
How will potential biodegradation be assessed?	See US EPA (2015a); ITRC, (2014). Professional judgement is required for sampling methodology as there is currently no established indoor air sampling methodology.
How many iterations of sampling will be undertaken?	
For how long will the sampling be undertaken?	
Will grab samples be employed?	
What meteorological information will be collected?	

Question	Source of information/Guidance
Measurement methods and assessment (cont.)	
What supplementary information will be collected and how will this be used?	Review multiple lines of evidence, see Johnson and Gibson (2015); US EPA, (2015).
Are there preferential pathways requiring measurement?	Review site-specific information from local council and water/power/communications companies.
Risk management	
What residential areas are nearby and are they within range of off-site impacts?	Refer local Council/planning data; ABS on-line data; local health agency survey data.
What landfill bulk gases will be examined?	See EA (2010; 2012a;2012b)
What landfill trace gases and vapours will be examined?	
Which GSVs endpoints will be used?	See Wilson, (2007); NSW EPA (2012);
How will the landfill sub-surface heterogeneity be examined?	See EA (2012a, b); Baker, (2009).
What off-site testing may be involved?	Review site-specific environmental setting and all exposures pathways – both direct and indirect. See EA (2012a, b); Baker, (2009); Wilson, (2007); NSW EPA (2012).
How will information to residents be communicated if off-site testing is required?	See Covello and Allen (1988); enHealth (2012a); US EPA (2014b, 2015b).
Has a sound conceptual site model been developed?	Seek qualified peer-review.
Is the conceptual site model supported by multiple lines of evidence?	
Have the subsurface vapour sources been characterized sufficiently to support risk management decisions for the site?	
What is the nature of the issues and what type of response action is required?	Review of all available information and discussion and agreement with all stakeholders. • Key concerns. • Timeframes. • Cost-benefit. • Sustainability. • Performance and risk-based corrective action. • Accountability documentation. US EPA, 2015a), ITRC, (2014); NEPC, (1999, as amended 2013).
What timeframes are required to mitigate current exposures?	
What advice will be provided to affected parties?	
Has a cost-efficacy evaluation been undertaken?	
Have sustainability issues ben considered as part of the cost-benefit evaluation?	
What performance measures will be used following implementation?	
How will corrective measures be applied if performance measures fail?	
What program selection, recommendation and documentation will be undertaken to ensure consistency with legislative frameworks and existing program guidance?	

Source of information/Guidance	Source of information/Guidance
Risk communication	
Who are the affected stakeholders?	Review site-specific data and local Council/planning data; ABS on-line data; local health agency survey data.
Who are the other stakeholders?	Identify property owners, local and state regulatory authorities.
How will technical information be communicated?	See Covello and Allen, (1988); US EPA (2014a).
How will the affected stakeholders be empowered?	
How will transparency and evidenced-based approaches be ensured?	
How will communications with the media be undertaken and by whom?	
How will the peer-review process be undertaken to ensure impartiality and scientific robustness in outcomes?	Decision-making through stakeholder committee following discussions with all stakeholders and consensus agreement.
How frequently will communications be undertaken and who will be responsible for delivery?	
How will accountability in risk management and remedial measures be ensured?	

2 INTRODUCTION

“Vapour intrusion” is the migration of chemical vapours and gases from sub-surface sources of volatile substances and gases through soils and into the indoor air spaces of overlying buildings. These vapours and gases may pose acute hazards in terms of fire and explosion while also presenting potential health effects to occupants of affected buildings, both on the basis of short-term and long-term exposure.

Vapour intrusion is a significant environmental health issue resulting from pollution across farming, agricultural and former industrialised areas in urban and rural regions of Australia. Progressive site re-development due to urban in-fill programs has required suitable assessment of human health risks for buildings yet to be constructed. In addition, in some cases, migration of volatile contaminants from soils or from plumes of dissolved volatile contaminants or light non-aqueous phase liquids (LNAPL) and/or dense non-aqueous phase liquids (DNAPL) have resulted in population exposure concerns. Sites under development and affected existing buildings subsequently require confident health risk assessments to ensure that unacceptable exposures do not occur and that where necessary suitable mitigation measures are established.

Nationally, for example, chlorinated hydrocarbons such as trichloroethylene (TCE) have been reported across many contaminated sites and, due to their fate and transport characteristics have migrated beyond site boundaries and affected buildings remote to the sources of the TCE. The presence of TCE is due to its former common use as an industrial solvent in manufacturing industries and resultant poor environmental waste management practices which has resulted in environmental distribution across soil and groundwater. The persistence of TCE coupled with its extensive toxicity which includes its ability to act as a proven human liver and kidney carcinogen (IARC 2014) highlights the need for ensuring thorough health risk assessments are undertaken.

National regulatory guidance provided in the recently amended National Environment Protection (Assessment of Site Contamination) Measure (1999) (ASC NEPM, NEPC, 1999 (as amended)), is limited in providing vapour intrusion assessment for all volatile hydrocarbons. The focus in the ASC NEPM is principally towards volatile petroleum hydrocarbons and the assessment of service station sites and associated storage depots. The international literature does not differentiate sub-surface vapour transport across differing volatile chemicals but notes that differences in transport, toxicology and epidemiology should be considered as part of the health risk assessment process.

There are significant gaps in the Australian public health assessment and management of exposures arising from hazardous ground gases (associated with landfills or waste dumps) and, e.g., volatile chlorinated hydrocarbons (associated with groundwater or land contamination) across residential areas. While traditionally, hazardous ground gases from landfills are considered distinct from vapour intrusion of sub-surface volatile hydrocarbons, their evaluation in terms of acute or chronic inhalation exposures in confined environments is similar.

The international literature and international regulatory guidance in this area is rapidly evolving and requires regular review and consideration of new information to update national regulatory guidance. Such updated guidance would facilitate improved assessment of vapour intrusion sites by government agencies, site contamination auditors and practitioners. This would enable reduced conservatism, greater confidence in the assessment process for public health authorities and the community; and cost-effective direction of funds for the establishment of mitigation measures.

3 OBJECTIVES OF REPORT

- The aim of the report is to develop updated public health guidance for the assessment and management of sites affected by vapour intrusion in Australia.
- The report structure seeks to provide a review of Australian and overseas information such that the current knowledge and deficiencies becomes evident after considering all aspects of vapour intrusion. The format is to pose many questions so as to guide the reader to read the available literature.
- The document theme is "*How to undertake a vapour intrusion risk assessment*".

4 SCOPE OF REPORT

- Comprehensive and current literature and regulatory report review.
- Review of national and international agency guidance and publications.
- Consideration of the following aspects of vapour intrusion:
  - The use of predictive vapour intrusion models and model input parameters.
  - Exposure factors – representativeness, realistic settings, point estimates, use of population data.
  - Uncertainty, sensitivity and variability analysis.
  - What reflects suitable multiple lines of evidence assessment, e.g. consideration of preferential pathways, spatial and temporal changes, concentration gradients, attenuation factors.
  - Measurement methods - methods of sampling, analysis and site soil vapour delineation.
  - Risk management/control options.
  - Risk assessment outcomes and risk communication.
- Supporting documentation for inclusion in Appendices as appropriate.

5 THE HUMAN HEALTH RISKS OF VAPOUR INTRUSION

5.1 CHEMICALS OF POTENTIAL CONCERN

A range of terminologies are employed when considering the hazardous substances that may be identified on contaminated sites. The basis to the determination of what volatile substances to test for rests with a thorough site history review which enables potentially contaminating site activities to be recognized from past site industrial practices. These activities provide information on the chemicals of interest (COI) for testing and subsequent results identify hazardous substances exceeding preliminary assessment criteria (Tier 1) as chemicals of potential concern (COPC). Further health risk assessment (Tier 2) enables evaluation of potential site exposures and associated health risks and determines those hazardous substances considered as chemicals of concern (COC) that warrant remedial measures to reduce or eliminate population exposures.

In terms of vapour intrusion, at standard temperature and pressure (STP) conditions, inhalation exposures may result from the presence of gases such as radon, methane or hydrogen sulphide or from vapours such as benzene and trichloroethylene. To distinguish between gases and vapours, the Oxford Dictionary (2016) defines a 'gas' as a "*gaseous substance that cannot be liquefied by the application of pressure alone*" while a 'vapour' reflects "*a gaseous substance that is below its critical temperature, and can therefore be liquefied by pressure alone*". The source of the latter therefore includes volatile liquids present in the environment as free phase product (e.g. fuels, solvents), dissolved in groundwater or adsorbed to soil, that, once partitioned into the air phase, are capable of diffusion through soils or advection along preferential pathways and into buildings.

The basis to considering a volatile substance for assessment in vapour intrusion depends on both its volatility and inherent toxicity.

The initial question posed for a volatile substance is:
"*Would its atmospheric concentration present a health risk over short or long periods of exposure*?" while a subsequent question may then be:
"*Is there a potential for sub-surface migration and would reactivity of the volatile in the sub-surface mitigate such a process*?"

Volatility may be demonstrated practically through air phase measurement or via established empirically-derived physico-chemical characteristics such as vapour pressure and Henry's constant (a ratio of air vapour pressure to water solubility). This characteristic combined with toxicological data then identifies a chemical for vapour intrusion consideration.

US EPA (2015) defines a volatile substance for the purposes of potentially toxic vapour intrusion if:
"*1) Vapor pressure is greater than 1 millimeter of mercury (mm Hg), or*

2) Henry's law constant (ratio of a chemical's vapor pressure in air to its solubility in water) is greater than 10^{-5} atmosphere-meter cubed per mole (atm m^3 mol^{-1}) (EPA 1991b, Section 3.1.1; EPA 2002c, Appendix D)". with a substance considered as 'potentially toxic' if

"*1) the vapor concentration of the pure component exceeds the indoor air target risk level, when the subsurface vapor source is in soil, or*

2) the saturated vapor concentration exceeds the target indoor air risk level, when the subsurface vapor source is in groundwater."

While an examination of international inhalation toxicity criteria such as air guidelines may aid in this process some agencies have produced databases to evaluate potentially toxic vapour intrusion chemicals. The earlier US OSWER guidance in the tables section (US EPA 2002) initially produced a table listing volatile chemicals of concern and generic target screening criteria based on attenuation factors (p1-37), however, more recently the updated OSWER guidance (US EPA 2015) provides a vapour intrusion screening level (VISL) calculator also using attenuation factors. The latter approach recommends that "*the user consider whether the assumptions underlying the generic conceptual model are applicable at each site, and use professional judgment to make whatever adjustments (including not considering the model at all) are appropriate*" (US EPA, 2014a, p3).

5.2 Applicable Environmental Settings

5.2.1 Sites under development

The planning process for the development of land in Australia is the conduit to the initiation of site assessment procedures. This process administered by local government agencies and under State and Territory Acts and Regulations requires evaluation of land to ensure that historical site activities have not resulted in residual risks to human health and the environment. As a consequence of urban consolidation strategies and the advantages of near city areas of greater economic value with established infrastructure, such areas are a significant part of site assessment requirements. They are also those that may present greater risks to human health and the environment from historical industrial and waste disposal activities. These include former petrol station sites and storage depots, dry cleaning facilities, chemical manufacturing plants, heavy manufacturing industries; paint/coatings manufacturing companies; landfills; and agricultural and farming areas where fuels, cleaning solvents, degreasers, and solvent based coatings/polymers were prevalent.

The ASC NEPM (NEPC, 1993, as amended) describes four generic scenarios used for the development of health-based investigation levels – (A) residential (garden/accessible soil), (B) residential (minimal access to soil, e.g. high density residential), (C) public open space and (D) commercial/industrial (NEPC, 1993 Schedule 7, p15-18). These are default scenarios to describe potential exposures to soil contaminants by site occupants whose exposures to soil contaminants across each scenario vary. In terms of vapour intrusion, each of these site scenarios could be implicated including variants about each scenario with a particular emphasis on population behaviours influencing the nature of the exposure (refer Figure 1; Figure 2; Figure 3; Figure 4).

5.2.1 Existing sites and dwellings

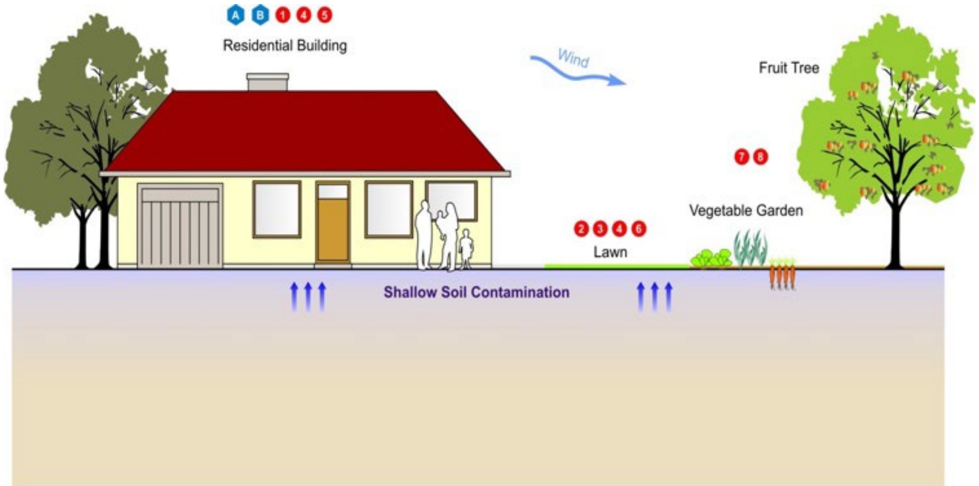
In the case of existing sites and occupied buildings a range of potential exposure settings exist and in order to understand potential indoor exposures to occupants a conceptual site model (CSM) should be considered. This is presented in the ASC NEPM (NEPC, 1999 as amended and is principally a description of the understanding of potential exposures for a subsurface volatile hydrocarbon source to the building occupant in a confined environment. In vapour intrusion assessment, however, this CSM, must be aligned with the physical and mathematical construct of any predictive vapour intrusion model for sites under development. If this is not undertaken the model predictions are invalid. This also applies to existing situations and when such modelling is employed, the uncertainties and limitations associated with site features should be clearly identified in order to justify the use of any one vapour intrusion model.

The establishment of measurement methods should also be based on the CSM which may be iterative in nature as volatile chemical test results are obtained. It is important to note that such analyses represent a point-in-time assessment and do not reflect the changing environmental conditions over space and time which can only be acquired from repeated evaluations and understanding which conditions may represent a “worst case” setting.

5.2.2 Landfills

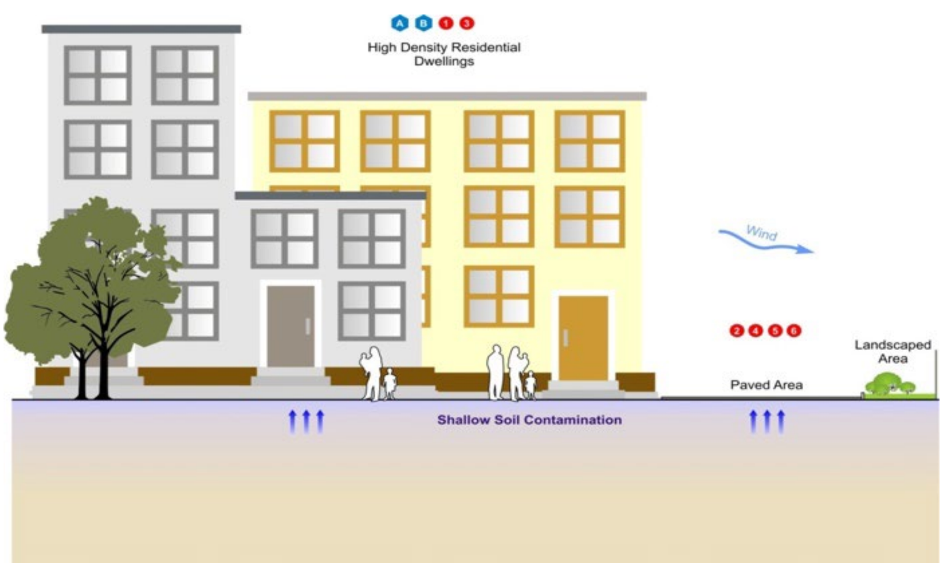
Landfills present an alternative vapour intrusion potential across both physical and chemical hazards compared with non-landfill settings. Uncontrolled landfills produce a much greater diversity in gas and vapour emissions arising from both source wastes and also decomposition gases from putrescible waste. Porter and Tepe (2013) reported seventy-nine (79) compounds were identified in ambient air in the vicinity of landfills for non-hazardous wastes across sites in Australia and overseas. The physical hazard of fire and explosion due to methane generation and confinement is the key determinant in acute assessments for landfill gases. In addition, a range of inorganic gases exhibiting high acute toxicity, e.g. hydrogen sulphide, carbon disulphide and carcinogenic organic vapours such as benzene present a need to consider both acute and chronic exposures. A CSM which can provide an understanding of the heterogeneity of the gas and vapour distribution and migration off-site via preferential pathways to residential areas are important considerations.

Figure 1: Residential low density



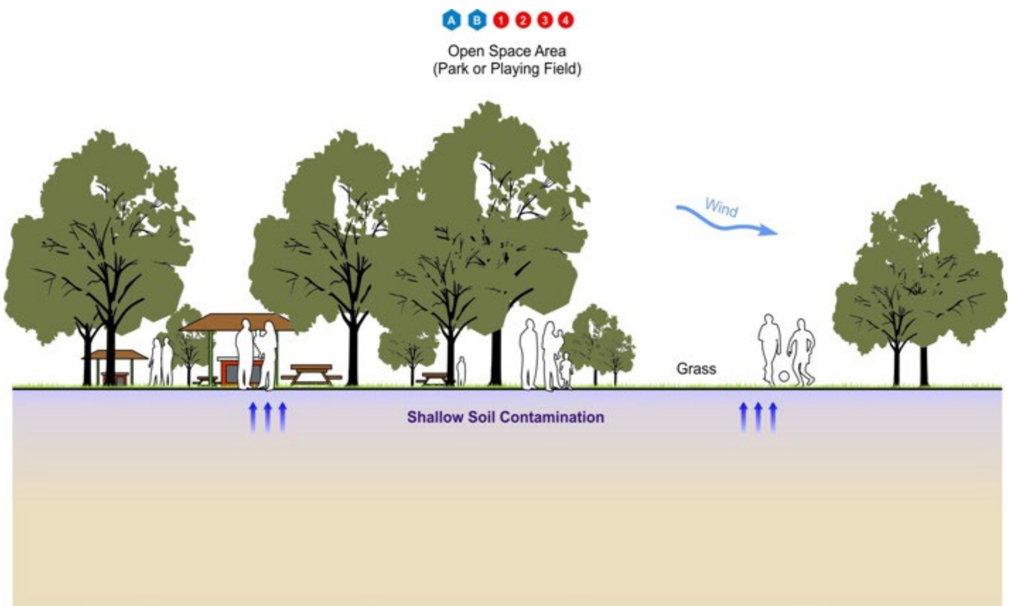
RECEPTORS	EXPOSURE PATHWAYS	
A Adult residents B Child residents (0 - 6 years)	1 Indoor inhalation of vapours derived from shallow soil 2 Outdoor inhalation of vapours derived from shallow soil 3 Incidental ingestion of surface soil and dust particulates 4 Dermal contact with surface soil and dust particulates 5 Indoor inhalation of dust particulates	6 Outdoor inhalation of dust particulates 7 Consumption of home-grown produce 8 Consumption of soil adhering to home-grown produce

Figure 2: Residential high density



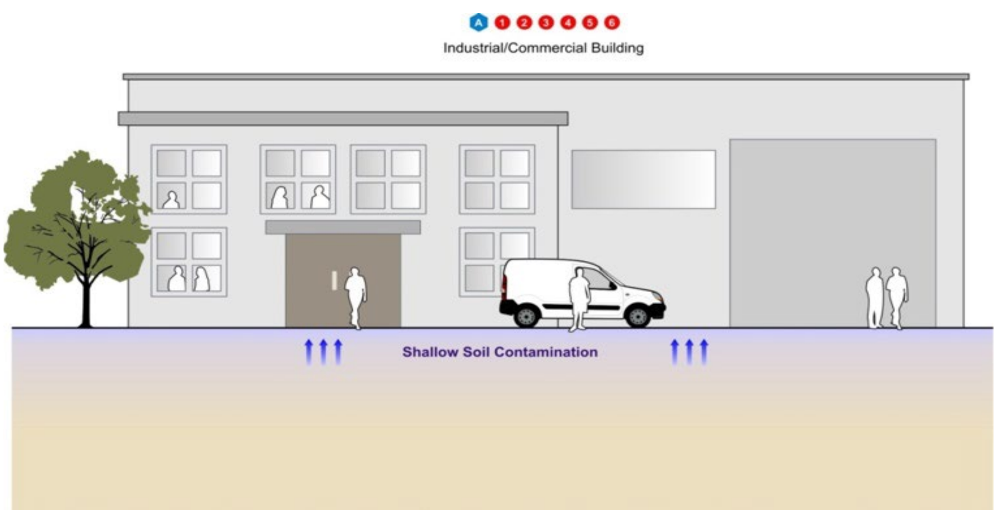
RECEPTORS	EXPOSURE PATHWAYS	
A Adult residents B Child residents (0 - 6 years)	1 Indoor inhalation of vapours derived from soil contamination 2 Outdoor inhalation of vapours derived from soil contamination 3 Indoor inhalation of dust particulates 4 Outdoor inhalation of dust particulates	5 Dermal contact with dust particulates 6 Incidental ingestion of dust particulates

Figure 3: Recreational



RECEPTORS	EXPOSURE PATHWAYS
A Adults recreational users	1 Outdoor inhalation of vapours derived from soil contamination
B Child recreational users (0 - 6 years)	2 Outdoor inhalation of dust particulates
	3 Dermal contact with soil and dust particulates
	4 Incidental ingestion of soil and dust particulates

Figure 4: Industrial



RECEPTORS	EXPOSURE PATHWAYS	
A Adult employees	1 Indoor inhalation of vapours derived from soil contamination	5 Dermal contact with dust particulates
	2 Indoor inhalation of dust particulates	6 Incidental ingestion of dust particulates
	3 Outdoor inhalation of vapours derived from soil contamination	
	4 Outdoor inhalation of dust particulates	

5.3 ISSUES OF CONCERN

5.3.1 Toxicology

5.3.1.1 Background exposures

Human health risk assessment requires evaluation of exposures through estimates of daily intake against acceptable daily intakes (ADIs) (or an equivalent intake duration) to determine a margin of safety expressed as a hazard quotient (HQ) for any one chemical and exposure pathway. The acceptable intake must consider all sources of exposure for any one chemical such that apportionment occurs. This includes air, water, food, use of consumer goods and exposures associated with individual behaviours.

Inhalation exposures are difficult to avoid and their management at the personal level is limited. The use of static atmospheric monitoring across areas does not measure the same outcome as personal monitoring in an individual's breathing space and this has been recognized for many years (Ott, 1982). As a consequence, it is important to understand the nature of background exposure data and allow a margin of uncertainty for that which is unknown. Such an approach reflects the 'precautionary principle' in public health (enHealth, 2012a).

5.3.1.2 Duration effects and population susceptibility

A thorough up-to-date review of the toxicology is critical in ensuring that the most appropriate toxicological endpoint is identified in order to review suitable dose-response data and the time scale associated with that adverse outcome. WHO (2001) have compiled exposure assessment terms and those for duration include:

Acute exposure - "*One or a series of short term exposures generally lasting less than 24 hours. (CARB, 2000: Glossary of Air Pollution Terms*)"; Contact with a substance that occurs once or for only a short time (up to 14 days) ATSDR, 2016: online glossary

Intermediate exposure - Exposure to a chemical for a duration of 15–364 days *[ATSDR, 2016: Online Glossary]*

Sub-chronic exposure – "*Exposure to a substance spanning approximately 10% of the lifetime of an organism. [IRIS, 1999: Glossary of IRIS Terms*]

Chronic exposure - "*Occurring over a long period of time (more than 1 year). [ATSDR, 2016: Online Glossary]*

While there are slight differences between terms across agencies where toxicological data are used in risk assessment it is important that the definition of the durations associated with that data are clearly understood as defined by the publishing authority.

As part of the toxicological assessment process the susceptibility of the population to volatile COPC should be recognized and considered. This region-specific factor may impart a greater emphasis to the evaluation of any particular volatile substance. For example, in Australia asthma prevalence in 2011-12 was 10.25% of the population with slightly higher levels in children (ABS, 2014). Volatile substances that may initiate Type 1 hypersensitivity reactions therefore warrant review and consideration.

5.3.1.3 Individual substances and mixtures

The majority of toxicological testing is undertaken on single substances of specific purities. Subsequently, they do not incorporate concurrent exposures to volatiles that are the more realistic in-situ exposure settings due to mixtures of wastes, technical grade products or multiple source exposures to differing volatiles. Consideration is therefore required of toxico-dynamic interactions and review of available assessment tools. Should such tools be lacking or incomplete, the incorporation of margins of safety, conservative estimates or qualitative discussion regarding how such information may affect the risk assessment outcome should be presented. The toxico-dynamics of volatile substances within environmental settings is an area acknowledged as requiring further research and ATSDR have begun to address this through a program undertaken by ATSDR's Division of Toxicology and Human Health Sciences (DTHHS) in developing interaction profiles (ATSDR, 2016).

5.3.2 Epidemiology

5.3.2.1 What is known?

Data from Australian environmental epidemiological studies involving population evaluations of vapour intrusion exposures and adverse outcomes are non-existent and there are only a few studies undertaken overseas.

Steffan et al., (2004) examined potential environmental exposure to hydrocarbons and the risk of acute childhood leukaemia in a multicenter hospital based case-control study in France. The group reported a "*particularly strong*" association between dwellings neighbouring a petrol station or repair garage during childhood and the risk of acute non-lymphocytic leukaemia (OR 7.7, 95% CI 1.7 to 34.3). Whether the exposures were mediated via ambient air or indoor air from vapour intrusion or a combination of both is uncertain.

Forand, Lewis-Michl and Gomez (2012) investigated the prevalence of adverse birth outcomes among mothers exposed to trichloroethylene (TCE) and tetrachloroethylene (PCE) in indoor air contaminated through vapour intrusion. They reported that maternal residence in TCE and PCE affected areas was associated with cardiac birth defects and residence in the TCE-affected was further associated with low birthweight and foetal growth restriction. According to the authors this study has been the first to evaluate TCE vapour intrusion health concerns in a population.

These limited data suggest that potential population health impacts may be occurring across similar site contamination settings. These initial studies warrant further research particularly in Australia where the urban environments and urban consolidation programs result in close proximity to a diversity of volatile hydrocarbon sub-surface sources.

5.3.3 Exposure assessment

5.3.3.1 Measurement methods

Exposure assessment in vapour intrusion assessment tends to employ indirect measurement of potential exposures as opposed to traditional occupational hygiene techniques using personal monitoring and biological monitoring (see enHealth 2012a, p50) which are considered as direct. These indirect approaches generally involve transport models (such as a vapour intrusion models) or static environmental monitoring (e.g. in air). While passive and active sampling devices may be employed, it is important to recognize that the exposure assessment should align with the nature and duration of measurement associated with the toxicological data to be used. If there is any deviation to the periods or measurement methods used, then the interpretation of the toxicological data to be applied should be reviewed. For example, in the Air Toxics NEPM (2004) measurement methods are specified for the use of the monitoring investigation levels (MILs) that have been established. Recently there has been debate regarding Haber's rule duration adjustment suggesting that a linear extrapolation of air data is not appropriate and needs to be based on a more in-depth case-by-case approach employing toxico-kinetics and toxico-dynamic data analysis for each toxicant (Belkebir et al., (2011). Further research into such adjustments, based on recent toxicological data, are required.

5.3.3.2 Time-dependence and averaged exposures

The passive (diffusive flow) and active (advective flow) atmospheric sampling protocols employed with volatiles measurement relies on capture of a mass of material onto an adsorbent surface over time with a specified air movement through the sampling device. Once the mass is analysed following cessation of sampling this quantum is expressed per volume of air that has flowed through the device as a concentration per volume which represents a time-weighted atmospheric air measurement. Shorter time intervals may be considered should toxicological data suggest it, for example sulphur dioxide, is measured over an hour and a day with a 10minute average also considered (see NEPC, 2004). On this basis it is important to reconcile the COPC and inherent toxicology with sampling durations.

Recent advances in real-time measurement such as portable GC-FID or GC-MS instrumentation also present additional information in terms of dynamically changing exposure measurements. While these are useful in understanding spatial and temporal indoor changes in air volatile concentrations there are limited data available to interpret such results. These may be useful in the interim to guide more conventional methods, however, with further research on time-dependent dose-response for inhalation exposures, it is anticipated such methods may become a dominant approach. In terms of hazardous gases or vapours and vapour intrusion, further research is required.

6 Regulatory Vapour Intrusion Guidance

6.1 Australia

6.1.1 National Environment Protection (Assessment of Site Contamination) Measure (1999)

The National Environment Protection (Assessment of Site Contamination) Measure (1999) was initially developed through a consolidation of information and developed criteria from a series of Monographs published by the South Australian Health Commission following National Workshops on the assessment and management of site contamination over the period, 1990 to 1998 (see Langley et al., (Eds.), 1991, 1993, 1996; 1998). Review of the NEPM in 2005 (NEPC, 2005) resulted in a series of recommendations for updating the Measure. The process for updating the NEPM by NEPC and NHMRC was outsourced with internal review by technical working groups. The outcome resulted in the publication of twenty-two volumes comprising the former Schedules under the Federal Register of Legislative Instruments (F2013L00768).

Information on vapour intrusion and guidelines is contained in the following volumes:

- Volume 2 (Schedule B1 pp5-12; p18)
- Volume 3 (Schedule B2, pp52-63)
- Volume 4 (Schedule B3, pp 19-23; pp36-40; pp63-72)
- Volume 5 (Schedule B4, p17; pp26-29; pp39-41)
- Volume 15 (Schedule B7, Appendix 6) - Interim HILs for chlorinated hydrocarbons
- Volume 19 (Schedule B7, p8; pp31-32; pp35-39; pp41-42) - Derivation of HILs

Volume 2 deals with background information regarding interim HILs for chlorinated hydrocarbons and the HSLs for petroleum hydrocarbons with a particular emphasis on the limitations on the latter. Volume 3 covers sampling design, conceptual frameworks and multiple lines of evidence approaches. Volume 4 discusses laboratory analyses with a focus on the analysis of total petroleum hydrocarbon and mixtures while Volume 5 discusses site-specific health risk assessment methodology. The latter is drawn from the enHealth (2012a) guidance documentation which was prepared at approximately the same time to ensure alignment in frameworks. The enHealth documents covering environmental health risk assessment (2012a; 2012b) should be referred to for more detail. Volume 15 discusses the derivation of the interim HILs for chlorinated hydrocarbons and Volume 19 covers the derivation process for the health-based investigation levels.

6.1.2 Cooperative Research Centre for Contamination and Remediation of the Environment (CRC CARE)

CRC CARE was established in 2004 in Adelaide as an industry, academia and regulatory environment multi-funded agency organization to undertake research and development across site contamination issues. CRC CARE has published a number of technical reports which are referenced in the ASC NEPM. The following documents are relevant to vapour intrusion assessment, noting that all the work is specifically related to petroleum hydrocarbons associated with service stations and storage depots:

CRC CARE (2006) Technical Report 02: Protocols and techniques for characterising sites with subsurface petroleum hydrocarbons - a review

CRC CARE (2007) Technical Report 04: The development of HSLs for petroleum hydrocarbons - an issues paper

CRC CARE (2008) Technical Report 08: Review of the current international approaches to total petroleum hydrocarbon assessment

CRC CARE (2009) Technical Report 09: Petroleum vapour model comparison

CRC CARE (2011) Technical Report 10: Health screening levels for petroleum hydrocarbons in soil and groundwater

CRC CARE (2009) Technical Report 11: Characterisation of sites impacted by petroleum hydrocarbons - National guideline document

CRC CARE (2009) Technical Report 12: Biodegradation of petroleum hydrocarbon vapours

CRC CARE (2013) Technical Report 13: Field assessment of vapours

CRC CARE Technical Report 23: Petroleum hydrocarbon vapour intrusion assessment - Australian guidance.

These reports are summary reviews of other published literature and/or international regulatory agency information and the reader should refer to the primary sources of information contained in these reports where available. In the case of Technical Reports 12 and 13, the former has included evaluation of Australian field data from seven Australian petroleum hydrocarbon impacted sites while the latter information has provided a review of factors to consider in field assessment and includes information on vapour and gas sampling and monitoring techniques (Section 6). Technical Report 23 provides a decision framework for petroleum vapour intrusion assessments and includes soil vapour testing techniques. Both Technical Reports 13 and 23 provide useful information on sampling methods while noting that all documents have a focus towards the site assessment of petroleum hydrocarbons.

6.1.3 State Environment Protection Agencies (EPAs)

6.1.3.1 New South Wales EPA (NSW EPA)

The NSW EPA has produced a number of documents related to vapour intrusion and was the first environment protection agency in Australia to produce guidance on the investigation of sub-surface volatile hydrocarbons through the investigation of service station sites (NSW EPA 1994: 2014). The 1994 document included soil petroleum hydrocarbon fraction concentrations for assessment purposes with the 2014 update incorporating alignment with the ASC NEPM and more recent NSW EPA documentation on volatile hydrocarbons from sub-surface sources. The latter include:

NSW DECCW (2010) Vapour Intrusion Technical Guidance Note. New South Wales Department of Environment, Climate Change and Water, Sydney.

NSW EPA (2012) Guidelines for the Assessment and Management of Sites Impacted by Hazardous Ground Gases. New South Wales Environment Protection Authority, Sydney.

The service station assessment guidance incorporates general advice on site investigation methods, the CSM, the COPC, sampling and analysis quality plans (SAQP) and soil, groundwater, soil vapour assessment methods. This guidance references:

- the ASC NEPM
- the Contaminated Land Management Act (CLM Act)
- the Work Health and Safety Act 2011 and subsequent Regulations
- the ASC NEPM Toolbox
- *Guidelines for Consultants Reporting on Contaminated Sites* (Office of Environment and Heritage (OEH) 2011)
- the Protection of the Environment Operations (Underground Petroleum Storage Systems) Regulations 2008 (UPSS Regulation)

and a number of other Acts and Regulations related to water impacts and soil contamination.

The Vapour Intrusion Technical Practice Note is a health-focused general guidance document which provides a useful overview of some of the key elements to consider with vapour intrusion assessments. This includes:

- General principles
- Planning and conceptual site models
- Site investigation methods across sampling methods and sampling design
- Reporting and interpretation of results

The section on interpretation of results encompasses information on health data, exposure assessment, vapour modelling and attenuation factors.

The guideline on hazardous gases is the only guidance document across the environment agencies which examines hazardous ground gases that are defined as "both gases and vapours" within the document (NSW EPA, 2012, p1) noting that vapours may exist in equilibrium with liquid or solid phases at ambient temperatures. This therefore is much broader than the ASC NEPM guidance framework which does not address gases or vapours that are associated with landfills or waste dumps. The range of chemicals specified include methane, carbon dioxide, carbon monoxide, petroleum vapours, hydrogen, hydrogen sulphide, radon, volatile organic compounds (VOCs) and mercury vapour. This breadth of substances incorporates both physical and chemical hazards which include fire and explosion, and acute, sub-chronic and chronic health risks. This document is comprehensive and based heavily on information from the United Kingdom where considerable evaluation of landfill sites has been undertaken and guidance frameworks developed (e.g. Wilson et al., 2007). It also considers human health risk assessment both in terms of risk analysis and risk assessment; vapour intrusion; and management measures. In addition, the document also references applicable NSW guidance and legislation.

6.1.3.2 South Australian EPA

The South Australian EPA has established an Environmental Audit system under the Environmental Protection Act, 1993 for site assessment and management purposes. This system defaults to the ASC NEPM for guidance frameworks and documentation, however, SA EPA has also released supplementary local guidance to ensure SA EPA's expectations for assessment and remediation of site contamination are met. Previous guidance included the SA EPA (2009) "*Site Contamination. Guidelines for the assessment and remediation of groundwater contamination*" and more recently a Draft for Public consultation, dated August 2015 was released entitled, "*Guidelines for the assessment and remediation of site contamination*". While the former has limited comment on vapour intrusion the latter has a number of sections devoted to vapour assessment frameworks, technical considerations and remediation (pp45-55).

6.1.3.3 Victorian EPA

In Victoria, environmental auditing under the Environment Protection Act 1970, enables decision making by planning authorities, prospective purchasers and other stakeholders over the environmental condition of a site and its suitability for a specific purpose. There are a range of Victorian EPA guidance publications that support the audit process but none specific to vapour intrusion. The Environmental Auditor (Contaminated Land) Guidelines for Issue of Certificates and Statements of Environmental Audit requires Auditors to refer to the ASC NEPM. On this basis the ASC NEPM default vapour intrusion guidance applies.

In terms of landfill gas, the main document reference is Publication 788.2 (Vic EPA, 2014) which provides guidance on siting, design, operation and rehabilitation of landfills. There is limited focus on human health risk assessment *per se* as the document has more of a management objective.

6.1.3.4 Western Australian EPA

The WA EPA as part of the Department of Environmental Regulation (DER), have developed contaminated site guidelines under the Contaminated Sites Act 2003 and the subsequent Contaminated Sites Regulations 2006. These embody the ASC NEPM as part of the process. The document encompasses a range of issues in assessing site contamination and includes vapour assessment information under "Detailed site investigation" (pp35-37). Brief comment is provided across petroleum hydrocarbons, chlorinated hydrocarbons and landfill gases with the document directing the reader to a range of predominantly US sources but references CRC CARE Technical Report 23; CIRIA (2007) and the NSW EPA (2012) guidelines for hazardous ground gases. The DER (2014) does recognize the differences in vapour intrusion between petroleum hydrocarbons and chlorinated hydrocarbons at Section 9.7.3 but does not provide any subsequence guidance or references specific to the assessment of chlorinated hydrocarbons.

6.1.3.5 Queensland EPA

In Queensland the Department of Environment and Heritage Protection have recently instigated contaminated land reforms under the Environment Protection Act 1994 to make it mandatory for contaminated land investigation documents to be certified by an approved auditor. This process commenced on 30 September 2015 following Parliamentary legislative changes. While there is no specific local vapour intrusion guidance, an Auditor would default to that presented in the ASC NEPM consistent with other jurisdictions.

6.1.3.6 Tasmanian EPA

In Tasmania, contaminated sites are regulated under the Environmental Management and Pollution Control Act 1994. While Regulations have been developed for some aspects such as underground storage tanks, there is no specific vapour intrusion guidance and the ASC NEPM is applicable and given effect in Tasmania as a State policy.

6.1.3.7 Northern Territory EPA

The Waste Management and Pollution Control Act (2016) in the Northern Territory administers environmental audits through accredited auditors in accordance with the ASC NEPM. There is no specific guidance on vapour intrusion with default to what has been prepared at the national level.

6.2 CANADA

In Canada site contamination guidance is provided by Health Canada and the Canadian Council of Ministers of the Environment (CCME). The guidance associated with vapour intrusion and risk assessment includes the following:

- CCME (2006) *A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines*. Canadian Council of Ministers of the Environment (CCME), Manitoba.
- Health Canada (2010a) *Federal Contaminated Sites Risk Assessment in Canada Part I: Guidance on Human Health Preliminary Quantitative Risk Assessment* (PQRA). Health Canada, Ontario.
- Health Canada (2010b) *Federal Contaminated Sites Risk Assessment in Canada Part II: Health Canada Toxicological Reference Values (TRVs)*. Health Canada, Ontario.
- Health Canada (2010c) *Federal Contaminated Sites Risk Assessment in Canada Part V: Guidance on Human Health Detailed Quantitative Risk Assessment of Chemicals (DQRAchem).* Health Canada, Ontario.
- Health Canada (2010d) *Federal Contaminated Sites Risk Assessment in Canada Part VII: Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites.* Health Canada, Ontario.
- CCME (2014) *A Protocol for the Derivation of Soil Vapour Quality Guidelines for Protection of Human Exposures via Inhalation of Vapours.* Canadian Council of Ministers of the Environment (CCME), Manitoba.

In terms of the recent guidance there are slight differences in what each agency provides for vapour intrusion assessment. Health Canada (2010d) provides a guidance document which depends heavily on the Johnson and Ettinger (1991) model (JEM) and its variants but also considers empirical attenuation factor data and numerically modelled bio-attenuation of hydrocarbon vapours beneath buildings. CCME (2014) provides generic Soil Vapour Quality Guidelines for indoor air quality ($SVQG_{IAQ}$) which are based on migration of vapour into indoor air using JEM with a series of limitations. If the limitations apply, then specific attenuation factors are recommended. The CCME guidance also allows re-calculation of generic guidelines based on site-specific data as additional tiers of assessment.

6.3 European Environment Agency

The European Environment Agency (EEA) co-ordinates information on site contamination across the European Union. A recent European Commission (EC) (2014) report cites some 340,000 contaminated sites requiring remediation across Europe.

The mission statement for the EEA is:

"*The European Environment Agency (EEA) aims to support sustainable development by helping to achieve significant and measurable improvement in Europe's environment, through the provision of timely, targeted, relevant and reliable information to policymaking agents and the public."* (2015).

The agency does not establish detailed assessment approaches but relies on each country's jurisdictional approaches to risk assessment and aids as a co-ordinating body across supporting agencies as detailed in EEA (2016).

As a coordinating body it facilitates aggregation of information across a range of supporting organisations such as the Joint Research Centre (JRC) which performs research on trans-frontier problems such as those associated with environmental or risk analyses and the Concerted Action on Risk Assessment for Contaminated Sites in the European Union (CARACAS). The latter have produced some guidance but this was generic in nature (Ferguson et al., (1998). Meetings of CARACAS have continued with some EU countries still at early stages of risk assessment frameworks, e.g. Switzerland.

6.4 New Zealand

The New Zealand Ministry for the Environment (MfE) developed guidelines for the assessment and management of petroleum hydrocarbon contaminated sites in 1999 (MfE, 1999). These have been revised in 2011 by incorporation of information on underground storage tanks and underground petroleum equipment removal and replacement. The incorporation of these sections was undertaken in order to bring the guidelines up to date with the Resource Management (National Environmental Standard for Assessing and Managing Contaminants in Soil to Protect Human Health – NES) Regulations 2011.

These petroleum hydrocarbon guidelines developed Tier 1 soil and groundwater acceptance criteria based on set input parameters and the use of a modified Jury (1983) model for deeper sources (diffusion based) and a modified JEM for sources up to one metre (advection based). Differing soil types, land uses, and populations were considered. The information did not provide guidance on soil vapour sampling, quality assurance and vapour mitigation strategies. It also did not provide guidance on other vapours such as chlorinated hydrocarbons and landfills.

MfE also specify that these criteria are not derived consistent with the NES and subsequently are under review. MfE (2011) discusses the methodology for deriving standards for contaminants in soil to protect public health and makes reference to volatiles inhalation and the need to consider other international guidance and its applicability to New Zealand (p28).

In terms of landfill hazardous gases there is comment on landfill gas under "A Guide for the Management of Closing and Closed Landfills in New Zealand" published in 2001 but the document is principally focused on landfill management (MfE, 2001).

6.5 The Netherlands

The Dutch National Institute for Public Health and the Environment (RIVM) is the key research organisation in the Netherlands for the provision of advice on health and the environment and has been operating since 1909. RIVM provides government with impartial advice on infectious diseases, vaccination, population screening, life style, nutrition, pharmaceuticals, environment, sustainability and safety. This work includes carrying out studies, providing advice and recommendations, and directing and implementing prevention and control responses.

RIVM has an extensive history in site contamination investigations and guideline development and has published a range of reports associated with contaminated site exposure assessment, vapour intrusion model development, modelling and health risk assessment of contaminated sites affected by volatile hydrocarbons. They have developed CSOIL (van den Berg, 1993), a site contamination exposure model used to develop site contamination human intervention levels and VOLASOIL (Waitz, 1996), a steady-state vapour intrusion model used in the Netherlands and Europe.

A selection of other key RIVM reports that provide guidance across exposure modeling, toxicological parameters, and regulatory policy include those by Janssen et al., (1992); Lijzen et al., (2003); and Otte et al., (2007) with some of the key publications listed below:

- Otte, PF, Lijzen, JPA, Otte, JG, Swartjes, FA, Versluijs, CW (2001) *Evaluation and Revision of the CSOIL Parameter Set. Proposed Parameter Set for Human Exposure Modelling and Deriving Intervention Values for the First Series of Compounds.* National Institute for Public Health and the Environment (RIVM). Bilthoven, the Netherlands. RIVM Report No.711701021, pp.125.
- Lijzen, JPA, Baars, AJ, Otte, PF, Rikken, MGJ, Swartjes, FA, Verbruggen, EMJ, Van Wezel, AP (2001) *Technical Evaluation of the Intervention Values for Soil/sediment and Groundwater.* National Institute for Public Health and the Environment (RIVM). Bilthoven, the Netherlands. RIVM Report No. 711701023.
- Lijzen, JPA, Otte, PF, Bakker, J, Swartjes, JFA, Baars, AJ, Oomen, AG, and Brand, E (2008) *Guidance for Site-Specific Human-Toxicological Risk Assessment of Soil Contamination.* National Institute for Public Health and the Environment (RIVM). Bilthoven, the Netherlands. RIVM report no. 711701050.
- Van Wijnen, HJ, and Lijzen, JPA (2006) *Validation of the VOLASOIL Model using Air Measurements from Dutch Contaminated Sites.*: National Institute for Public Health and the Environment (RIVM). Bilthoven, the Netherlands. RIVM report no. 711701401.

6.6 United Kingdom

In the United Kingdom, the Environmental Protection Act 1990 Part 2A regulates site contamination. The Contaminated Land Statutory Guidance (DEFRA, 2012) provides information on implementation, remediation provisions, liability arrangements and local authority recovery costs. It is legally binding and adopts a risk-based approach to site assessment.

The overarching objectives of the Government's policy on contaminated land and the Part 2A regime are:

"*(a) To identify and remove unacceptable risks to human health and the environment.*
(b) To seek to ensure that contaminated land is made suitable for its current use.
(c) To ensure that the burdens faced by individuals, companies and society as a whole are proportionate, manageable and compatible with the principles of sustainable development."

A range of published documents are available that support Part 2A including historical publications. Early work by Ferguson et al., (1995) and Krylov and Ferguson (1998) on vapour modelling enabled development of a Contaminated Land Assessment Model (CLEA) which Ferguson (and others) also helped develop (EA, 2002). Further work by the Environment Agency on toxicological assessments (EA, 2009a); updates to the CLEA model (EA, 2009b) and advice on using soil guidance values (EA, 2009c) have been published. More recent publications on screening criteria, software and policy have been produced as follows:

- DEFRA (2014) SP1010 – *Development of Category 4 Screening Levels for Assessment of Land Affected by Contamination.* Final Project Report (Revision 2). Contaminated Land: Applications in Real Environments, Department for Environment, Food and Rural Affairs, London.
- EA (2015) *CLEA Software (Version 1.05) Handbook.* Environment Agency, Bristol. Science report: SC050021/SR4.
- EA (2016) *Managing and Reducing Land Contamination: Guiding Principles (GPLC).* Environment Agency, UK. Available at https://www.gov.uk/government/publications/managing-and-reducing-land-contamination. [accessed 23 June 2016].

A subsequent review by Evans et al., (2002) led to a shift in policy from the Ferguson et al., (1995) vapour intrusion model to the model of Johnson and Ettinger (1991). (It is noted that Professor Ferguson's unfortunate passing on 28th August 1999 occurred just prior to this policy shift).

There have been a few more updates to the overall assessment processes but essentially the CLEA model (which incorporates the JEM) is used to develop generic soil guidance values (SGVs). The associated documentation with the CLEA model can also be used for site-specific assessment which is recommended as part of the assessment process for indoor inhalation of vapours. There is a focus on the limitations on the JEM within the documentation and a strong emphasis towards site-specific measurement and attenuation assessment.

The UK has also developed a range of guidance documentation associated with landfill and hazardous gas assessments which require slightly differing approaches to gas and vapour risk assessment due to the acute risks of fire, explosion and asphyxiation. Landfills also may generate a range of volatile organic compounds which require concurrent or secondary assessment once acute risks are dealt with.

The UK documentation includes that from the Environment Agency but also from other not-for-profit or research organisations such as Contaminated Land: Applications in Real Environments (CL:AIRE); BRE Group; British Standards Institute (BSI); Chartered Institute for Environmental

Health; and the Construction Industry Research and Information Association (CIRIA). A useful UK summary of reports for assessment of risks associated with gases and vapours can be found on the CL:AIRE website at http://www.claire.co.uk/index.php?option=com_content&view=article&id=924:assessing-risks-associated-with-gases-and-vapours-info-ra2-4&catid=981:environment-agency-document-archive&highlight=WyJ2YXBvdXIiLCJpbnRydXNpb24iLCJ2YXBvdXIgaW50cnVzaW9uIl0=&Itemid=310

Landfill gas documentation from the UK is extensive and includes guidance on general management and assessment (EA, 2004a, b); hazardous gases risk assessment (Wilson et al., 2007), VOCs (Baker, 2009); monitoring practices (EA, 2010; 2014), exposure assessment (EA, 2012a, b) and ground gas risk assessment (CL:AIRE, 2012). The most recent have focused on mitigation measures and include:

- Mallett, H, Cox, L, Wilson, S, and Corban, M (2014) *Good Practice on the Testing and Verification of Protection Systems for Buildings against Hazardous Ground Gases.* Construction Industry Research and Information Association (CIRIA), London, UK. CIRIA C735.
- Wilson, S, Abbot, A and Mallett, H (2014) Guidance on the Use of Plastic Membranes as VOC Vapour Barriers. Construction Industry Research and Information Association (CIRIA), London, UK. CIRIA C748.

6.7 United States

6.7.1 Federal agencies

6.7.2 United States Environment Protection Agency (USEPA)

The United States Environment Protection Agency (USEPA) has a long history of involvement with vapour intrusion and human health risk assessment and has developed extensive documentation, databases and tools. These may be readily accessed at www.epa.gov/oswer/vaporintrusion/index.html. In addition, the US EPA CLU-IN (Clean-Up Information) website at www.clu-in.org/issues/default.focus/sec/Vapor_Intrusion/cat/Site_Investigation_Tools is also a useful and extensive source of information across various vapour intrusion-related areas including sampling and analysis; predictive modelling; building design; pneumatic conductivity testing; meteorological monitoring; forensic approaches and with examples of site investigation case studies.

Key documentation includes that of the original OSWER publication (US EPA, 2002); information on mitigation approaches (US EPA, 2008), data on background indoor air VOC concentrations (US EPA, 2011c); differences between petroleum hydrocarbons and chlorinated hydrocarbons (US EPA, 2011d); information on attenuation factors based on the US EPA database (US EPA, 2012a); conceptual site model scenarios (US EPA, 2012c); and the evaluation of empirical data in soil vapour intrusion screening for petroleum hydrocarbons (US EPA, 2013). The most recent publications related to screening level calculations, informed decision making and technical guides include the following:

- US EPA (2014a) *Vapor Intrusion Screening Level Calculator. User's Guide.* Office of Superfund Remediation and Technology Innovation, Office of Solid Waste and Emergency Response, US Environmental Protection Agency, Washington, DC 20460.
- US EPA (2014b) *Framework for Human Health Risk Assessment to Inform Decision Making.* Office of the Science Advisor, Risk Assessment Forum, US Environmental Protection Agency, Washington, DC 20460.
- US EPA (2015a) *OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air.* Office of Superfund Remediation and Technology Innovation, Office of Solid Waste and Emergency Response, US Environmental Protection Agency, Washington, DC 20460. OSWER Publication 9200.2-154.
- US EPA (2015c) *Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites.* Office of Underground Storage Tanks, US Environmental Protection Agency, Washington, DC 20460. EPA 510-R-15-001.

The progressive documentation released by the US EPA has shifted from predictive vapour intrusion modelling to a greater emphasis on empirical data and understanding the dynamic relationships between transport compartments for any one site. Over this period there has been a great focus on attempting to determine the relationships between vapour concentrations within various transport compartments across data for many sites in the United States. This evaluation has resulted in generic attenuation factors being established (refer Section 8.5.6.1). A key factor to also recognize is that volatile petroleum hydrocarbons are considered quite differently from volatile chlorinated hydrocarbons as a results of their differing physico-chemical differences. US EPA considers these differences to be sufficient to warrant separate publications on volatile chlorinated hydrocarbons.

The US EPA considers landfill gases and vapours as a different scenario and has developed documentation for evaluating closed or abandoned facilities. Regulatory information can be found at https://www.epa.gov/landfills where landfills are differentiated between municipal solid waste landfills; industrial waste landfills and hazardous waste landfills. National regulation is under the Resource Conservation and Recovery Act (RCRA) Laws and Regulations. Documentation associated with landfill gas assessment include that related to evaluation of emissions and general guidance for closed and abandoned facilities (US EPA, 2005a, b).

6.7.2.1 The Interstate Technology and Regulatory Council (ITRC)

The Interstate Technology and Regulatory Council (ITRC) was established in 1995 and is a state-led national coalition of personnel from the environmental regulatory agencies of some 46 states and the District of Columbia, three federal agencies, Indian tribes and public and industry stakeholders. It operates as a committee of the Environmental Research Institute of the States (ERIS), a public charity that supports the Environmental Council of the States (ECOS) through educational and research activities. (see http://www.itrcweb.org/About/About). The range of available reports can be found at http://www.itrcweb.org/Guidance. The reports are designed to assist regulators and other bodies across a range of fields include vapour intrusion, but are not government policy. Specific documents include practical guides and investigative approaches (ITRC, 2007a, b) with a more recent publication covering the fundamentals of screening, investigation and management (ITRC, 2014). Note that the ITRC emphasis in recent years has been towards volatile petroleum hydrocarbon assessment rather than all volatile hydrocarbons.

6.7.2.2 United States Department of Defence (US DoD)

The United States Department of Defence (US DoD) commissioned and published its own handbook on vapour intrusion guidance (US DoD, 2009). The objective was to provide its own resource for remedial project managers to be used at active installations, installations closed or realigned under the Base Realignment and Closure Act (BRAC), or at Formerly Used Defence Sites (FUDS). The handbook reference is:

US DoD (2009) *DoD Vapor Intrusion Handbook.* Office of the Under Secretary of Defense, Department of Defense, Washington DC 20301-3000.

6.7.2.3 ASTM International

The American Society for Testing and Materials (ASTM) formed in 1898, and which changed its name to ASTM International is a global organization in the development and delivery of voluntary consensus standards. There are more than 12,000 current ASTM standards that are used across a range of fields (see https://www.astm.org/ABOUT/full_overview.html).

A number of standards have been developed for vapour intrusion with the most recognized being:

- ASTM E1739-95 (1995) *Standard guide for Risk-based Corrective Action Applied at Petroleum Release Sites.* ASTM International, West Conshohocken, PA. USA.

This 1995 standard has recently been updated:

- ASTM E1739-95 (2015b) *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites.* ASTM International, West Conshohocken, PA. Available at www.astm.org. [accessed 25 June 2016].

This standard covers a diversity of information across toxicity, risk assessment, vapour intrusion modelling (JEM) and controls, specific to volatile petroleum hydrocarbons.

A range of other relevant publications include those providing detail on active soil gas sampling (ASTM D7663-12, 2012); passive gas sampling (ASTM D7758-11, 2011); vapour encroachment screening on property transactions (ASTM E2600-15, 2015); methane evaluation (ASTM E2993-16, 2016); and the use of direct push or manual-hand driven sampling equipment (ASTM D7648-12, 2012).

A key ASTM publication that is pertinent to risk assessment and has been a fundamental approach to site assessments is:

- ASTM E2081-00 (2015c) *Standard Guide for Risk-Based Corrective Action*. ASTM International, West Conshohocken, PA. Available at www.astm.org. [accessed 25 June 2016].

6.7.2.4 US Department of Health and Human Services (DHHS) and US health agencies

The US Department of Health and Human Services issued a Memorandum in 2008 (DHHS, 2008a) advising on a short document prepared by DHHS on the evaluation of vapour intrusion pathways at hazardous waste sites (DHHS, 2008b). This document was focused on the use of the existing large volume of information produced by other US agencies with the emphasis being that those guidance documents "….*are used as references and springboards for discussion of public health practices when evaluating vapor intrusion*" DHHS, 2008, pp1-2). DHHS commented that "*many experienced investigators, including those who produced the ITRC guidance, believe that a multiple lines of evidence approach provides the best means of evaluating the vapour intrusion pathway*." (DHHS, 2008, p4). DHHS, (2008) subsequently outline that public health evaluation process.

In terms of landfill gas, ATSDR, (part of DHHS), produced a guidance document in 2001 (ATSDR, 2001) as a primer and overview for environmental health professionals. That document is now historical but may still be accessed at the ATSDR web-site at http://www.atsdr.cdc.gov/HAC/landfill/html/intro.html.

6.7.3 Other US State environment agencies

A number of US states have produced guidance in terms of technical guidance specific to each jurisdiction across areas such as methods of investigation, spreadsheet models, soil gas sampling protocols, and indoor air sampling and evaluations. A list of all states links are provided by US EPA at https://clu-in.org/issues/default.focus/sec/Vapor_Intrusion/cat/Policy_and_Guidance/

Some examples of documentation provided at that source include:

California

- DTSC (2015a) *Advisory Active Soil Gas Investigations.* Department of Toxic Substances, California Environment Protection Agency, California, USA.
- DTSC (2015b) *Guidance for the Evaluation and Mitigation of Sub-surface Vapor Intrusion to Indoor Air (Vapor Intrusion Guidance).* Department of Toxic Substances, California Environment Protection Agency, California, USA.

Massachusetts

- MDEP (2002) *Indoor Air Sampling and Evaluation Guide WSC Policy #2-430.* Office of Research and Standards, Department of Environmental Protection, Boston, MA, USA.
- MDEP (2011) *Interim Final Vapor Intrusion Guidance.* Massachusetts Department of Environment Protection, Boston, MA, USA.

New Jersey

- NJDEP (2013) *Vapor Intrusion Technical Guidance. Site Remediation Program.* New Jersey Department of Environment Protection, New Jersey, USA.

New York

- NYSDoH (2006) *Final. Guidance for Evaluating Soil Vapor Intrusion in the State of New York.* New York State Department of Health, New York, USA.

7 Risk assessment methods

7.1 Introduction

International approaches to human health risk assessment exhibit a consistency in frameworks, albeit slight deviations in content across the main themes of assessment. WHO (2010) provided a health risk assessment toolkit on chemical hazards as part of a harmonization process and have considered the relationship to environmental health as presented in Figure 5. It is important to recognize that the objective of any human health risk assessment is the protection of public health as a preventative practice to minimize the potential for population disease burden. The goal of human health risk assessment across all evaluations should therefore seek to meet this objective.

US EPA has a long history associated with the development of risk assessment protocols with the earliest framework in 1983 developed by the National Research Council (NRC, 1983). The US EPA has developed extensive documentation for human health risk assessment across the diverse elements of human health risk assessment and these resources are readily available (see https://www.epa.gov/risk/human-health-risk-assessment). They provide detail across the various stages of health risk assessment taking note that their use in Australia requires consideration of applicable region-specific differences across population demographics and behaviours and also environmental conditions and settings. Recently US EPA (2014) have updated their framework by agreeing "*that adopting a human health risk assessment framework would increase the Agency's ability to maximize the utility of risk assessment by emphasizing the need to focus the design of risk assessments on the decision-making process*", (pVIII). Furthermore, this was to include more emphasis on planning and scoping, problem formulation and ensuring scientific peer review and public, stakeholder and community involvement were sustained. The ability to incorporate changes in the science of risk assessment was considered important as part of this framework. This updated framework is presented in Figure 6.

In advancing the science of risk assessment, the US EPA Office of Research and Development has directed research efforts for the next 3 years (US EPA, 2015) towards integrated science assessments (ISAs); further development of the Integrated Risk Information System (IRIS) and cumulative risk assessment. The latter works towards understanding key biological, social, spatial, temporal and environmental factors and how they contribute to disproportionate risk.

In Australia the original enHealth Council model (2012a) as presented in Figure 7 was an adaptation of the original National Research Council (NRC) framework published in 1983 but has recently been revised to expand on current concepts (Figure 8) with again a greater focus towards scoping and planning. The enHealth Council documentation represents Australian health agency guidance on human health risk assessment.

The ASC NEPM has also structured a site-specific health risk assessment methodology for site contamination assessment (Federal Register F2013C00288, Volume 5, Schedule B4). The basis to the Schedule is the enHealth framework, albeit with additional content relevant to site contamination. According to Schedule B4, *"… in the assessment of contaminated sites, this Schedule takes precedence over the enHealth framework, and documents referenced therein, where there are contradictions. It is noted that the enHealth framework has a wider remit than* *the assessment of contaminated sites only, and some elements of the guidance are not relevant in a contaminated sites context*" (p5).

The basic unrefined elements of human health risk assessment include issue identification, hazard assessment, exposure assessment, risk characterization and risk management with an overarching risk communication and community engagement phase.

Figure 5: Environmental health paradigm and human health risk assessment (from WHO (2010), as adapted from Sexton et al., 1995; IPCS, 2000).

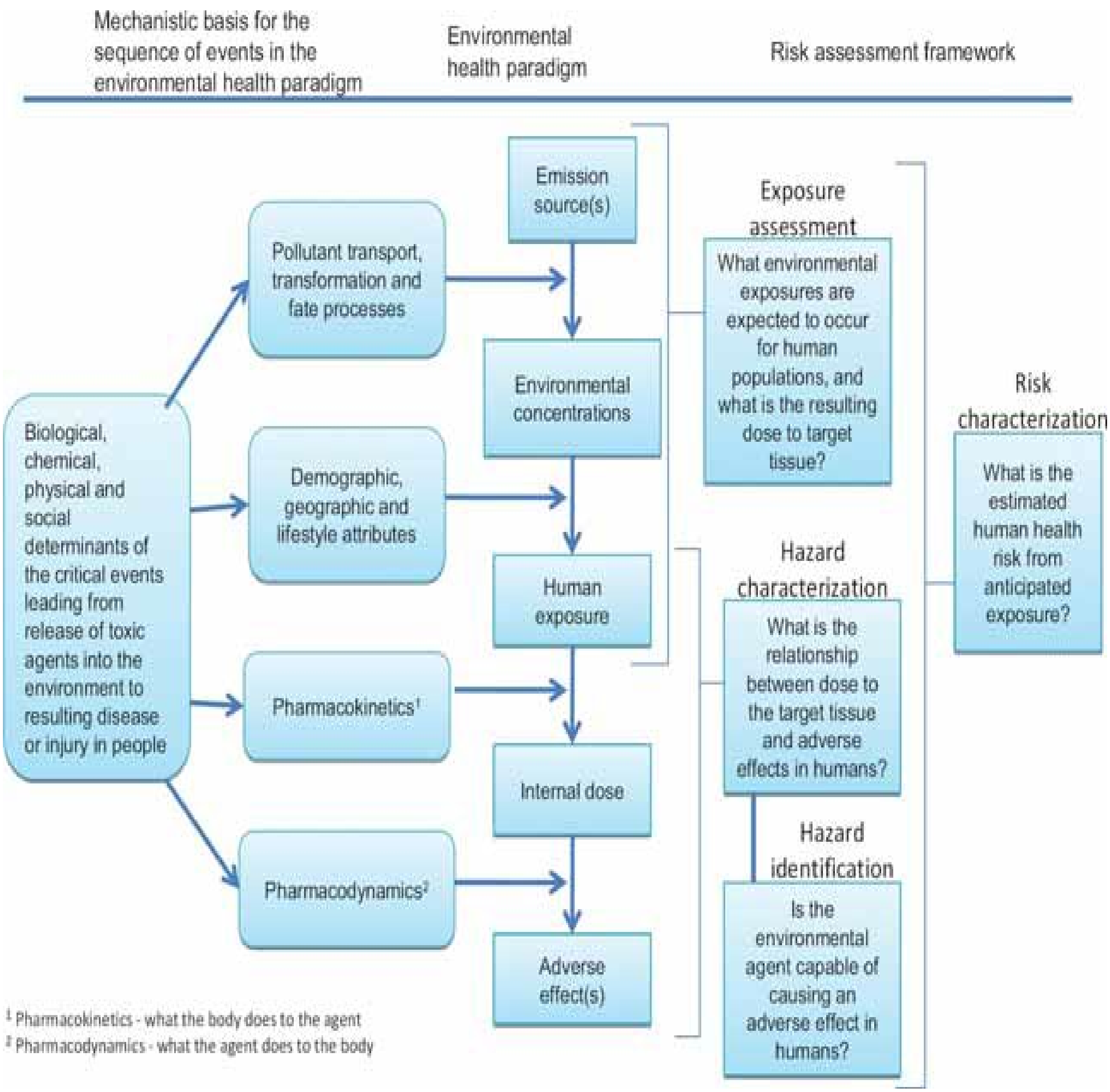


Figure 6: Framework for human health risk assessment to inform decision-making (from US EPA, 2014)

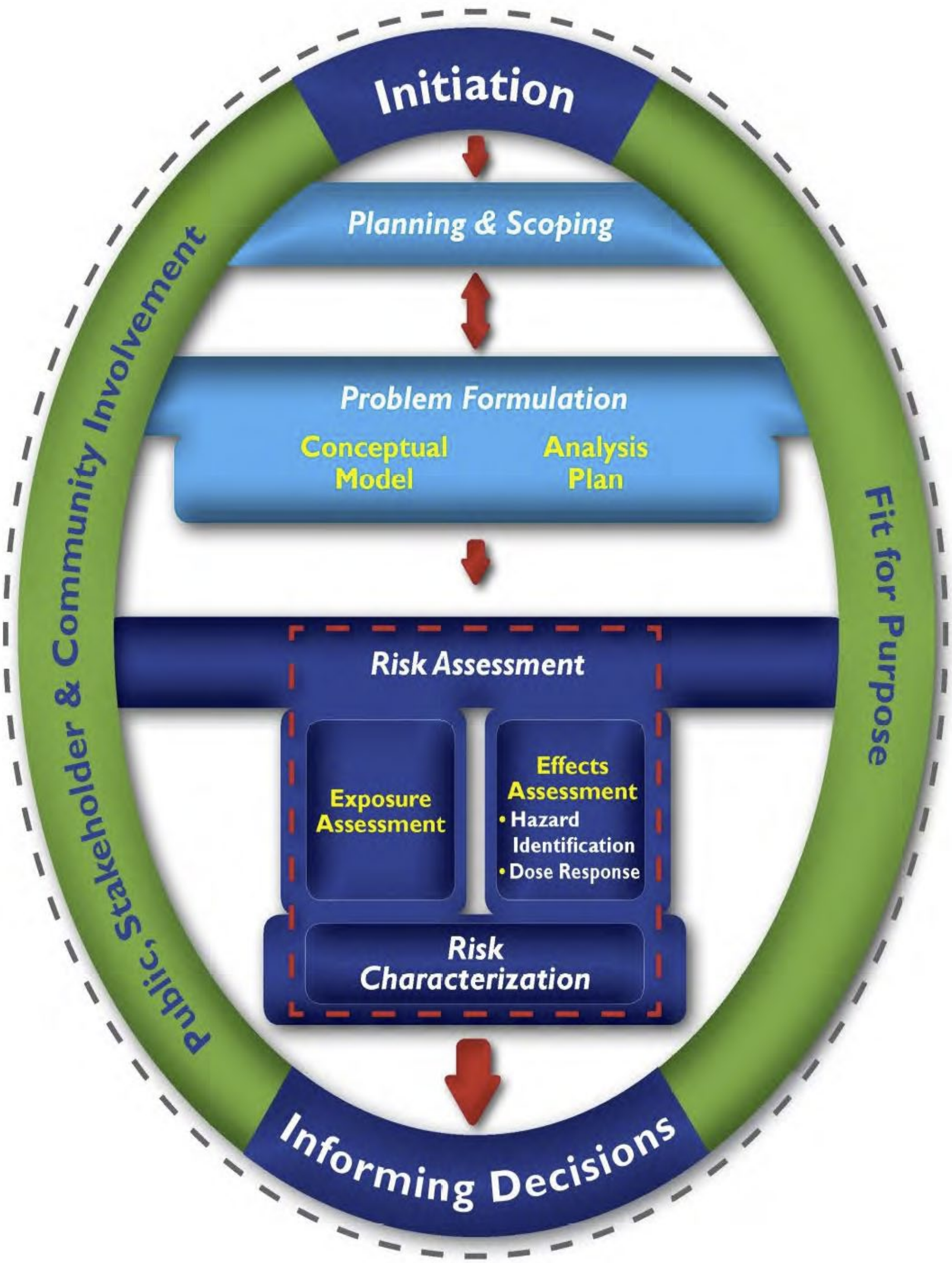


Figure 7: enHealth risk assessment framework

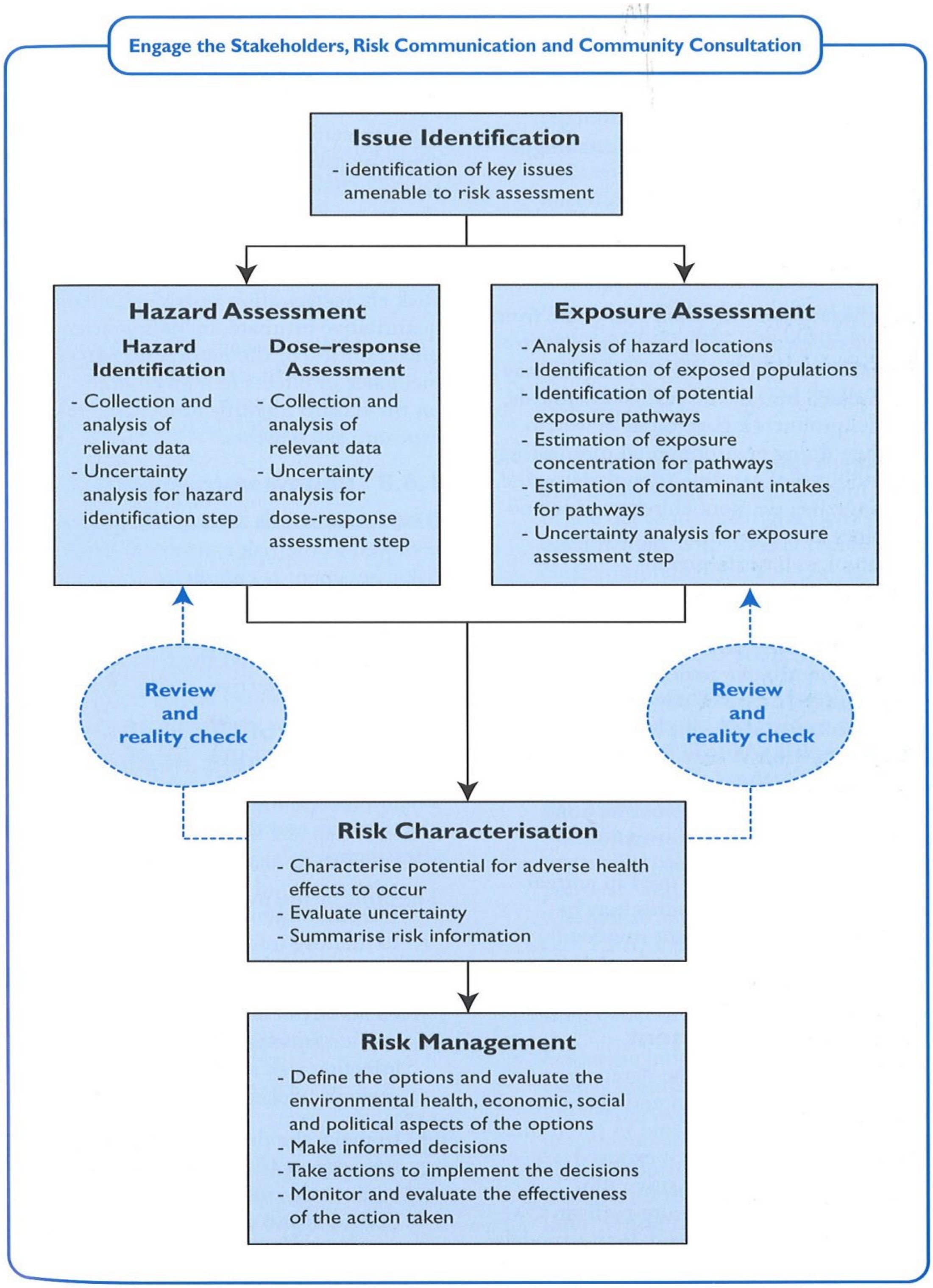
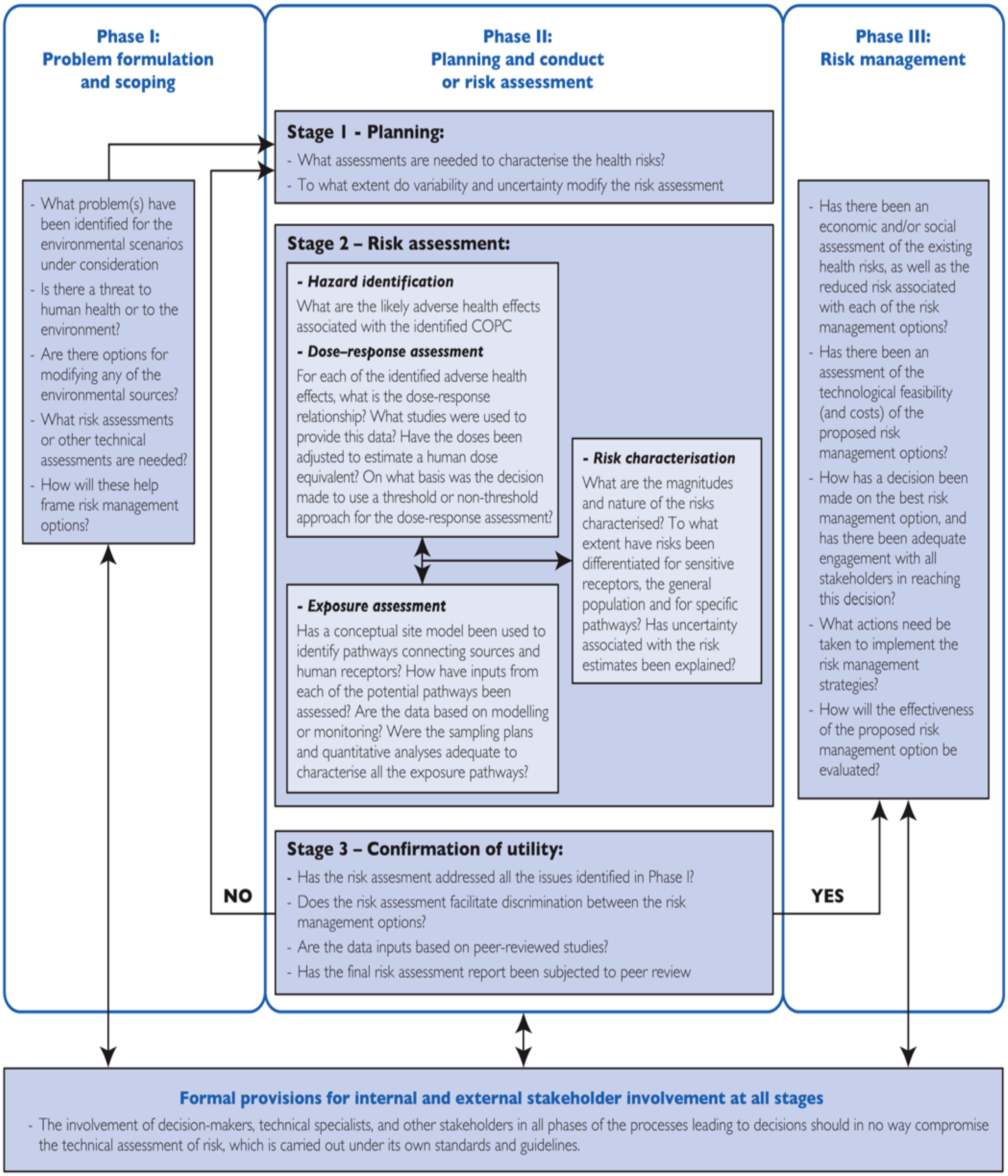


Figure 8: Revised outline of the interlinked processes of EHRA (from enHealth (2012a) as adapted from NRC, (2008))



7.2 Identifying concerns (Problem formulation and scoping)

As highlighted in the introduction a growing consensus in human health risk assessment is a greater focus towards scoping and planning of the risk assessment approach. This is particularly important in vapour intrusion (including hazardous gases) assessments due to the:

(a) Dynamic nature of the exposure.
(b) Potential that retrospective, current and prospective exposures need to be considered.
(c) Exposures as inhalation exposures are difficult for the community to avoid for existing dwellings and settings.
(d) Issue that acute hazards of fire, explosion, asphyxiation or irritant/asthmatic responses may prevail.
(e) Environmental setting in the case of sites under development, will change once above ground structures and below ground services are established.

In preparing for a vapour intrusion assessment a series of questions should be posed, reviewed and the responses understood to enable an appropriate sampling framework to be developed. These questions have been presented at the beginning of this document.

7.3 Hazard assessment

7.3.1 Understanding toxicology

Hazard assessment refers to understanding the intrinsic capacity of a substance to cause adverse health effects in human and animals (US EPA 1995). This capacity may be evidenced across a range of toxicological parameters. Data may be available across the following:

- Time scales - Acute/sub-chronic/chronic toxicity.
- Localised reactions- Irritation, corrosivity, sensitisation.
- Immuno-toxicity and hypersensitivity reactions (Type 1 to 4).
- Teratogenicity (malformations).
- Genotoxicity/mutagenicity.
- Carcinogenicity.
- Reproductive toxicity.
- Developmental toxicity.
- Specific organ toxicity (unique to the substance).
- Idiosyncratic reactions.
- A range of *In-vitro* toxicity testing endpoints designed to reduce the need for *in-vivo* testing.

Data across these parameters may be obtained from laboratory animal studies; individual human data based on human experiences (e.g. case studies of poisoning or controlled chamber studies) and population studies (epidemiological evaluations) in environmental or occupational settings. *In-vitro* data and structure-activity relationship data provide additional information but through less direct methods. Dose-response data subsequently obtained may include those related to substances exhibiting a lower limit (threshold) below which adverse effects are not reported to those where no threshold is observed. The latter may employ probabilistic expressions of risk of the adverse outcome per unit intake (based on linear low dose extrapolation) or as a unit intake for a set proportion of the experimental population (Benchmark dose, based on non-linear low dose extrapolation) (refer Filipsson et al., 2003).

In reviewing the hazard of a substance it is important to ensure that population-specific and pathway-specific factors are considered concurrent with the timeframes for a particular adverse effect. These timeframes will be important in considering the seriousness of an effect in a population and the nature of the exposure mitigation that may be required. enHealth (2012a, p25) consider key issues in hazard identification to include:

- Nature, reliability and consistency of studies
- Mechanistic information and mode of action
- Relevance to humans

Information across the above parameters is used in establishing pathway-specific toxicological reference values (TRVs) or population-based air quality guidelines which reflect a dose-response relationship for that effect and are used as risk assessment endpoints.

7.3.2 Toxico-kinetics and toxico-dynamics

Toxico-kinetics reflects the processes of absorption, distribution, metabolism and excretion in the human body while toxico-dynamics reflects the ability of individual substances within the body to interact. The latter may change the magnitude of the co-exposure resulting in the effect being additive, potentiated, synergistic or antagonistic.

The kinetics of chemical intake plays a role in estimating uptake and the potential for the body burden to increase with sustained exposure while interactions for mixtures may result in a residual uncertainty of concern for a human health risk assessment. These factors are important considerations in exposure measurement or estimations and in particular with biological monitoring which may be used to provide confirmatory information on exposure assessments.

A range of factors related to exposure estimations; alignment of measurement methods to toxicological outcomes, data interpolation and extrapolation; peak exposures and population behaviours require consideration.

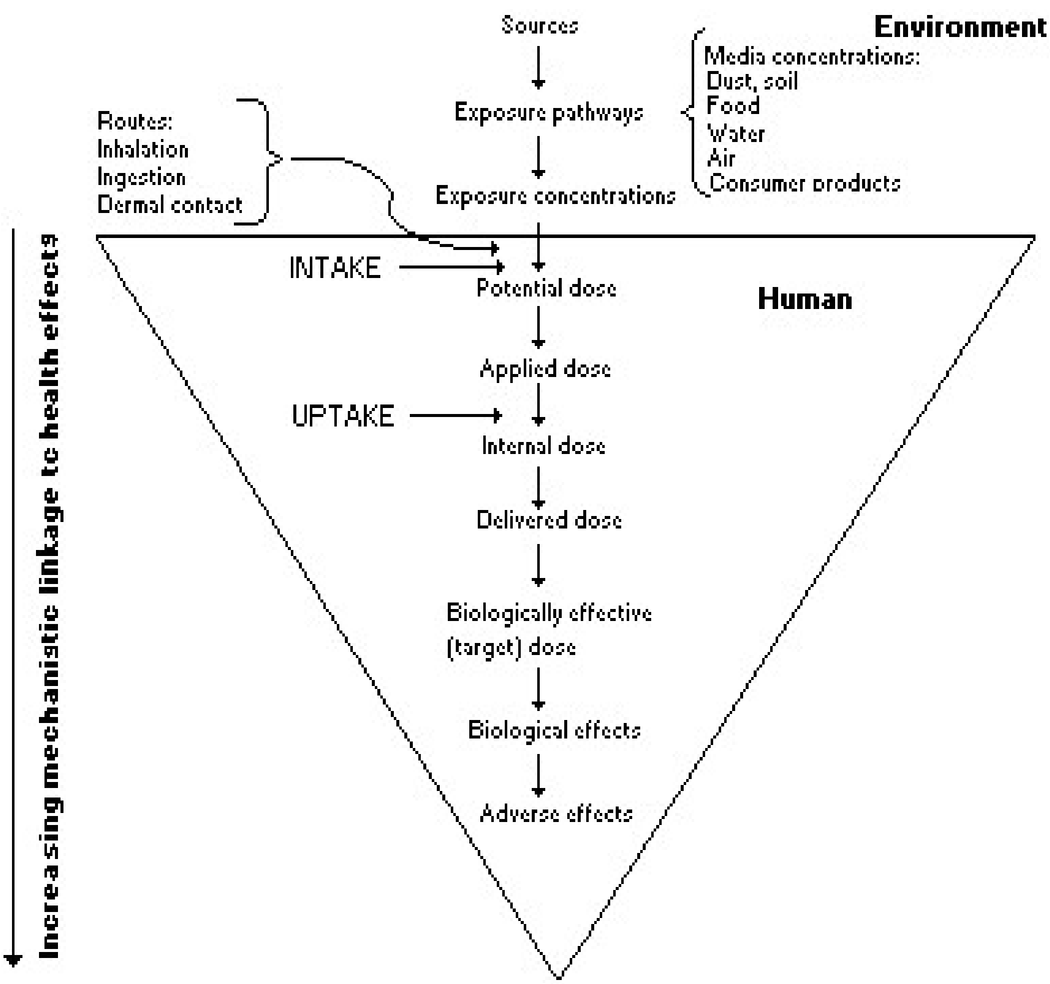
7.4 EXPOSURE ASSESSMENT

7.4.1 Exposure measurement and estimations

Exposure assessment refers to the measurement or estimation of intake of a chemical into the human body. This may be measured within the breathing zone of an individual for volatiles or from a static location as undertaken in population studies of exposure. This may also be estimated using exposure equations and exposure factors associated with those equations. A representation of the role of exposure in environmental health is presented in Figure 9.

The latter were based on inhalation rates and bodyweight once the atmospheric concentrations were known. More recently, changes in inhalation dosimetry brought about by concerns over child susceptibility and increased internal dose (see Ginsberg et al., 2008) has led to reviews in how inhalation doses are calculated (see Turczynowicz et al., 2012, pp996-999 for additional discussion). This US EPA position led to changes in inhalation assessment from that originally proposed (US EPA 1994). Status reports on inhalation dosimetry were produced in 2009 and 2011 (US EPA, 2009; 2011a) with a final position paper in 2012 for risk assessment purposes (US EPA, 2012). While this updated review is focused on chronic inhalation reference concentrations, the derivation of acute reference concentrations is contained within OECD guidance (OECD, 2011). Current US EPA guidance (US EPA 2009a (RAGS F), (adopted by enHealth 2012a, p52) now considers the use of an exposure concentration and duration calculation rather than the use of inhalation and body weight calculations. This is on the premise that dosimetry considerations as presented in US EPA (2009) have been included in the derivation of the chronic reference inhalation concentration of interest.

Figure 9: The role of exposure in the environmental health framework (from IPCS,1999)



In considering exposure assessment, a range of issues should be reviewed and these have been presented at the beginning of this document as a series of questions.

7.4.2 Environmental and COPC parameters and exposure factors

Environmental parameters reflect those input variables used in modelling that describe soil properties (e.g. soil porosity, organic carbon content, bulk density, moisture content, soil permeability) while COPC parameters include those related to physico-chemical properties such as volatility measures, diffusion coefficients in soil or water; soil, water and air degradation rates and aqueous solubility which will affect fate and transport in the environment. The other group of environmental parameters include building characteristics such as area, volume, structural design (stilt elevation, concrete slab, suspended floor, waffle pods, foundation/floor; double brick/brick veneer/timber), ventilation rates, pressure differentials, multiple levels, stairwells, lift wells, internal atria, cooling and heating systems and location (meteorological factors).

Exposure factors are those related to the population of interest such as population demographics, activity patterns, residence time, inhalation rate (when applicable), bodyweight (when applicable), inhalation sensitivity adjustments for children, uptake factors (where available), background exposures and sensitive sub-populations. While some of these are not specific variables in exposure equations they are factors required for consideration in exposure.

7.4.2.1 Site-specificity and representativeness

There is a substantial body of published literature across exposure assessment parameters including those associated with the COPC (from physical/chemical databases); across soil (soil science databases, regulatory standards and publications) and across building characteristics (Federal government and other surveys, peer-reviewed literature).

In the case of exposure factors for populations both enHealth (2012b) and US EPA (2011a) have developed comprehensive exposure factors handbooks. The US EPA (2009b) also prepared a child-specific exposure factors publication in view of concerns regarding childhood susceptibilities to environmental toxicants.

Across this plethora of data, it is important to ensure that all parameters are representative of site-specific and region-specific conditions. They should be representative of site conditions and the population group that warrants public health protection and if there are residual uncertainties the ‘precautionary principle’ should apply and conservative estimates presented. This level of protection should be ensured until residual conservatism can be reduced with the acquisition of new data from peer-reviewed scientific research.

These exposure assessment factors represent point-in-time analyses and it is important that the influences of changes over time across parameters (particularly environmental factors) be reviewed and discussed.

7.4.2.2 Point estimates (deterministic) and population distributions (probabilistic)

Exposure factors may be point estimates (one value representing a factor) referred to as deterministic while a range of values across the population for a factor may also be used and this is called probabilistic.

Concerns over compounded conservatism in the use of single values (NEPC, 1999 as amended, Volume 5, p15) has tended to lead to the use of a distribution of values across the population for that factor in order to refine and reduce such conservatism. This is highly dependent on the availability of that data for a region or country. In Australia these data are not readily available. However, it would be anticipated that future research may allow such data to become available.

The use of internationally available population distribution exposure factor data should be used with caution and reviewed against local population demographics with suitable justification if used. Techniques such as Monte Carlo analysis may be used to “*assess and manage uncertainty, inter-individual heterogeneity and other sources of variability*” enHealth, 2012a, p14) and are further explored in enHealth 2012a, pp154-160).

A review of the variability of point estimates and their impact on the exposure outcome (sensitivity analysis) in addition to concurrent review of the exposure setting and its plausibility may be sufficient to reduce inherent conservatism.

7.4.2.3 Sensitivity, variability and uncertainty in exposure assessment

Variability reflects true differences in attributes due to diversity or heterogeneity and cannot be reduced by further measurement or study (NRC 2008 as cited in enHealth, 2012a). In contrast uncertainty is the lack of knowledge about the correct exposure factor value while sensitivity analysis is a qualitative and quantitative tool to ascertain the impact on the exposure by a single factor while all others are held constant. The latter enables an understanding of the range of exposure outputs across an exposure factor (quantitative) or enables identification of the exposure factor that has the greatest impact on the exposure, i.e. the most sensitive exposure factor (qualitative). Further discussion is presented in enHealth (2012a, p85).

Issues to consider across environmental, COPC parameters and exposure factors have been presented at the beginning of this document as a series of questions.

7.5 RISK CHARACTERISATION

Risk characterization reflects the expression of the evaluation of the conceptual site model of exposure, toxicological review of the relevant COPC and subsequent exposure estimates to produce a measure for the human health risk. It is thus the final integrative step of risk assessment.

It may be estimated using margins of safety indices such as the Hazard Quotient which is a ratio of pathway- and chemical-specific estimated intake to acceptable intake (threshold substances) with the HQ sum of the pathways reflecting the Hazard Index (target of unity). In the case of non-threshold substances, the risk estimate is presented as a probability of disease in a population at a certain exposure concentration which is compared against an ‘acceptable’ probability. The latter may also be expressed in terms of a benchmark dose such that an exposure intake is compared against an intake reflecting 5% or 10% in the population based on low dose extrapolation modelling and the application of uncertainty factors to the dose (See Filipsson etal., 2003).

“*A good risk characterization will restate the scope of the assessment, express results clearly, articulate major assumptions and uncertainties, identify reasonable alternative interpretations and separate scientific conclusions from policy judgements*”. (US EPA, 2011b, as cited in US EPA, 2014b).

US EPA (2014b) consider the following principles to be consistent with their risk characterization policy – transparency; clarity; consistency and reasonableness.

A risk characterization may be qualitative or quantitative in nature and describe the assumptions and uncertainties on which it has been based.

Factors to consider include the degree of confidence in the assessment outcomes; method of delivering results to affected parties; any residual issues; additional information requirements for improved confidence and what level of information is sufficient for provision to risk managers.

7.6 Biological monitoring

Biological monitoring is a "*measuring procedure whereby validated indicators of the uptake of contaminants, or their metabolites, and people's individual responses are determined and interpreted*" (enHealth 2012a, p161).

Biological monitoring therefore provides information on the uptake of a chemical into the body and is an integrated measure of combined environmental exposures. It provides a direct indication of exposure and potential effects if those relationships have been established. Langley (1991) suggested that, if practical, such monitoring is more valuable in determining the level of risk from environmental contaminants as it measures current exposure and its degree.

Further information regarding pre-requisites for biological monitoring, planning, conduct and interpretation of results are presented in enHealth (2012a, pp161-168).

While biological monitoring or biomonitoring is an integral part of occupational health practice (see Manno et al., 2010) in environmental health it is more commonly undertaken as part of population health data baseline studies such as NHANES, although more recently the use of such data has been suggested for chemical risk assessment (Sobus et al., 2015). Swartjes (2015), in specific reference to contaminated sites, suggests that although there are a number of constraints in biomonitoring it can be applied in specific cases. For example, in Adelaide, South Australia the health risk assessment of public housing tenants who had lived on a gasworks site also included the assessment of urinary 1-hydroxy-pyrene as an index of exposure to polycyclic aromatic compounds (Turczynowicz et al., 2007a).

The use of biomonitoring has also been incorporated as part of a multiple lines of evidence evaluation of environmental health risk by adopting Bayesian Markov Chain Monte Carlo methods to an integration of human health risk assessment, biomonitoring and epidemiological data (Schleier III et al., 2015).

With the availability of biomonitoring protocols for volatile hydrocarbons, further research is required for Australian conditions in order to provide an integrated approach to vapour intrusion risk assessment.

7.7 Environmental epidemiology

"*Epidemiology is the study of the distribution and determinants of health-related states or events (including disease), and the application of this study to the control of diseases and other health problems*" (WHO, 2016)

Epidemiology and toxicology are considered complementary in risk assessment (enHealth 2012a) and epidemiology may be environmental or occupational in nature with the former based on community settings and the latter on workplaces.

enHealth (2012a, p119, based on Moolgavkar et al., 1(999)) refer to four main categories in environmental epidemiological studies, being case-control studies; cross-sectional studies; cohort or longitudinal studies and ecological studies (containing a sub-group referred to as time-series studies).

Epidemiological studies are considered as part of human dose-response data which also includes case reports and controlled exposure studies (with substances that produce reversible short-term effects). The study designs in epidemiology most likely to contain useful dose-response data are either case-control studies (population chosen on the basis of illness and exposures followed) or cohort studies where the population is selected on the basis of exposure (Grassman et al., (1998)).

Epidemiological data regarding the impacts of contaminated sites on populations are limited. The case control study by Steffen et al., (2004) and exploratory community study by Forand et al., (2014) were mentioned in Section 5.3.2 and these are specific to vapour inhalation exposures. Pirastu et al., (2013) reviewed environment and health in contaminated sites for the region of Taranto in Italy and reported excesses in mortality and morbidity in residents living in districts close to the industrial area. Martuzzi et al., (2014), further suggest that there is a growing body of evidence on the human health impacts even considering the challenges in such evaluations. As Europe has some hundreds of thousands of contaminated sites, the authors support the need for sustained efforts and resource development to meet these challenges.

In Australia, environmental epidemiological studies associated with contaminated sites and particularly vapour intrusion, have not been researched or published and the impact on the population is not known. It is considered that research efforts towards these challenges be considered to ensure resources in contaminated site assessments are efficiently directed.

8 VAPOUR INTRUSION ASSESSMENT METHODS

8.1 THE DIFFERENCES BETWEEN LANDFILL GAS AND NON-LANDFILL ASSESSMENTS

There are differences in terms of the hazardous substances involved such that the inherent toxicity and exposure potential results in alternative assessment approaches to gases and vapours arising from landfill sites and vapours that arise from subsurface contamination of soils or groundwater.

These differences are associated with the physico-chemical properties of the volatiles involved and the heterogeneity of undisturbed soils as opposed to the heterogeneity of disturbed soils as found in landfills. In the former, contamination arises from spills/losses onto surface soils with migration to the groundwater table or from leaks of underground storage tanks with passage through soil below the tank into groundwater. Generally, these soils are undisturbed with the local geology defining the stratigraphy with relative compaction. Preferential pathways tend to be limited to soil shrinkage, alluvial deposits or other permeable layers or the installation of service lines. Vapour intrusion processes thus involve predominantly diffusion with advection (1) along preferential pathways due to pressure differentials or (2) near to the surface due to barometric pumping. Volatiles associated with site contamination tend to be petroleum hydrocarbons, chlorinated hydrocarbons and commonly used organic solvents, (e.g. methyl ethyl ketone). Assessment processes may involve predictive vapour intrusion modelling, measurement across transport compartments and the determination of indoor air exposure concentrations enabling human health risks to be estimated. The international consensus is currently to adopt a multiple lines of evidence approach.

In the case of landfill sites, an excavation or natural gully may be infilled, with differing types of wastes such as putrescible wastes, sewage sludge, reclaimed wetlands materials, hazardous wastes and foundry sands as some examples (refer NSW EPA, (2012), Table 1, pp5-6). This diverse range of wastes may subsequently produce ground gases such as:

- Methane
- Carbon dioxide
- Carbon monoxide
- Hydrogen
- Hydrogen sulphide
- Radon
- Mercury vapour
- Volatile petroleum hydrocarbons (individual compounds and mixtures)
- Volatile organic compounds (from NSW EPA 2012, p2).

Landfills exhibit a greater opportunity for advective processes rather than diffusion due to a greater range of contaminant vapours and gases that are low molecular weight hydrocarbons and inorganic gases. This diversity of low molecular weight elements and compounds exhibit high volatility and may be generated in large quantities over a long period of time, e.g. methane. In addition, the acute risks of fire, explosion and asphyxiation prevail and tend to dominate the assessment process taking into account the acute toxicity of some inorganic gases such as hydrogen sulphide. The heterogeneity within the landfill sub-surface combined with this advective migration potential result in assessment methods which are focused on measurement of gas concentrations and volumetric flow and the development of gas screening values (GSVs) (see NSW EPA; Wilson et al., 2007). This also includes the usual desktop history, site inspections, CSM development and multiple lines of evidence characterization process similar to the evaluation of volatiles-impacted contaminated sites.

8.2 VAPOUR INTRUSION/HAZARDOUS GASES RISK ASSESSMENT FRAMEWORKS

There is a diversity of frameworks presented throughout the regulatory and published literature and these have differing objectives depending on jurisdictional and public expectations. Three frameworks have been presented to attempt to capture the breadth of the areas that require assessment.

Figure 10 provides some perspective in terms of an extension of the basic risk assessment framework towards vapour intrusion exposure assessment which captures three key elements. These include the following:

- Determination of the vapour concentration at the building boundary based on sub-surface fate and transport models and measurement protocols. This area of investigation has been fundamental and extensive, being a main focus of international investigations and peer-reviewed publications.
- Determination of changes in indoor volatile concentrations in space and over time. The dynamics of vapour entry, distribution and elimination processes within a building is a non-steady-state condition. There are rapid changes in surface flux through the lower building boundary due to pressure differentials, non-homogeneous vapour distribution within the house, and peaks and troughs associated with volatile concentration measurements throughout the house due to meteorological influences. These also occur over differing seasonal conditions. While ventilation modelling and assessment have been undertaken for sustainability evaluations (thermal comfort, energy ratings) these types of investigation have had limited application to vapour intrusion assessment. Further work in this area is required.
- Determination of absorbed doses over time is the fundamental assessment requirement. The use of averaged indoor air target concentrations (over various periods) does not reflect the time-dependent dosimetry that occurs in vapour intrusion. While some advances in inhalation dosimetry have been made, the question remains over whether or not peak exposures at ‘critical windows of opportunity’ for specific toxicology outcomes play a part in adverse population health outcomes for specific sub-populations. This question is a matter for debate and further research.

Figure 10: Sub-surface fate and transport, ventilation and inhalation dosimetry within the human health risk assessment framework (from Turczynowicz, Pisaniello and Wiliamson, 2012)

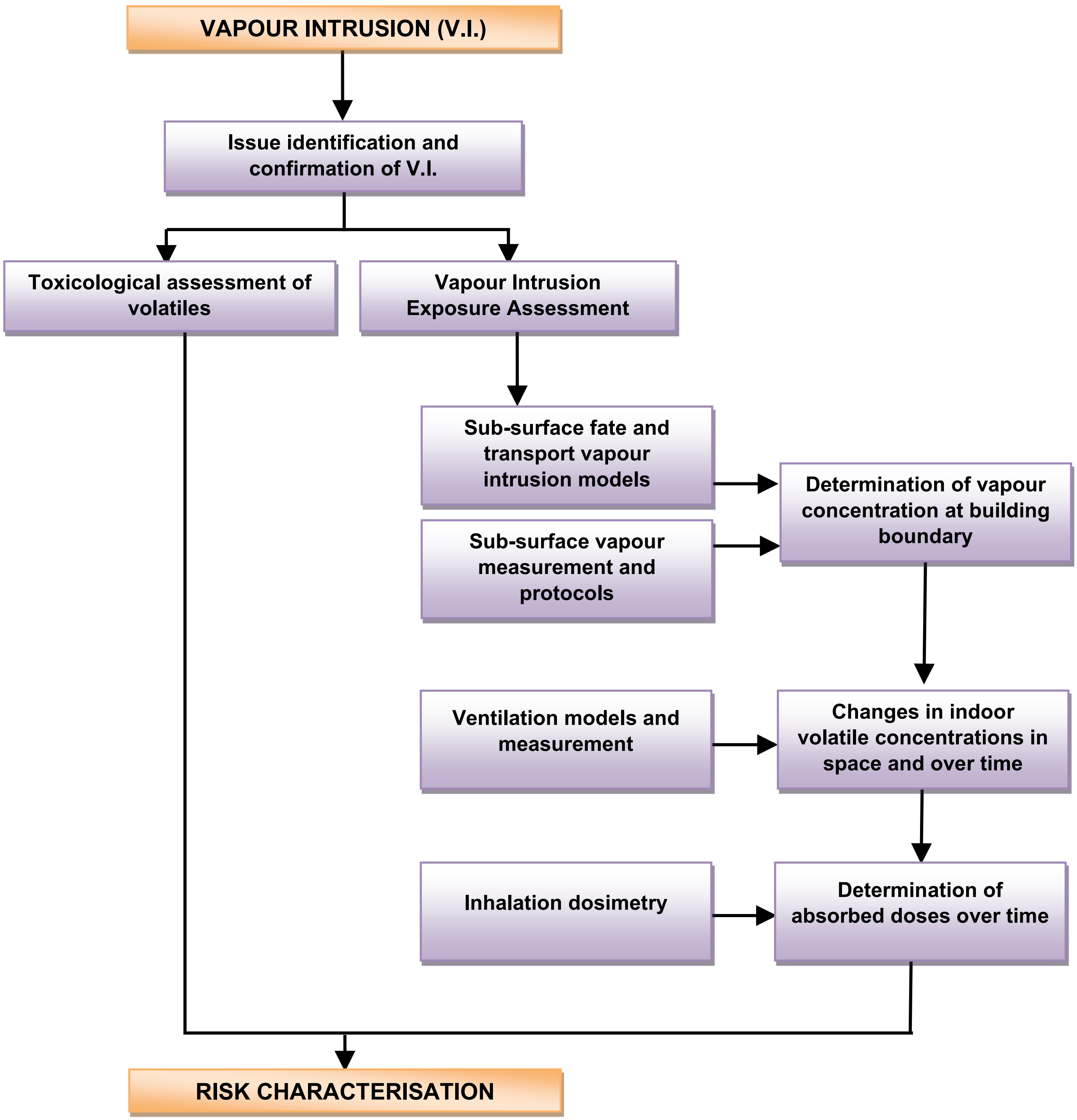


Figure 11 represents a general framework for planning, scoping and conducting vapour intrusion investigations as presented by US EPA (2015) in its most recent OSWER guidance. This focusses on risk-based decision making with community involvement from the commencement of investigations. The outcome of the framework is to conduct and interpret a health risk assessment taking into consideration the CSM; the prioritization of objectives; establishment of data quality objectives, the scoping and work plan associated with data collection, subsequent refinement of the CSM and the evaluation of the data.

Figure 12 represents a management framework for hazardous ground gases from the United Kingdom (Wilson et al., 2007). This encompasses all phases of the process from site characterization to risk assessment and then to the determination and validation of remediation efforts.

Note that across all these figures, for each respective phase depicted, there are multiple layers of evaluation that can be expanded upon as considered and referenced in the US EPA (2015) framework and document.

It is important to recognize that the key to successful delivery in any assessment, is the detail and uncertainty understanding that enables confidence in the determinations of exposure and risk. This confidence can only be achieved if preliminary planning is comprehensive and robust, particularly where time constraints may not allow re-visitation to the site and additional testing to be undertaken.

Figure 11: General Framework from US EPA (2015)

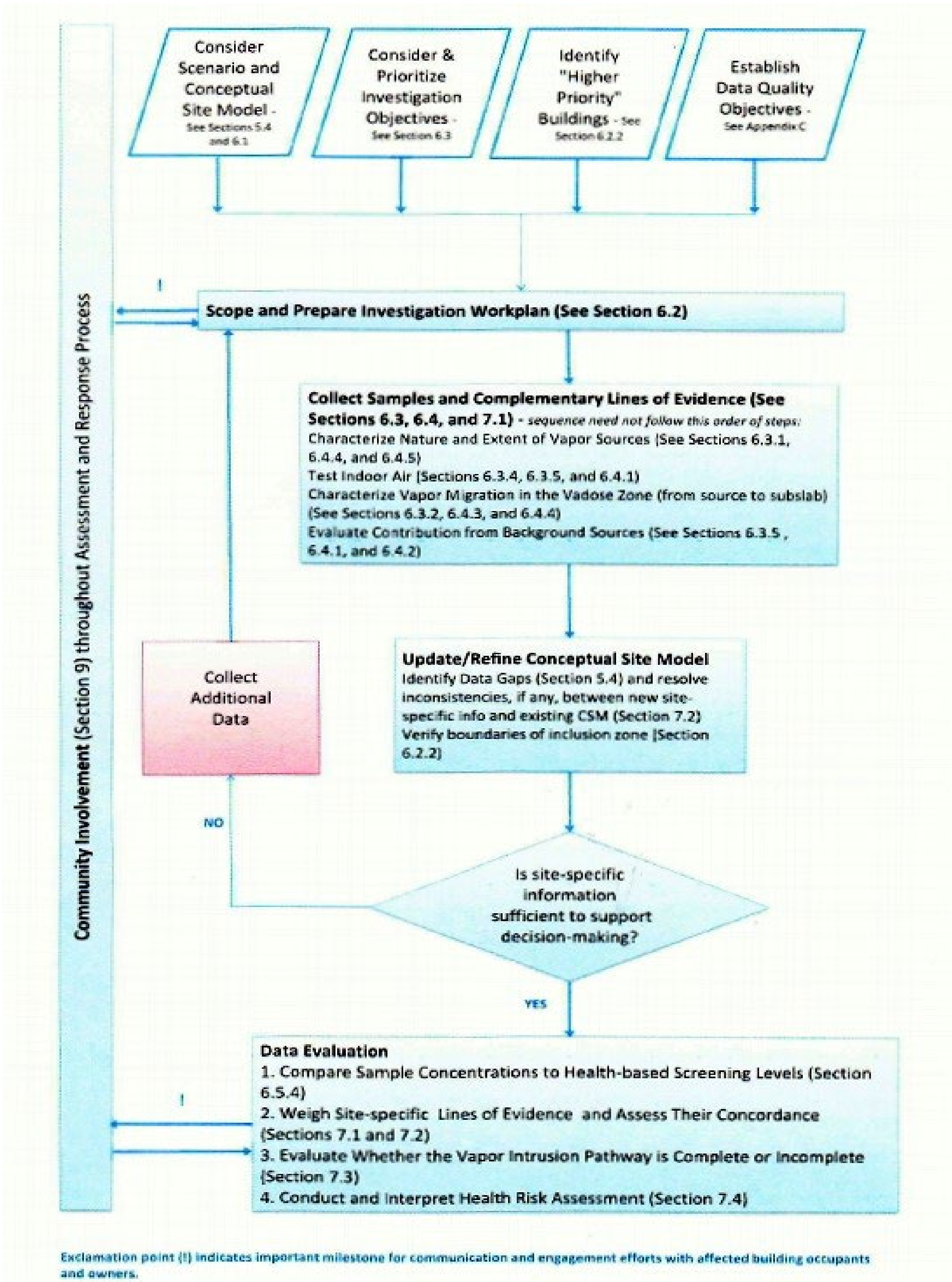
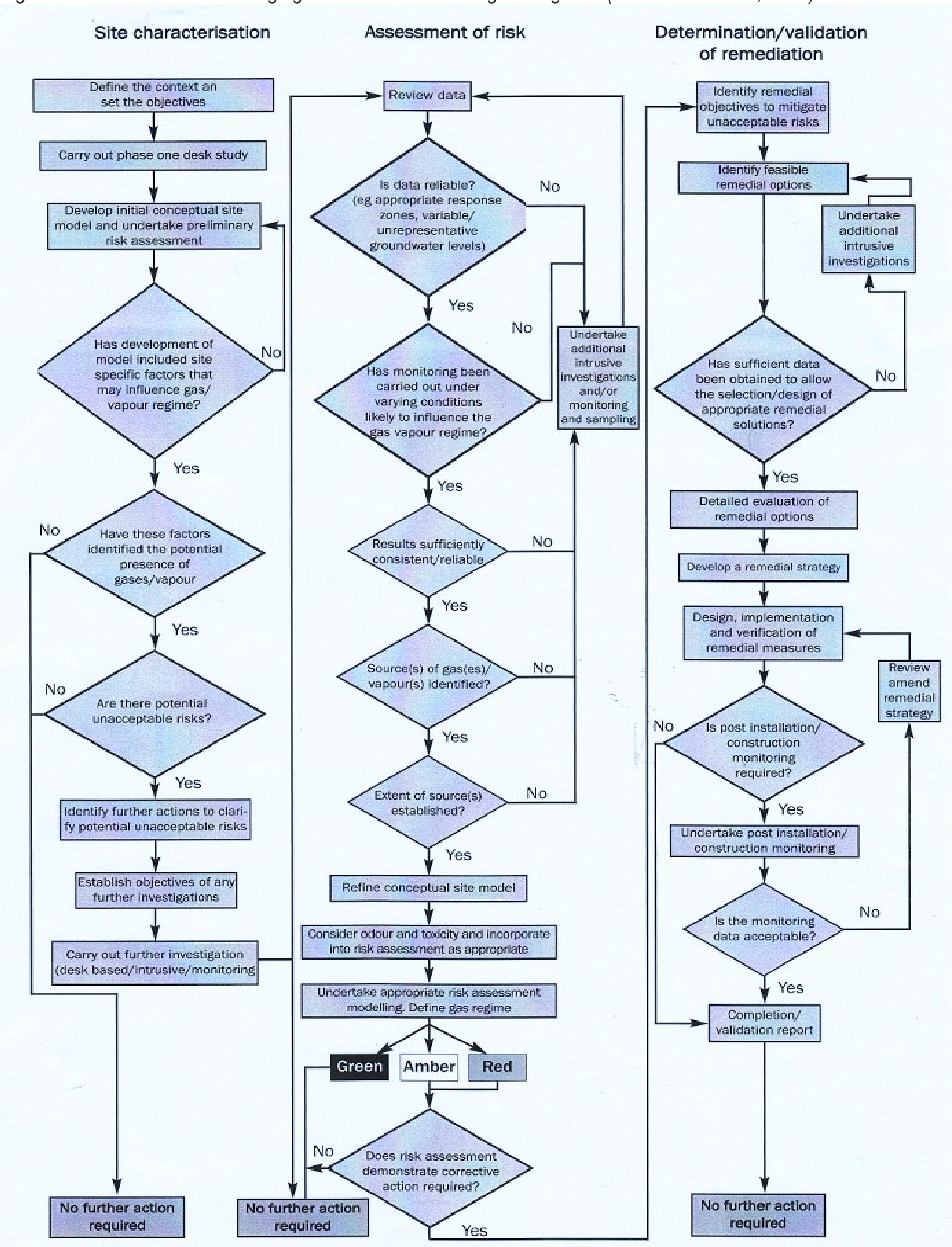


Figure 12: Framework for managing risks from hazardous ground gases (from Wilson et al., 2007)



8.3 PREDICTIVE VAPOUR INTRUSION MODELLING

8.3.1 The role of vapour intrusion modelling

Vapour intrusion modelling plays an important role in preliminary evaluations when site-specific data may be lacking and aids in developing the understanding at the site-specific level. In undertaking vapour intrusion modelling the purpose and objectives of the exercise should be clearly understood and structured, to enable appropriate evaluation of the problem being investigated. This understanding enables the determination of suitable input parameters and the inherent limitations and uncertainties to be characterised.

ITRC (2014, p42-43) provides examples of how petroleum vapour intrusion modelling can be used in vapour intrusion and related assessments and these include:

a. "*Site-specific predictive modelling to assess current or future conditions"*. This represents the case where a risk assessment is required or future building construction is planned and an understanding of vapour impacts is required.
b. *"Site-specific modelling to help develop a CSM*." Modelling can aid in understanding the conceptual site model by preliminary generic modelling and then refinement through the use of site-specific input parameters.
c. "*Inverse modelling to develop site-specific clean-up goals*." Modelling can be used in the derivation of site-specific clean-up goals through the use of inverse modelling. Acceptable indoor air concentrations are used to back-calculate the predicted concentrations required in soil gas, soil or groundwater to reach the acceptable indoor air contaminant concentrations.
d. *"Remedial design and selection."* A suitable model can be used to assess oxygen flux flow per unit area to the sub-surface that is required to achieve clean-up goals as part of mitigation management.
e. *"Modelling to support the development of PVI screening criteria and distances."* When differing substances are identified, site-specific vertical screening distances or modified source-to-indoor air ratios may be developed.

As in risk assessment practice, a tiered process may also be used for vapour intrusion modelling. Preliminary modelling using generic data may be undertaken with subsequent refinement depending on the preliminary outcomes and the acquisition of additional site-specific data.

8.3.2 Vapour intrusion models

There are a limited number of vapour intrusion models and not all are commercially or publicly available. Vapour intrusion models are based on steady-state (a constant indoor air concentration prediction) or non-steady-state (time varying prediction) conditions. All of these models are based on specific algorithms and each of them is based on mathematical constructs representing differing scenarios and differing building structures. It is important to understand and recognize what a vapour intrusion model is actually representing before using the model.

There has been progressive review over the last decade of available models and algorithms. Evans et al., (2002) reviewed ten soil vapour transport models including JEM; GSI; British

Columbia (BC); Unocal model; Modified Johnson model; Vapex3 model; Ferguson et al., model and Modified Ferguson model; Volasoil; BPRISC and the Jury model. BPRISC (Johnson and Ettinger sub-model) was recommended for regulatory purposes due to a number of positive attributes albeit with noted limitations.

Further reviews of vapour intrusion models include those of Tillman and Weaver (2005) and Turczynowicz and Robinson (2007b) with the latter presenting a tabulated summary of software and algorithms (Table 1, p1623). Turczynowicz and Robinson (2007b) also present a summary table of the attributes of some soil to indoor VOC migration models (Table 1).

A review of seven algorithms presented by Provoost et al., (2009) cited Vlier-Humaan (Belgium); JEM (USA); Volasoil (Netherlands); Csoil (Netherlands); RISC (UK) and the dilution factor models from Norway and Sweden. Provoost noted that, "*For the indoor air it is concluded that all algorithms have a tendency to overestimate the predicted indoor air concentrations except for the JEM and Vlier-Humaan algorithms, which produced frequent underestimations*" (Provoost et al., (2009) p25). Provoost et al., 2009, concluded that the most suitable algorithms for screening purposes were Csoil, Volasoil and RISC since "*they are sufficiently conservative, have fewer false negative predictions and have still sufficient discriminatory power*" (p25).

Davis et al., (2009) in a review for CRC CARE of an Australian non-steady-state vapour intrusion model (Robinson, 2003) and the JEM recommended the JEM principally due to the historical support behind the model such as field studies, ready availability and lack of need for further development (time frames in developing generic petroleum hydrocarbon criteria at that time were limited).

Further recent discussion on the available vapour intrusion algorithms can be found in the comprehensive review in Provoost, Tillman, Weaver et al., (2010) and Provoost et al., (2013) and Yao et al., (2013).

ITRC (2014) and US EPA (Weaver, 2012) have recently included the Biovapor model, a one-dimensional similar to JEM but with the inclusion of aerobic biodegradation (DeVaull, 2007; API 2010). This model is based on estimation of O_2-limited aerobic degradation using an analytical solution to determine the aerobic depth below ground surface where first order occurs. Without the biodegradation component it produces similar results to JEM (ITRC, 2014). Note that the Biovapour model has been developed for petroleum hydrocarbon vapour assessment where aerobic biodegradation is an important factor.

In considering the current position in differing countries with respect to available vapour intrusion models the predominance of any particular model is a reflection of the funding and support for development within that country in order to ensure region-specific applicability. This is particularly noted with CSoil and Volasoil development in the Netherlands with field studies and refinement over a number of years and the support for JEM evaluations and investigations following adoption in the US by The US EPA (with modification). This funding and support in Australia has been lacking and Australia has not progressed in further vapour intrusion model development since 2003.

Table 1: Attributes of Some Soil to Indoor VOC Migration Models (from Turczynowicz and Robinson, 2007)

Attributes of Some Soil to Indoor VOC Migration Models

Attribute	Australian, CSIRO	Dutch, VOLASOIL	United Kingdom, Ferguson	United States, Johnson-Ettinger
Soil migration				
Steady-state	√	√	√	√
Time dependent	√	-	-	-
Phase partitioning	√	√	√	√
Free phase[a]	-	-	-	√
One component	√	√	√	√
Multicomponent[a]	-	-	-	√
Multiple layers	√	-	-	-
Subsurface barriers	√	-	-	-
Water table	√	√	-	√
Seepage advection	√	√	-	√
Pressured advection[a]	√	√	√	√
VOC degradation	√	-	-	?
Soil fracture[a]	-	-	-	-
1D model	√	√	√	√
3D model	√	-	-	?
Outdoor air				
Air concentration	√	√	√	√
Boundary layer	√	√	-	-
Indoor air				
Crawl space	√	√	-	-
Basement	-	√	-	√
Concrete slab[a]	√	-	√	√
Suspended concrete[a]	-	-	-	-
VOC degradation	√	-	-	-
Ambient concentration	√	-	-	-
Sources and sinks	√	-	-	-
Ventilation	√	√	√	√
General				
Diurnal effects[a]	-	-	-	-
Seasonal effects[a]	√	-	-	-

Note. ?, Considered but problematic in use.
[a]New or improved modeling required.

Footnote: The Australian CSIRO model is based on the work of Robinson (2003).

8.3.3 Understanding models – verification and validation

Predictive vapour intrusion modelling is an important tool when attempting to estimate future indoor air concentrations in buildings that are yet to be constructed. On this basis its use is necessary while taking into account an understanding of supporting lines of evidence and the uncertainties and limitations across the vapour intrusion models that are available.

Vapour intrusion models are simply an attempt to represent a reality using mathematical representations of the physics involved. Saltelli and Funtowicz (2014) cite the widely quoted observation of pure statisticians epitomized by George E.P. Box's 1987 observation that *'all models are wrong but some are useful*'" (p80). Models are only as 'useful' as their representation of the physical realities. In order to ascertain such 'usefulness' both the programming code and confirmation of the model's prediction are required.

When a model prediction is checked using another model construct, verification of the model is undertaken. Verification is not validation (Robinson, pers. comm.). A number of papers report verification in their analyses which should not be confused with validation.

When field studies are undertaken and site-specific data are incorporated into a vapour intrusion model then validation is undertaken to compare prediction with reality. However, in the case of vapour intrusion models, no vapour intrusion model has been completely field validated. Studies using contaminated sites which have incorporated field measurements into model predictions and then measured indoor concentrations are prone to the effects of heterogeneity and spatial and temporal changes. These are complex settings and control or measurement of all influencing variables is problematic. Synthetic controlled experiments have not been attempted.

Provoost, Tillman, Weaver et al., (2010) in a comprehensive review of vapour intrusion cite that the '*difficulty in evaluating whether or not vapor intrusion is occurring stems from the temporal and spatial variability in soil gas and sub-slab measurements, unknown indoor sources confounding indoor air sampling and a lack of information on the accuracy of algorithms"* (from Tillman and Weaver, 2005).

The subsequent uncertainty associated with the use of predictive models has resulted in significant caution in the application of predictive models. Schuver (2010) reported that "*to a large degree the USEPA has not been using predictive models for making vapor intrusion risk management decisions for some time"* and *"… we have been devoting all available energies to lessons from observational studies"* (p1).

While there are limitations in vapour intrusion modelling, such modelling still plays an important part in vapour intrusion risk assessment, particularly when site development is yet to occur. On this basis, it is therefore important to appreciate the details within such models, what they represent, how they can be used, and the limitations they are associated with.

8.3.4 Using media inputs and predicting indoor air concentrations

Environmental media inputs for vapour intrusion models such as JEM include groundwater concentrations, soil concentrations and soil vapour concentrations. Each of these media concentrations reflect a certain level of uncertainty as follows:

1. Soil contaminant concentrations as inputs to vapour intrusion modelling require equilibrium phase partitioning assumptions which have not aligned with laboratory experiments. Subsequently, using soil concentrations as inputs to vapour intrusion modelling is not recommended (including the development of generic soil screening levels) and has, not been undertaken by the US EPA (Johnson, 2009). This introduces uncertainty to the modelling. On this basis, the preference has been to use soil vapour concentrations as inputs to the modelling.

2. Groundwater contaminant concentrations – vapour intrusion modelling from groundwater is considered to over-estimate the indoor air concentrations due to a lack of

consideration of the capillary fringe zone and its impact on vapour diffusion.
In addition, heterogeneity of contaminant distribution across well sampling locations from which samples are drawn and tested may also influence results. Recently (refer Provoost et al., 2011) the use of Henry's Law partitioning from groundwater to soil air as an accurate tool, based on laboratory experimentation with toluene, has recently been questioned. Pennell et al., (2016) further commented that on the basis of field data and numerical modelling, groundwater concentrations were not an appropriate indicator of vapour intrusion risks for the neighbourhood studied.

Taken collectively while groundwater concentration inputs exhibit some uncertainty based on the above issues the potential to underestimate indoor air concentrations appears limited, principally due to the influence of the capillary fringe zone, however, this needs to be reviewed on a case-by-case basis.

3. Soil vapour concentrations are considered to represent the most appropriate contaminant concentrations as inputs to vapour intrusion modelling as they inherently address the partitioning assumptions. They are however, prone to spatial and temporal change with the latter of greater concern closer to the surface. Soil vapour profiling, however, is a useful tool in the examination of the attenuation of vapours with depth, provided the soil vapour sampling is undertaken consistent with validated techniques.

8.3.5 Uncertainty, variability and sensitivity in vapour intrusion modelling

A sensitive model variable or parameter is one whose variance has the greatest impact on the model outcome (in this case a predicted indoor air concentration). Uncertainty reflects precision in the way a variable is measured while variability is the naturally expected variation. Uncertainty can be considered using a probability distribution and one can improve this by gathering more data, however, variability is inherent in the system and cannot be eliminated by gathering more information (see Provoost et al., 2014)

A number of authors have examined the sensitivity of vapour models with generally consistent results.

Tillman and Weaver (2005, p31) in examining the JEM undertook an "*automated uncertainty analysis that accounted for synergism across model input parameters, identified the nonlinearity of the JEM equation and subsequent response to parameter variation (with a skew toward increased risk) and the limitations of a "one-at-a-time" uncertainty analysis (increased model uncertainty compared to grouped variable analysis). Of particular interest was the finding that the air exchange rate was ranked as "the single most sensitive input parameter of the model" (Weaver & Tillman, 2005, p. 31)*" (from Turczynowicz and Robinson, 2007, p1624).

Turczynowicz and Robinson (2001) in the development of a non-steady state model for a crawl space house found that variance in house parameters were the greatest contribution to the changes in the cumulative indoor human dose (CIHD). Recently Moradi et al., (2015) reported that results from a global sensitivity analysis technique based on Sobol indices used to evaluate the JEM found that building air exchange rate, regardless of soil type and soil depth was the most sensitive model parameter.

Provoost et al., (2014) in a probabilistic risk assessment examined uncertainty and variability across parameters for six vapour intrusion algorithms. These parameters were grouped into those that were uncertain and those that were variable and field data was drawn from two well documented sites to contrast predictions and observations. Deterministic and probabilistic approaches were used. The authors reported that a clear trend in the contribution of parameters to indoor air concentrations between algorithms or contaminants could not be established. Furthermore, the sensitivity analysis revealed that depending on the algorithms and contaminants, different parameters drive the variation in the indoor air concentration; and consistent with Fisher et al., (2002) they recommend using more than one algorithm to account for uncertainty and variability.

8.3.6 Limitations of available vapour intrusion models

There are a range of limitations across vapour intrusion models that have been described by various authors and may be summarized as follows:

- Lack of complete field validation.
- Do not account for spatial and temporal change.
- Do not account for aerobic or anaerobic degradation (some of these may result in increased human health risks).
- Partitioning assumptions from soil and groundwater may not reflect reality and are not consistent with field or laboratory observations.
- Partitioning characteristics of phase separated hydrocarbons not understood.
- Some variables are difficult to measure or unmeasurable (e.g. crack distribution, geometry and flow through cracks).
- Do not account for meteorological influences on air exchange rates.
- Do not account for reversibility of pressure gradients or differential flux through the surface.
- Do not account for soil heterogeneity.
- Do not account for climatic factors and all building designs.
- Do not incorporate ventilation or inhalation dosimetry models.
- Do not account for preferential pathways.
- Do not account for the influences of water tables.
- Do not consider mixtures.

These limitations provide perspective to the uncertainties and variability that occurs and recognition that model outputs are not absolute measures of exposures.

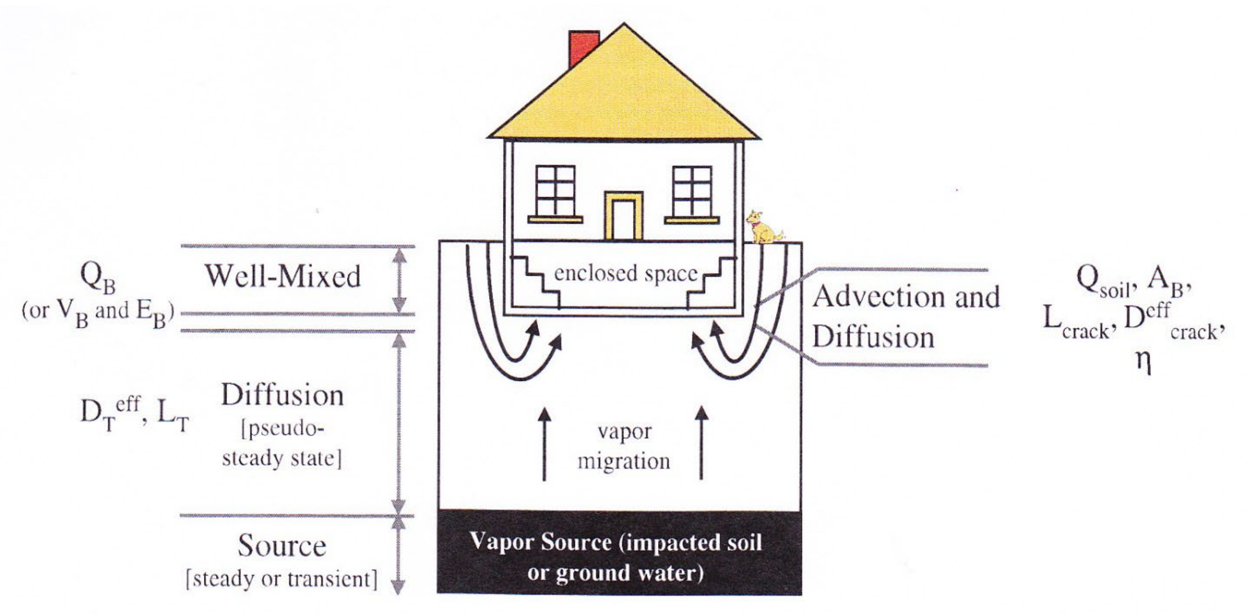
USA EPA (2015) in discussing principles and recommendations for mathematical modelling (p113) suggest that "*when suitable constructed, documented and verified, mathematical models can provide an acceptable line of evidence supporting risk management decisions pertaining to vapor intrusion*". However, US EPA (2015) consider that modelling should be used in conjunction with other lines of evidence and are useful when used to verify magnitudes; explore the range of outcomes through uncertainty analysis and generate bounding estimates.

8.3.7 Vapour intrusion input parameters

This discussion is focused towards the JEM and variants due to its widespread use in Australia but information is also applicable across other vapour intrusion models.

Input parameters may be grouped across environmental properties (soil properties, source depth), physico-chemical contaminant properties (e.g. vapour diffusion coefficients, Henry's Constant), and building properties (e.g. volume, area, air exchange rate). Johnson (2005), in providing commentary on application-specific critical inputs, considers eight primary model inputs and thirteen secondary inputs. The model characterization is as depicted in Figure 13.

Figure 13: J&E Conceptual Model showing primary model inputs and system components (from Johnson 2005)



In terms of the primary inputs and reasonable values these have been suggested by Johnson (2005) and are reproduced from his paper in Table 2 being based on a combination of literature, physical constraints and experience. Note that Johnson (2005) states that his model is only designed to generate the attenuation factor (α) which is the ratio of the predicted indoor air concentration ton the estimated soil vapour at a specific depth. A number of software packages (e.g. BPRISC) and structured spreadsheets extend this ratio to the predicted steady-state indoor air concentration over the period of interest.

Primary inputs reflect the key variables as depicted in Figure 13. Secondary input components include additional parameters as presented in Table 3 as reproduced from Johnson (2005, p72).

Note that the effective diffusion coefficients are dependent on moisture saturation and total porosity relationships and these relationships are outlined in Figure 3 of Johnson (2005, p71). It is important to note that the inter-relationships between some variables need to be understood to ensure that realistic values are used as JEM inputs.

The reference to Parameters A. B and C in Table 3 refer to the elements of the J&E algorithm:

$$\alpha = \frac{[A]\exp(B)}{\exp(B) + [A] + \left[\frac{A}{C}\right](\exp(B) - 1)}$$

Table 2: Johnson (2005) recommendations for reasonable primary input values

Primary Input	Definition	Reasonable Range	Comments	References
Inputs reasonably estimated from available site assessment data				
L_T	Depth from foundation to the vapor source or other point of interest [m]	0.01–50 m	To be determined from site assessment data, sampling depths, or defined scenario	Experience
Inputs reasonably estimated from experience and intuition				
(V_B/A_B)	Ratio of enclosed space volume to exposed surface area [m]	2–3 m (could be larger if entire building is well mixed)	Approximately equal to the height of the enclosed space (e.g., basement height or height of first-floor room for slab-on-grade construction)	Experience
L_{crack}	Foundation thickness [m]	0.15–0.5 m	Based on typical construction practices	Experience
η	Fraction of surface area with permeable cracks	0.0005–0.005	η = 0.01 (worst case) corresponds to finger-width cracks spaced 1 m apart and running across the floor; η = 0.0003 corresponds roughly to a 0.1-cm floor-wall seam perimeter crack around a 225-m^2 area	Intuition and Eaton and Scott (1984)
E_B	Indoor air exchange rate [d^{-1}]	4.8–24	Based on building ventilation/ energy efficiency studies	ASHRAE (1985); Koontz and Rector (1995)
Inputs reasonably estimated indirectly from literature data				
Q_{soil}/Q_B	Ratio of the soil-gas intrusion rate to the building ventilation rate	0.01–0.0001	Based on vapor attenuation coefficients reported for radon studies and contaminant vapor intrusion case studies	Mose and Mushrush (1999); Fischer et al. (1996); Little et al. (1992); Olson and Corsi (2001); Fitzpatrick and Fitzgerald (1996)
Inputs reasonably estimated from correlations and secondary inputs				
D_T^{eff}	Effective overall vapor-phase diffusion coefficient between $z = L_T$ and the foundation	Figure 3	Necessary to use empirical correlations and secondary inputs—Equations 2 and 3	Brooks and Corey (1966); Carsel and Parrish (1988); Johnson and Ettinger (1991)
D_{crack}^{eff}	Effective overall vapor-phase diffusion coefficient through foundation cracks	Figure 3	Necessary to use empirical correlations and secondary inputs—Equations 2 and 3	Brooks and Corey (1966); Carsel and Parrish (1988); Johnson and Ettinger (1991)

[1]In this work, a reasonable range is one that spans the range of values representative of most sites: the reasonable range does not include extreme or unlikely values: therefore, for some sites, the appropriate values might fall outside of these ranges.

where

$$A = \left[\frac{D_T^{eff} A_B}{Q_B L_T}\right],\ B = \left[\frac{Q_{soil} L_{crack}}{D_{crack}^{eff} \eta A_B}\right],\ C = \left[\frac{Q_{soil}}{Q_B}\right]$$

and

A is the vapour attenuation coefficient where there is no foundation.

B is a measure of the relative significance of advection and diffusion for transport across the building foundation (B>>1: advection; B<<1: diffusion).

C is equal to the vapour attenuation coefficient for vapours immediately below the foundation and indoor air provided B>>1.

Table 3: Example inputs and outputs across 4 scenarios from Johnson (2005)

Primary Input	Secondary Input	Units	Scenario 1, Shallow Soil-Gas Source	Scenario 2, Shallow Ground Water Source	Scenario 3, Deep Soil-Gas Source	Scenario 4, Deep Ground Water Source
V_B/A_B	—	[m]	2.4	2.4	2.4	2.4
L_{crack}	—	[m]	0.15	0.15	0.15	0.15
η	—	[m^2-cracks/m^2-total]	0.001	0.001	0.0005	0.0005
Q_{soil}/Q_B	—	[dim]	0.01	0.01	0.001	0.001
E_B	—	[d^{-1}]	14	14	20	20
L_T	—	[m]	0.2	0.2	10	10
	θ_T	[m^3-voids/m^3-soil]	0.3	0.3	0.3	0.3
	S_m	[dim]	0.1	0.1	0.1	0.1
	H_i	[m^3-H$_2$O/m^3-air]	0.1	0.1	0.1	0.1
	D^{air}	[m^2/d]	1.0	1.0	1.0	1.0
	D^{H_2O}	[m^2/d]	10^{-4}	10^{-4}	10^{-4}	10^{-4}
D_{crack}^{eff}		[m^2/d]	0.14	0.14	0.14	0.14
	θ_T-vadose	[m^3-voids/m^3-soil]	0.3	0.3	0.35	0.35
	S_m-vadose	[dim]	0.1	0.1	0.2	0.2
	θ_T-cap	[m^3-voids/m^3-soil]	NA	0.3	NA	0.4
	S_m-cap	[dim]	NA	0.90	NA	0.90
	L_{cap}	[m]	NA	0.10	NA	0.30
	H_i	[m^3-H$_2$O/m^3-air]	0.1	0.1	0.1	0.1
	D^{air}	[m^2/d]	1.0	1.0	1.0	1.0
	D^{H_2O}	[m^2/d]	10^{-4}	10^{-4}	10^{-4}	10^{-4}
D_T^{eff}		[m^2/d]	0.14	0.00036	0.14	0.012
		Parameter A	0.02	0.00007	0.00025	0.000019
		Parameter B	360	360	100	100
		Parameter C	0.01	0.01	0.001	0.001
		Critical primary inputs from flowchart	V_B/A_B, L_T, D_T^{eff}, E_B, Q_{soil}/Q_B	V_B/A_B, L_T, D_T^{eff}, E_B	V_B/A_B, L_T, D_T^{eff}, E_B, Q_{soil}/Q_B	V_B/A_B, L_T, D_T^{eff}, E_B
		Noncritical primary inputs from flowchart	L_{crack}, D_{crack}^{eff}, η	L_{crack}, D_{crack}^{eff}, η, Q_{soil}/Q_B	L_{crack}, D_{crack}^{eff}, η	L_{crack}, D_{crack}^{eff}, η, Q_{soil}/Q_B
		α	6.8×10^{-3}	6.9×10^{-5}	2.0×10^{-4}	1.8×10^{-5}

Cap = capillary fringe.

All these parameters require site-specific consideration and application. It is important in considering the selection of inputs that site-specific data be obtained preferably through field measurements but if not available, then alignment with the site characteristics should be attempted. For example, examination of field soil bore logs to confirm geology with subsequent literature associated information on characteristics; geotechnical testing may provide data on soil moisture and soil properties while on-site inspection may provide information on geometries and sources. Johnson (2005) subsequently proposed a generalized flow chart for identifying application-specific critical and non-critical parameters based on calculation of parameters A, B and C (see Figure 2, p68).

Although, the JEM model details have been presented because of widespread use, it should be stressed that there are problems with the model and other models might also be used.

A range of review questions have been presented in the front of this document to aid the reader in the use of vapour intrusion models.

8.4 Measurement and Assessment Methods

8.4.1 Significance of empirical data

It is important to recognise that vapour measurement data contains information that is richer in detail and takes into account processes that modelling currently cannot, particularly in complex systems where spatial and temporal change can influence results. As such, empirical data are highly valued and preferred as a tool in the assessment process. This is evident in the recent US EPA (2015) guidance where the move away from predictive modelling towards understanding changes in transport compartment has occurred with vapour intrusion modelling now considered as a line of evidence provided that they are "…suitably constructed, documented and verified." (p113). Unfortunately, many models do not fulfil such criteria.

In structuring and collecting empirical data it is important that the sampling and analytical procedures meet the data quality objectives set for the investigation and that methods are validated and consistent with the ratifying agency methodologies. Deviations from any standard methodologies need to be validated to ensure they are representative of the objective of the method.

8.4.2 Sampling design

The sampling plan is generally expressed as part of a sampling and quality assurance plan (SAQP) which details:

- The site history and potential site source distribution and nature of COI.
- The objectives of the sampling plan and scope.
- A preliminary conceptual site model subject to iterative development.
- The sampling and analytical techniques to be used and data quality objectives.
- Time frames for sampling durations of vapour and gases.
- The lateral and vertical distribution of sampling locations.
- Methods of drilling and sampling installations.
- Use of generic techniques to identify elevated source concentrations prior to more detailed sampling.
- Methods of interpretation and relevant screening target concentrations for results.

Some of the factors requiring consideration include:

1. Distribution of gas wells, and appropriate instrumentation methods for preferential pathway assessment.
2. Concurrent transport compartment assessment – the dynamic nature of vapour migration increases as one progresses from soil at depth to soil within the top 1.5 m to the sub-slab, to indoor air and to ambient air. There are different gradients applying at different locations such that diffusion-based concentration gradients are replaced by permeability-based pressure differentials leading to indoor entry, distribution and partial elimination processes. These dynamic forces require concurrent or near-concurrent sampling strategies to be employed enabling comparisons of results obtained to be made if relationships are required.

3. Sampling techniques may be passive (diffusion-based matrix) or active (adsorbent-based matrix, evacuated canisters). Which techniques to employ will be a reflection of:
    a. objectives (relative comparisons and “hot-spotting” for delineation purposes to quantitative data for exposure assessment;
    b. Cost
    c. Timeframes for assessment.
    d. Consistency between the COI and the sampling analytical profile and
    e. Required limits of reporting.
4. The evaluation of worst-case scenarios (WCS) and best case scenarios (BCS) and comparisons with the realities of the population of interest and their activity patterns is important. The sampling durations for atmospheric exposure should match the potential population residence times. Settings where closed doors and windows may apply should be considered and sampling within areas or greatest occupancy time.
5. Spatial and temporal variability should be evaluated through concurrent sampling at different sampling locations with a dwelling. Temporal variations in terms of diurnal or seasonal differences should be factored into the sampling program due to published differences in indoor concentrations within the day and across seasons.
6. Delineation methods using rapid techniques, e.g. Geoprobing™ or passive samplers, e.g. Waterloo Membrane Samplers should be considered as these may provide cost-efficient means of determining the nature and extent of soil vapour distribution. This is particularly the case for large sites where the site history presents the potential for extensive contamination. Furthermore, the use of portable GC-MS instrumentation should be considered although such techniques are well established in the US, in Australia they are still considered relatively novel and expensive.

8.4.3 Sampling methods, analysis and assessment

8.4.3.1 Non-landfill vapour and gas

Non-landfill vapour and gas sampling and assessment refer to vapour intrusion processes associated with contaminated soils or groundwater.

Sampling methods across transport compartments have been detailed over a number of recent documents that have addressed field assessment of vapours (Davis et al., 2009); vapour intrusion assessment (CRC CARE, 2013); the fundamentals of screening, investigation and management (ITRC, 2014) and the more recent updated OSWER (US EPA, 2015a) assessment and mitigation guidance.

Davis et al., (2009) discuss vapour and gas sampling (pp29-44) including the use of:

- Temporary spear probes (e.g. GeoProbe™)
- Permanent multi-level probes/samplers.
- On-line VOC and oxygen probes.
- Sub-slab sampling.
- Measurement across the capillary fringe.
- Soil gas sampling issues such as location, depth frequency, probe integrity tubing type, sample volume, purge volumes, sample flow rates, environmental conditions.

- Flux chambers (static and dynamic) and factors to consider such as:
    - Area coverage.
    - Deployment period.
    - Environmental conditions.
    - Differing COIs e.g. petroleum vs chlorinated hydrocarbons.
    - Basements.
    - Changed land form.
    - Sub-surface condition.
- Crawl space and indoor/outdoor air sampling.
- Passive implant sampling.
- Sample collection and analysis.
- Active methods and the range of adsorbent materials (e.g. US EPA TO-17 methods).
- (Evacuated) Canisters (i.e. US EPA TO 14A/TO-15 methods).
- Passive methods.

Across all these methods it is important to understand the conceptual site model, exposure pathways, preferential pathways, transport across the various compartments, the COI and the required limits of reporting. The placement of sampling locations should limit confounding (use of pre-sampling surveys for indoor air sampling and removal of indoor sources) and uncontrollable influences such as shallow <1.5m soil vapour implants that are affected by atmospheric and precipitation infiltration.

Further information on respective sampling practices is also presented in CRC CARE (2013) in Appendices F and G. The CRC CARE documentation, however, is orientated towards petroleum hydrocarbons and any information obtained from those sources should ensure the information is relevant to the volatile compound or substance of interest.

Comprehensive information is available in recent publications from ITRC (2014) and US EPA (2015a). The latter being devoted to all vapour intrusion assessment and not being specifically focused on petroleum hydrocarbons which was the ITRC (2014) objective. US EPA (2015a, pp87-105) present general principles and recommendations for sampling across indoor air, outdoor air, soil gas and groundwater for volatiles but do not recommend bulk soil sampling on the basis of volatile losses during sampling and limited use in vapour intrusion modelling due to uncertainties regarding partitioning assumptions.

Some of the US EPA (2015a) recommendations are as follows:

1. Sampling and analytical methods should be capable of obtaining reliable analytical detection of concentrations less than project appropriate risk-based screening levels (e.g. VISLs) with established site-specific data quality objectives.
2. Sampling locations and durations should take into account spatial and temporal variability for characterization of human exposures.
3. Several rounds of sampling are recommended to develop an understanding of temporal variability in order to "*ensure that final risk management decisions are based upon a consideration of a reasonable maximum vapor intrusion condition*" (p88).

4. Indoor air testing is for the assessment of human health risk and to determine whether vapour intrusion is occurring. It provides a direct approach and time-integrated sampling over appropriate exposure durations are recommended. Due to variability, "*a single indoor air sample collected at a randomly chosen time is insufficient information to estimate an average exposure*" (p89).
5. Indoor air time-integrated samples may be collected using:
    a. Evacuated canisters as described in EPA Methods TO-14A and TO-15. Canisters should be certified clean with flow rates checked periodically during the period of sampling. Variability acceptance rates should be +/- 30% (p90).
    b. Sorbent samplers as used in occupational hygiene. These may include those in active model where air is drawn through the sampler (advection) or those in passive mode based on diffusion of air. The latter have shown good correlation with active techniques provided the limitations of the samplers are understood.
6. Samples should be collected directly above the foundation floor (basement or crawl space) and in the living areas at the breathing level zone height for the most sensitive population. In larger areas consideration should be given based on internal partitions; HVAC layout; sub-surface contaminant distribution; observable entry points, closed rooms.
7. Multiple rounds of indoor air testing are recommended and indoor source identification (e.g. pre-sampling survey) and subsequent removal of identified sources should be undertaken to avoid or minimize confounding. Indoor sources should be removed 24-72 hours prior to the start of sampling.
8. Concurrent sampling should be undertaken for indoor air, sub-slab and outdoor (ambient) air.
9. Grab samples may be used in some cases to examine entry points, identify indoor contributors, and identify indoor vapour intrusion volatiles.
10. Supplementary data that should be collected include:
    a. Building occupancy – occupant characteristics, hours of occupancy- USEPA recommends considering hours of building occupancy when establishing the sampling duration for characterizing indoor air exposures.
    b. Pressure differentials be measured between indoors and sub-slab.
    c. Presence and operation of a mitigation system.
    d. Physical conditions – cracks, drains, crawl spaces, foundation modifications.
    e. Building heating, ventilation and cooling.
    f. HVAC operating characteristics
    g. Indoor and outdoor sources of vapour-forming chemicals
    h. Basement sumps and groundwater testing.
    i. Presence and operation of any indoor air treatment systems.
11. Outdoor sampling to characterize ambient air at one to two locations surrounding the building of interest at equivalent durations to indoor air samples
12. Evaluation and development of analyte lists.
13. Complementary data such as measured air exchange rates.
14. Sub-slab sampling consistent with US EPA-ERT 2007 Standard Operating Procedure.
    a. Due to spatial variability multiple sample locations should be used, e.g. 3 samples per 1500 square feet (~150m^2).
    b. Should include one centrally located sampling point.

   c. Several rounds are recommended for assessing temporal variability.
   d. Leak testing be performed, e.g. helium.
   e. An equilibrium time of at least two hours be allowed prior to sampling following sampler implants.
   f. Identifying sub-slab cables, avoiding groundwater areas, and underground utilities and structures.
   g. Basement wall samples should be considered.
   h. Additional complementary data as per 10. Above.
   i. Collection of relevant meteorological data that can influence soil gas concentrations.
   j. Installation after indoor air sampling or before provided sufficient indoor clearance of introduced volatiles from the sub-slab installation occurrs.

15. Soil gas installation consistent with US EPA-ERT 2001 Standard Operating Procedure.
   a. Equilibration time of 2 hours for temporary driven probes and 48 hours for permanent probes.
   b. Meteorological conditions be recorded.
   c. Samples should preferably be taken directly beneath the building as vapours are greater beneath the building than from those outside, i.e. ‘exterior’ gas samples.
   d. Deeper soil gas samples collected in the vadose zone immediately above the source of vapour contamination are less susceptible to ambient air infiltration and should be collected.
   e. Several rounds of sampling are recommended due to temporal variance

ITRC (2014) has developed a comprehensive guidance document with detailed information on sampling practices presented in Appendix G, “*Investigation Methods and Analysis Toolbox*”, pp179-246. Some useful summary table information has been included from this source in Appendix 1, 2 and 3 being respectfully:

- “*Summary of analytical methods for soil gas, indoor, and ambient air samples*”.
- “*Matrix of recommendations for various quantitative options to evaluate vapor intrusion*”.
- “*Advantages and disadvantages of various investigative strategies*”.

The interpretation of sampling data for assessment purposes seeks to determine (a) whether vapour intrusion is occurring and (b) what risks are associated with the indoor air exposures by occupants. Concurrent testing across transport compartments including ambient air, enables evaluation of relationships of COPC across those compartments and potentially source apportionment. In order to achieve this, it is important that the analytical profiles are consistent and that reporting limits are sufficient. Lower reporting limits will be required as one progresses to above ground sampling. Extension of the vapour transport compartment analysis can be made by inclusion of soil and groundwater contaminant concentrations in order to examine potential sources. Source characterization is important in ensuring impacts associated with that source are confirmed and can subsequently be remediated or mitigated.

In terms of exposure assessment and risk, once available data have been collected the options default to those associated with risk assessment practice (refer earlier) and will vary depending on the stage and level of assessment being undertaken:

Tier 1 assessment – Semi-quantitative assessment of preliminary information on soil vapour, soil or groundwater concentrations through evaluation of health-based screening levels (e.g., the ASC NEPM interim HILs for chlorinated hydrocarbons or HSLs for petroleum hydrocarbons, noting their limitations and uncertainties). Should data be unavailable e.g. the US EPA (2014a) VISLs could be reviewed taking into account their limitations (US EPA 2015a, pp106-108). Soil vapour results may also be compared to regulatory agency-derived toxicological contaminant endpoints for inhalation as a conservative measure, with subsequent consideration of exceedances via consideration of attenuation factors and other variables at the Tier 2 level.
If screening levels are exceeded, unavailable or not valid:
Tier 2 assessment – Quantitative assessment using existing or additional data to support vapour intrusion modelling using site-specific variables, measurement data across transport compartments and examination of generic attenuation factors or site-specific attenuation factors. Exposure modelling and estimations to enable quantitative estimates of human health risk.
Tier 3 assessment – Further more detailed evaluations should Tier 2 assessment be insufficient and/or lacking in confidence. This may involve refinement and increased detail in elements of the exposure assessment. May include the collection of additional data, such as soil vapour sampling, ambient air sampling, analysis of dust, biological monitoring and additional site investigations may be needed to support Tier 3 assessments.

8.4.3.2 Landfill gas

Land fill gas also considered as "*hazardous ground gases*" (NSW EPA 2012) reflect gases and vapour arising from waste repositories.

Sampling of these gases and vapours are similar in many ways to hydrocarbon-contaminated sites albeit with an emphasis on advection, limited attenuation, volumetric flows of high concentrations of explosive, combustible and acutely toxic gases and vapours.

Other differences in terms of site assessment include:

- A larger range of volatile substances including inorganic and organic compounds and elements (radon, mercury).
- Substances at greater concentrations, with greater volatility and acute risks (fire, explosion, toxicity).
- A greater emphasis on sub-surface heterogeneity resulting in preferential pathways enabling pressure driven advective flows that are influenced more heavily by barometric pressure changes.
- Sub-surface source material bio-degradation and reaction processes that continue to generate hazardous ground gases over time such that source depletion may take many years.
- In addition, these sites are considered in terms of "emissions" and "intrusions" with models examining atmospheric emissions from these sites; groundwater transport of volatile materials with subsequent off-site vapour intrusion and advective distribution and diffusion off-site of sub-surface gases and vapours.

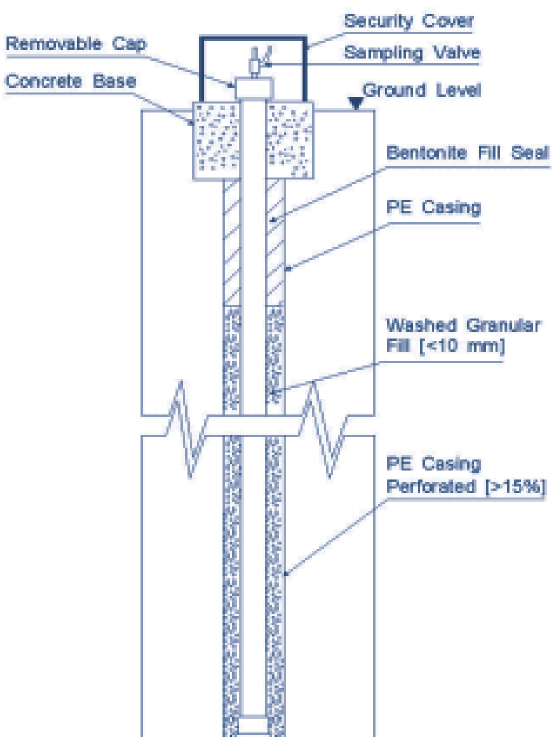
An extensive range of key documents are available across sampling, analysis and assessment procedures. These include those from the UK Environment Agency (EA, 2004; 2010; 2012a. b; 2014) encompassing monitoring, risk assessment and management guidance; US EPA guidance specific to closed and abandoned landfill facilities (US EPA, 2005a, b); NSW EPA (2012) guidance on hazardous ground gas assessment and UK CIRIA guidance (Wilson et al., 2007; Baker, 2009) focused on risk assessment and management.

Both the US EPA and the UK EA have provided structured methodologies for sampling and analyses in terms of gases such as methane and carbon dioxide subject to large scale volumetric flows, and other lower concentration hazardous gases and vapours. NSW EPA has based their guidance on UK approaches as published in the CIRIA and EA documentation as the information is extensive and current. It is considered that this is a reflection of the issues in the UK from landfill sites and the subsequent input into the development of resources for assessment (which are extensive).

Sampling/testing approaches to landfills for both ground gases and trace components may include:

- Field measurement equipment (instrumentation using Infra-red (IR); electrochemical cells (EC); photo-ionisation detection (PID); flame ionization detection (FID); gas chromatograph (GC) with or without mass spectrometry(MS))
- monitoring wells with implants (as in vapour intrusion assessment) or for ground gas (Figure 14).
- flux chambers
- passive samplers
- ambient measurement
- surface emission measurement
- flow and pressure measurement – bulk gases
- field measurement – trace gases (as above- PID; FID; GC/MS)
- sampling – bulk gases (Summa canisters/Tedlar bags)
- sampling - trace gases (Summa canisters/Tedlar bags/ Sorbent tubes/Passive samplers) (from NSW EPA, 2012, Appendix 4, refer Table 4.3 for more detail)

Figure 14: Features of a landfill gas monitoring borehole (from EA, 2004)



Typical analytical approaches need to cover both volumetric gas determination/concentrations for bulk ground gas and qualitative and quantitative determination for trace gases. Bulk gases are detailed in Table 4 with measurement based on field instrumentation (on-site) or off-site, following sampling with canisters or Tedlar bags.

Table 4: Typical range of bulk gases in landfill gas (from EA, 2004)

Bulk landfill gas	Typical value (%v/v)	Observed maximum (%v/v)
Methane	63.8	88.0
Carbon dioxide	33.6	89.3
Oxygen	0.16	20.9#
Nitrogen	2.4	87.0#
Hydrogen	0.05	21.1
Water vapour (typical % w/w, 25°C)	1.8	4.0

Derived entirely from the atmosphere.

In terms of trace gases, a diverse range has been identified and EA (2010) cite over 500 substances that have been reported in landfill gases (EA, 2002b). The average concentrations of some of these are presented in Table 5. Recommended trace components for monitoring are suggested in Table 6 with additional components also including mercury (as Hg), PCDDs and PCDFs and carbon monoxide.

Table 5: Average concentration of a variety of trace vapours in landfill gas (from EA, 2004; 2002b)

Name	Chemical group	Median concentration ($\mu g/m^3$)	Average concentration ($\mu g/m^3$)
1,1-Dichloroethane	Halogenated organics	13,260	476,223
Chlorobenzene	Halogenated organics	11,880	246,589
1,1,1-Trichloroethane	Halogenated organics	12,905	189,826
Chlorodifluoromethane	Halogenated organics	11,570	167,403
Hydrogen sulphide	Sulphured compounds	2,833	134,233
Tetrachloroethene	Halogenated organics	16,640	112,746
Toluene	Aromatic hydrocarbons	11,995	86,221
Chloroethane	Halogenated organics	5,190	77,867
n-butane	Alkane	13,623	67,412
Chloroethene	Halogenated organics	5,600	64,679
Carbon monoxide	Carbon Monoxide	5,822	62,952
Ethylbenzene	Aromatic hydrocarbons	6,480	37,792
1,2-Dichlorotetrafluoroethane	Halogenated organics	3,200	34,046
α-pinene	Cycloalkenes 2	9,300	33,248
cis-1,2-Dichloroethene	Halogenated organics	7,700	33,129
Xylene	Aromatic hydrocarbons	4,700	23,900
Dichlorofluoromethane	Halogenated organics	3,500	20,131
n-hexane	Alkanes	5,000	19,850
Dichloromethane	Halogenated organics	1,240	19,054
n-nonane	Alkanes	8,120	19,015
Butan-2-ol	Alcohols	5,400	18,704
1,2-Dichloroethane	Halogenated organics	1,575	16,495
3-Methyl-2-butanone	Ketones	1,984	13,614

Table 6: Priority trace components for monitoring (from EA, 2010)

Trace component	CAS number	Potential impact	Category
1,1-dichloroethane	75-34-3	Health	Halocarbon
1,2-dichloroethane	107-06-2	Health	Halocarbon
1,1-dichloroethene	75-35-4	Health	Halocarbon
1,2-dichloroethene	540-59-0	Health	Halocarbon
1,3-butadiene	106-99-0	Health	Aliphatic hydrocarbon
1-butanethiol	109-79-5	Odour	Organosulphur
1-pentene	109-67-1	Odour	Aliphatic hydrocarbon
1-propanethiol	107-03-9	Odour	Organosulphur
2-butoxyethanol	111-76-2	Health	Alcohol
Arsenic (as As)	7440-38-2	Health	Inorganic
Benzene	71-43-2	Health	Aromatic hydrocarbon
Butyric acid	107-92-6	Odour	Carboxylic acid
Carbon disulphide	75-15-0	Odour and health	Organosulphur
Chloroethane	75-00-3	Health	Halocarbon
Chloroethene (vinyl chloride)	75-01-4	Health	Halocarbon
Dimethyl disulphide	624-92-0	Odour	Organosulphur
Dimethyl sulphide	75-18-3	Odour	Organosulphur
Ethanal (acetaldehyde)	75-07-0	Odour	Aldehyde
Ethanethiol	75-08-1	Odour	Organosulphur
Ethyl butyrate	105-54-4	Odour	Ester
Furan (1,4-epoxy-1,3-butadiene)	110-00-9	Health	Ether
Hydrogen sulphide	7783-06-4	Health and odour	Inorganic
Methanal (formaldehyde)	50-00-0	Health	Aldehyde
Methanethiol	74-93-1	Odour	Organosulphur
Styrene	100-42-5	Health	Aromatic hydrocarbon
Tetrachloromethane	56-23-5	Health	Halocarbon
Toluene	108-88-3	Health	Aromatic hydrocarbon
Trichloroethene	79-01-6	Health	Halocarbon

CAS = Chemical Abstracts System

Typical analytical methods for priority trace gases are detailed in Table 7.

Table 7: Recommended methods for monitored priority trace components in landfill gas (from EA, 2010)

Category	Sampling method	Analytical method*
Priority components		
Speciated VOCs#	Dual solid sorbent	ATD-GC-MS
Aldehydes	Reactive sorbent	HPLC
Hydrogen sulphide	Direct on-site measurement of raw gas or Tedlar Bag and GCMS	Hand held instrument Laboratory GC
Arsenic	Solid sorbent	ICP-MS/AAS
Additional components		
Mercury	Solid sorbent	ICP-MS/CV-AAS
PCDDs and PCDFs	Solid sorbent	GC-HRMS
Carbon monoxide	Gresham tube/Tedlar bag	Laboratory GC

VOC = Volatile organic compounds

Assessment methods are presented in NSW EPA (2012) for both ground gases and trace gases.

In terms of bulk ground gases, a multi-level risk assessment based on the Department of Planning (now Department of Planning and Infrastructure) is recommended. The components of this include preliminary screening, risk classification and prioritization followed by risk analysis and assessment. Preliminary screening determines whether further evaluation is required and risk classification and prioritization determines the response and complexity of the required assessment across 3 levels of iterative assessment of increasing complexity.

Level 1 assessment is qualitative in nature and based on hazard identification and the traditional risk analysis frameworks embodying likelihood and consequence. Level 2 reflects a semi-quantitative evaluation based on the determination of gas screening values (= maximum borehole flow rate (L/hr) x maximum gas concentration (%) for methane and carbon dioxide). The GSVs are then assessed against classification criteria for risk severity outputs as presented in Table 8. The evaluation of trace gases (and vapours) follows the processes of risk assessment previously described for site contamination assessments.

Further information on exposure assessment is presented in detail in EA (2010a, b) taking note that the exposure assessments described therein involve all media concentrations and not just gases and vapours and this subsequently involves a higher degree of complexity.

A range of review questions is presented at the beginning of this document which will aid the reader in considering the pertinent aspects of sampling, analysis and assessment.

Table 8: Modified Wilson and Card classification (from NSW EPA, 2012, p31)

Gas screening value threshold (L/hr)	Characteristic gas situation	Risk classification	Additional factors	Typical sources
<0.07	1	Very low risk	Typically methane <1% v/v and/or carbon dioxide <5% v/v, otherwise consider increase to Situation 2	Natural soils with low organic content Typical fill
<0.7	2	Low risk	Borehole flow rate not to exceed 70 L/hr, otherwise consider increase to Situation 3	Natural soils with high organic content Fill
<3.5	3	Moderate risk		Old inert waste landfill Flooded mine workings
<15	4	Moderate to high risk	Consider need for Level 3 risk assessment	Mine workings susceptible to flooding Closed putrescible waste landfill
<70	5	High risk	Level 3 risk assessment required	Shallow, un-flooded abandoned mine workings
>70	6	Very high risk		Recent putrescible waste landfill

Notes:

1. Site characterisation should be based on gas monitoring of concentrations and borehole flow rates for the minimum periods defined in Section 3.4.
2. Source of gas and generation potential must be identified in the conceptual site model.
3. Soil gas investigation should be in accordance with the guidance provided in Section 3.4.
4. Where there is no detectable flow, the lower measurement limit of the instrument should be used.
5. To determine a GSV of <0.07, instruments capable of making accurate concentration measurement to 0.5% v/v and flow measurement to 0.1 L/hr are recommended.

8.5 MULTIPLE LINES OF EVIDENCE

The complexity of the vapour intrusion process and the difficulty in the evaluation of dynamic indoor air exposures in space and time has led to a multiple lines of evidence approach being considered the optimal strategy. Pennell et al., (2016) combined field data with numerical modelling as a multiple lines of evidence approach. This considers results from modelling and measurement but in addition supplementary information relevant to gas or vapour migration may also contribute as individual lines of evidence. These lines of evidence discussed below.

8.5.1 Modelling and measurement

A variety of vapour intrusion models have been mentioned and available software allows predictions to be made of (ultimately) indoor air concentrations. Site-specific input data and/or the use of probability distribution functions aid in model calibration. Measurement methods have also been discussed as a means to evaluate model predictions but also to record sub-surface, indoor air and ambient air concentrations to enable source characterization, source apportionment and exposures to be estimated and compared against exposure levels not considered to represent a risk to human health.

8.5.2 Spatial and temporal concerns

The evaluation of spatial differences and changes over time coupled with their influencing variables provides confidence that worst case settings have been evaluated. This facet is a significant limitation of current vapour intrusion modelling practices. This ensures that changing environmental conditions will not impact on the most sensitive subgroup of the population and at any time that has not been captured during sampling regimes. This area is the most difficult area to assess and may require significant resource commitment in order to fulfil as it requires extended monitoring programs. This is an area for further research outcomes that may enable the establishment of relationships which could minimize the sampling regimes that are currently required to achieve confidence and hence overall save costs.

8.5.3 Building design and ventilation

Architectural and engineering information related to existing or proposed buildings provides supplementary information relevant to indoor air exposures. Active ventilation systems; passive structural ventilation designs; suspended concrete or wooden floors; “waffle-pod” foundation designs; heating and cooling systems; internal atria which are sealed to the indoor environment but open to atmosphere; and sub-surface service lines/drains/sumps through the foundation are all factors that may play a part in influencing the indoor exposures.

8.5.4 Preferential pathways

Preferential pathways are pathways of least resistance to vapour flow and enable pressure-driven advection to occur which minimizes the influence of attenuation processes and can increase exposures and risks indoors. In the case of existing buildings these require evaluation through identification and measurement while for buildings under construction it is important to ensure that service lines are sealed and do not result in entry points into the building interior. The treatment of preferential pathways is thus a line of evidence that minimizes exposure risks which cannot be assessed with current vapour intrusion models.

8.5.5 Phyto-assessment methods

Phyto-assessment methods are methods of assessment that are based on plant uptake of contaminants. There are a few publications related to soils contaminated with hydrocarbons which suggest that plant biomass may be used as an indicator of the presence of hydrocarbons at various depths in soil, depending on the plant root zones. These studies (e.g. Ikhaiagbe et al., 2013; Ikhajiagbe and Unuagbokhe, 2013; Bramley-Alves et al., 2014) are generally related to growth impacts and yields and/or phytoremediation aspects, however, they do support the potential that the presence of soil hydrocarbons may be assessed using plants. Further research is required in this area.

8.5.6 Attenuation factors

8.5.6.1 Generic

A number of publications have cited various generic attenuation factors (NSW EPA, 2012; US EPA 2002; US EPA 2012) and these have been drawn from various databases. The reader is referred to those publications. In the most recent US EPA (2015) publication information on the use of generic attenuation factors the outcomes of the US EPA's vapour intrusion database analyses are presented. According to US EPA (2015a, pA3),

"*The information in EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings (EPA 2012a) is used to derive recommended attenuation factor values for use in evaluating subsurface sample concentrations collected as part of vapor intrusion investigations. EPA's vapor intrusion database consists of numerous pairings of concentrations in indoor air and subsurface samples (groundwater, sub-slab soil gas, exterior soil gas, and crawlspace vapor) from actual sites. It represents the most comprehensive compilation of vapor intrusion data for chlorinated hydrocarbons (CHCs) available at this time.*".

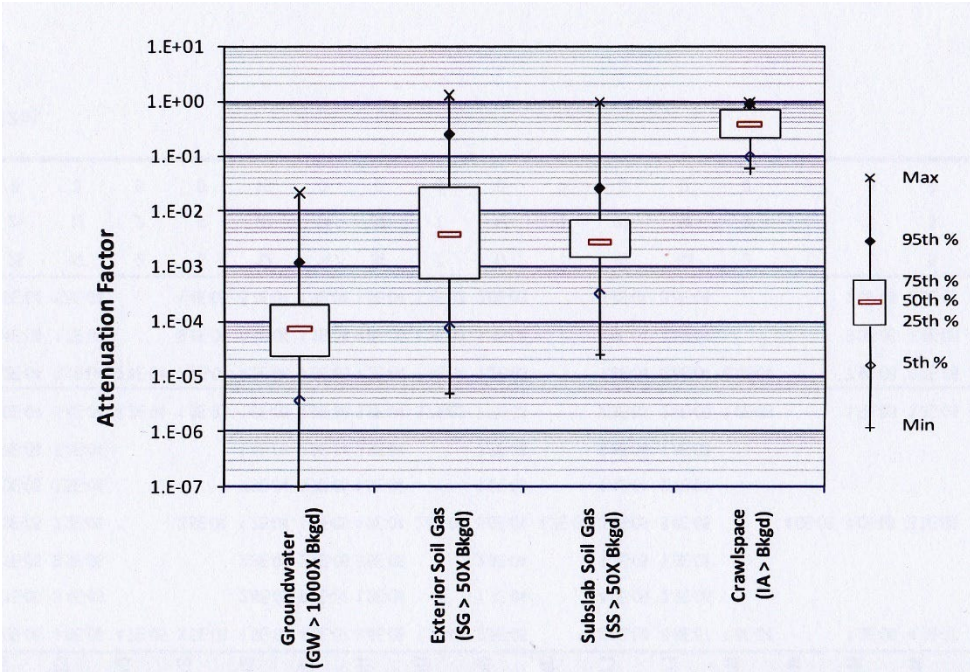
The attenuation factor distribution across the transport compartments for that database is presented in Figure 15 and the recommended attenuation factors are presented in Table 9. These attenuation factors support the derivation of the US EPA (2014a) VISLs. There are a number of considerations required in the use of these attenuation factors as presented in Table 9, with a specific focus on:

- whether site conditions fit the generic model of vapour intrusion described at Section 6.5.2 (see (Figure 13)) with sub-surface conditions characterized based on recommendations at Section 6.3 (pp71-86) and Section 6.4 (pp.87-105).
- The reader is also referred to pp 105-112 (US EPA, 2015a) for an understanding of the VISLs and attenuation factors and their application.

Table 9: Recommended vapour attenuation factors for risk-based screening of the vapour intrusion pathway (from US EPA, 2015a)

Sampling Medium	Medium-specific Attenuation Factor for Residential Buildings
Groundwater, generic value, <u>except</u> for shallow water tables (less than five feet below foundation) or presence of preferential vapor migration routes in vadose zone soils	1E-03 (0.001)
Groundwater, specific value for fine-grained vadose zone soils, when laterally extensive layers are present[185]	5E-04 (0.0005)
Sub-slab soil gas, generic value	3E-02 (0.03)
"Near-source" exterior soil gas, generic value <u>except</u> for sources in the vadose zone (less than five feet below foundation) or presence of routes for preferential vapor migration in vadose zone soils	3E-02 (0.03)
Crawl space air, generic value	1E-00 (1.0)

Figure 15: Box-and-whiskers plot summarising attenuation factor distributions for groundwater, exterior soil gas, sub-slab gas and crawl space (from US EPA 2015a).



8.5.6.2 Site-specific

Site-specific attenuation factors may be estimated should there be sufficient factors to support such determinations. These include but are not limited to:

- Single source at depth with overlying uncontaminated material.
- Depth concentration profiling from source to near surface (1.5m).
- Consistent sampling and test results in terms of the analysis method and the COPC.
- Consistent geology/hydrogeology although heterogeneity is inherent in these systems.
- Concurrent depth profiling such that measurements are undertaken at the same time and under the same environmental conditions.
- Multiple rounds of depth profiling which may capture differing environmental conditions.

Caution is required due to the inherent heterogeneity of the sub-surface such that explicit comparisons (e.g. using only a couple of results) should be avoided. Statistical analyses and averaging processes with an understanding of variability is suggested.

8.5.7 Concentration gradients

The estimation of concentration gradients of soil vapour in the sub-surface is a useful tool and should be considered as part of the conceptual site model of exposure. These may be undertaken using cost-effective passive sampling methods. These can aid in establishing sources and source apportionment and provide additional information for targeted sampling using more robust standards methods for quantitative determinations.

8.5.8 Potential sub-surface changes over time of key influencing variables

A key factor associated with environmental assessment is that environmental conditions are constantly changing and that change over time may provide additional information to support decision making. For example, newly constructed very large foundation slabs may result in "wetting up" over time depending on topography and drainage systems limiting vapour migration. The changes that may be introduced by construction and landscaping that could impact some of the key variables facilitating vapour intrusion may be an additional useful line of evidence.

9 Risk Management

9.1 Basis of management

Risk-based corrective action (RBCR) was one of the initial approaches for risk management of petroleum release sites (see ASTM- E1739- 95, 1995) and this approach has been sustained, having been recognized as important, with increasing attention paid to using risk assessment to facilitate decision-making (see US EPA, 2014a).

General recommendations about risk-informed decision-making in relation to vapour intrusion are well detailed in a series of publications from the US (ASTM E1739-95, 2015; US EPA 2015a; ITRC, 2014), the UK (EA, 2004) and in Australia by the NSW EPA (2012). The reader is referred to these documents for further detailed information.

It is important to recognize that the risk management information detailed below assumes that the precursors to the risk management options have been evaluated. Specifically, that:

- A sound conceptual site model has been developed.
- The conceptual site model is supported by multiple lines of evidence.
- That the subsurface vapour sources have been characterized sufficiently to support risk management decisions for the site.

9.2 Risk management measures

Vapor control strategies can be managed by three approaches being, environmental remediation, institutional controls (ICs), building mitigation or any combination of these. The former reduces or eliminates the exposure threat by removing the contaminant from the environment; ICs are administrative and legal controls that help minimize the potential for human exposure and may protect site integrity while building controls prevent or minimize by truncating the exposure pathway prior to building entry (ITRC, 2014).

US EPA (2015a, p132), in considering options for response action when it has been determined that reduction of indoor air exposures is warranted, recommends that such program selection, recommendation and documentation be consistent with legislative frameworks and existing program guidance. Furthermore, the selection of a health-protective interim response action or actions will be dependent on site-specific considerations including:

- Nature of sub-surface vapour source.
- Magnitude of the exposure above clean-up levels.
- The severity of the potential adverse health effects or health hazard.
- Building features and conditions.
- Climate and season (which influence ventilation).
- The quality of ambient air in the vicinity.
- The feasibility of implementing a given option quickly.

The response actions should limit the amount of time individuals are exposed to concentrations that correspond to unacceptable human health risk. US EPA (2015a) have considered a matrix of options in this regard and these are presented in Table 10. In addition to the matrix options a mitigation quick guide for decision-making is also presented in Table 11. Finally, a summary of mitigation methods (ITRC, 2014) is included as Appendix 4 including costings (note that these costings are in US dollars).

NSW EPA (2012) also present similar site management approaches as gas protection measures which may include:

- Passive measures such as:
    - source removal
    - membranes
    - passive venting
    - upgraded slabs and vertical barriers.
- Active protection measures such as:
    - sub-slab depressurization systems
    - active venting systems
    - vented sumps
    - active gas extraction wells or trenches
    - building over-pressurisation systems and sub-slab over-pressurisation systems.
- Management controls for ground gases are considered to include:
    - Restrictions on land use
    - Restrictions on building design or use
    - Safe work procedures and practice
    - Monitoring systems
    - Alarms and management plans.

Guidance for gas values and scores for the efficacy of protection measures are reproduced in Table 12 and Table 13.

Table 10: Matrix of options to respond to human health risk from vapour intrusion (from US EPA 2015a).

Option for Response Action	Applicability of Response Action for Common Sources of Sub-surface Vapors		
	Groundwater	Vadose Zone Soil	Sewer & Drain Lines
Remediation of Source*	•	•	•
Removal of contaminated soil via excavation	#	•	
Treatment of contaminated soil *in situ*	#	•	
Treatment of contaminated groundwater *in situ*	•		
Removal of contaminated groundwater (e.g., pump-and-treat)	•		
Decontaminating and/or rehabilitating sewer and drain lines			•
Interim Measures to Reduce or Eliminate Vapor Intrusion*	•	•	•
Subslab de-pressurization and ventilation systems	•	•	
Sealing major openings for soil gas entry, where known and identified+	•	•	
Building over-pressurization	•	•	
Installing, repairing, or maintaining vapor traps			•
Interim Measures to Reduce or Avoid Exposure to Vapors	•	•	•
Notification to local fire department about potential explosion hazards+	•	•	•
Notification and risk communication to building occupants and owners, including institutional controls (e.g., deed notices)	•	•	•
Increasing building ventilation*	•	•	•
Treating indoor air*	•	•	•
Temporary relocation+	•	•	•
Monitoring Indoor Air to Characterize Human Exposure	•	•	•

KEY: • designates potentially appropriate response action for indicated vapor source

FOOTNOTES:

* includes: associated institutional controls to maintain operations and provide public notification of residual contamination; and associated monitoring to assess effectiveness and protectiveness of the response action

remediation of soil may also be warranted for purposes of protecting groundwater from further contamination, even if contaminated soil in the vadose zone is not a source for vapor intrusion directly (e.g., due to the absence of an existing building near the contaminated soil)

\+ response option primarily applies to existing buildings

Table 11: Vapour intrusion building mitigation quick guide (from US EPA, 2015a).

Step 1: Consider Prompt Response Actions

It may be appropriate to implement certain interim measures before engineered controls are constructed and operated, as warranted and feasible. For example, building ventilation can be increased, cracks and other openings in the floor or foundation (that otherwise allow soil gas entry) can be sealed, or indoor air treatment can be conducted (refer to Section 8.2.1).

Step 2: Select a Building Mitigation System

The initial step in selecting the appropriate vapor intrusion mitigation technology is to conduct a visual inspection of an existing building. The selection of a vapor intrusion mitigation system primarily depends on building characteristics and contaminant concentrations. In the majority of cases, a type of active depressurization technology (ADT) can be an efficient, reliable, and cost-effective vapor intrusion mitigation technique. In some cases, however, other approaches may be preferable.

Factors that may prompt consideration of vapor intrusion mitigation approaches other than ADT include foundation conditions that prevent development and extension of a suction field below the building.

If there are no factors that would rule out an ADT technology, appropriate systems that can be considered include:

- Sub-slab depressurization (SSD) systems, particularly in houses having slabs (basements and slabs on grade) where drain tiles are not present.
- Drain-tile depressurization (sump/DTD or remote discharge/DTD) when drain tiles are present.
- Sub-membrane depressurization (SMD) in buildings with a crawl space foundation or a basement with a dirt floor,
- Block-wall depressurization (BWD), usually used only as a supplement to SSD, DTD, or SMD to better mitigate vapors found to be migrating through the wall.

Step 3: Design Building Mitigation System

EPA recommends the final detailed design of the selected vapor intrusion mitigation technology specify the number and location of suction points, location and size of piping, suction fan, piping network and exhaust system, and sealing options to be used in conjunction with the ADT technology. Pre-mitigation diagnostic testing can provide information about the suction field underneath a building and pressure differences that will need to be overcome (EPA 1993a) if the ADT system is to be effective. Diagnostic testing during installation can also help verify the adequacy of the design.

Step 4: Install Building Mitigation System

EPA recommends that the vapor intrusion mitigation system be installed consistent with design specifications by equipment manufacturers, local permit conditions and regulations, and relevant industry standards.

Step 5: Confirm the Installed System is Operating Properly

EPA recommends a visual inspection of the installed system as a routine quality assurance step to confirm that all construction details have been completed. Post-construction monitoring is recommended (refer to Section 8.4) to demonstrate the ADT system is operating appropriately and effectively. Where a vapor intrusion mitigation system is not performing adequately, post-construction diagnostic tests can be helpful in trouble-shooting (EPA 1993a).

Step 6: Ensure Proper Operation and Maintenance of Vapor Intrusion Mitigation System (refer to Sections 8.3 and 8.4)

EPA recommends proper system maintenance and periodic inspections and monitoring to ensure the system is operating as designed and is effective at reducing indoor air concentrations to (or below) target levels. EPA recommends that site managers provide the building owner/occupant with information to help ensure proper operation and maintenance of the system.

EPA recommends that periodic inspections include periodic measurements to confirm that the building mitigation system is continuing to perform adequately.

Table 12: Guidance values for gas protection (from NSW EPA, 2012, p46)

Characteristic gas situation (CS)	Required gas protection guidance value				
	Low density residential	Medium–high density residential (strata title)	Public buildings, schools, hospitals, shopping centres	Standard commercial buildings (offices, etc.)	Large commercial (warehousing) and industrial buildings
1	0	0	0	0	0
2	3	3	3	2	1 [a]
3	4	3	3	2	2
4	6 [b]	5 [b]	5	4	3
5	6 [b]	6 [b]	6 [c]	5	4
6	6 [b]	6 [b]	6 [c]	6	6

(a) If maximum measured methane concentration exceeds 20%, increase to CS3.

(b) Residential development not recommended at CS4 and above without pathway intervention and high level of management.

(c) Consideration of evacuation issues and social risks required.

Table 13: Scores for protection measures (from NSW EPA, 2012, p47).

Measure or system element	Score	Comments
Venting and dilution measures		
Passive sub-floor ventilation with very good performance (steady state concentration of methane over 100% of ventilation layer remains below 1% v/v at a wind speed of 0.3 m/s)	2.5	
Passive sub-floor ventilation with good performance (steady state concentration of methane over 100% of ventilation layer remains below 1% v/v at a wind speed of 1 m/s and below 2.5% v/v at a wind speed of 0.3 m/s)	1	If passive ventilation cannot meet this requirement an active system will be required.
Subfloor ventilation with active abstraction or pressurisation	2.5	Robust management systems must be in place to ensure long-term operation and maintenance.
Ventilated car park (basement or undercroft)	4	Assumes that car park is vented to deal with exhaust fumes in accordance with BCA[(a)] requirements.
Floor slabs		
Reinforced concrete ground bearing floor slab	0.5	It is good practice to install ventilation in all foundation systems to effect pressure relief as a minimum. Breaches in floor slabs, such as joints, have to be effectively sealed against gas ingress to maintain these performances.
Reinforced concrete ground bearing foundation raft with limited service penetrations cast into slab	1	
Reinforced concrete cast in situ or post-tensioned suspended slab with minimal service penetrations and water bars around all penetrations and at joints	1.5	
Fully tanked basement	2	
Membranes		
Taped and sealed membrane to reasonable levels of workmanship with inspection and validation	0.5	The performance of membranes is dependent upon the design and quality of the installation, protection from and resistance to damage post installation and the integrity of joints in membranes that require joints. Materials that offer some degree of self-sealing and repair are preferred.
Proprietary gas-resistant membrane to reasonable levels of workmanship under independent construction quality assurance (CQA)	1	
Proprietary gas resistant membrane to reasonable levels of workmanship under independent CQA with integrity testing and independent validation	2	
Monitoring and detection (alarms)		
Intermittent monitoring using hand-held equipment	0.5	Monitoring and alarm systems are only valid as part of a combined gas protection system. Where fitted, permanent systems should be installed in the underfloor venting system but can also be provided in the occupied space as a back-up.
Permanent monitoring system installed in the occupied space of the building	1	
Permanent monitoring system installed in the underfloor venting / dilution system	2	
Pathway intervention		
Vertical barriers	–	Required for residential and public buildings at CS4 and above.
Vertical venting systems	–	

[(a)] Building Code of Australia

9.3 Post-mitigation assessment and sustainability/cost benefit

An important concept for building community confidence is to ascertain the efficacy of the mitigation measures and to provide information on how that efficacy was evaluated. This may range across differing types of investigations including indoor air assessments or sub-surface vapour distribution assessments following remedial site measures.

In addition, for the mitigation measure chosen, sustainability evaluations combined with cost benefit assessments should be considered. This would enable low environmental impact and efficient measures to be selected and implemented.

A range of issues should therefore be reviewed as part of the risk management framework including details of the CSM, sub-surface sources, assessment efficacy, nature of issues and corrective response actions. Review questions are presented at the beginning of this document.

10 Risk Communication

10.1 Objective of risk communication

The enHealth (2012a) risk assessment framework presented in Figure 5 includes a stakeholder, risk communication and community consultation element which is embodied across all stages of the risk assessment process. This fundamental premise seeks to ensure that all stakeholders are involved and engaged in issues which directly affect them, particularly communities potentially affected by vapour intrusion where exposures may have already been occurring over many years. enHealth (2012a, p88) further states that "*engaging with stakeholders as part of the EHRA risk process is a cornerstone to effective risk management… over which a concerned community can feel a sense of 'ownership'*" while "*effective community engagement can also facilitate transfer of risk assessment and risk management information, a process referred to as risk communication".* The objective of risk communication is therefore knowledge transfer, engagement and empowerment of the affected community such that transparency and evidence-based approaches to exposures are mitigated building confidence and acceptance by both the regulatory agencies and the community and other impacted stakeholders.

10.2 US EPA and the Seven Cardinal Rules of Risk Communication

Fundamental work on risk communication was published by Covello and Allen (1988) as part of the US EPA's "*Seven Cardinal Rules of Risk Communication*". These rules are:

"*Rule 1: Accept and involve the public as a legitimate partner.*

Rule 2: Plan carefully and evaluate your efforts.

Rule 3: Listen to the public's specific concerns.

Rule 4: Be honest, frank, and open.

Rule 5: Co-ordinate and collaborate with other credible sources.

Rule 6: Meet the needs of the media.

Rule 7: Speak clearly and with compassion."

These principles have been the cornerstone of subsequent publications on community engagement and risk communication to avoid community outrage on public health issues.

10.3 enHealth and ASC NEPM Guidance

enHealth (2012a, pp88-94) discuss community engagement in environmental health risk assessment with further emphasis towards risk perception and heuristics where the latter reflects the psychological term to describe the process whereby people frame their perceptions of risk. Issues of the social context of risk perception and the differences in 'real' and perceived' risk is explored and the Australian context is presented. The discussion extends to 'risk communication – things to know and things to avoid'; understanding conflicts and planning in risk communication and concludes with an illustrative example.

The ASC NEPM (Volume 20, Schedule B8) also discusses community engagement and risk communication and presents a "*systematic approach to effective community consultation and risk communication in relation to the assessment of site contamination*". As a 'tool' for effective consultation by consultants and regulators, three principles to the approach were taken in the Schedule including:

- "*that an evaluation regarding the probable need, nature and extent of community engagement for a project should be carried out by site managers with expertise in risk communication at an early stage in the preliminary assessment of site contamination, and should detailed investigations identify contamination that has the potential (or the perceived potential) to have an impact on any stakeholder*
- *that interaction with the community cannot simply be a technical process; it requires skills in listening and communicating and should be a two-way process*
- *that for sites with contentious issues, engagement with the community is considered to be essential. This is particularly the case when the contamination at the site has the potential (or the perceived potential) to have an impact on any stakeholder and where impacts are known to extend outside the boundaries of the site*." (p1).

The document subsequently specifies situations required with the community which include amenity/nuisance; significant contamination; site proximity; controversial sites issues. The guidance explores Covello and Allen's Cardinal rules and provides community engagement techniques; consultation 'do's' and 'don'ts' and concludes with a case study.

10.4 CRC CARE GUIDANCE

Heath and Pollard (2010) produced a "*Guideline for stakeholder engagement*" under a title of "*Remediation and management of contaminated sites*" for CRC CARE. This document was orientated towards practitioners to enable effective engagement with "*individuals and groups who may have an interest in the remediation and management of a contaminated site*" (p11).

The document builds on the ASC NEPM information and is considered as ancillary to any regulatory guidance from individual State EPAs and the Territory EPA that may have specific requirements. The document explores the concepts of understanding stakeholder engagement, risk communication and risk perception and provides supportive documentation for further reference throughout the discussions. Stakeholder techniques and planning are considered together with the most appropriate methods of documentation and reporting across the stakeholder groups.

10.5 OPTIMAL COMMUNICATION STRATEGIES

The success of structured risk communication will be dependent on optimal consideration and incorporation of the seven cardinal rules as developed by Covello and Allen (1998). It is important to ensure an evidence-based and transparent approach is used in risk assessment which can be explained in non-technical terms to affected stakeholders and in particular the public. Engagement through their understanding and empowerment in decision making will enable successful and confident outcomes to address not only present exposures but also those that occurred in the past and those that may occur in the future.

Review questions to consider have been presented at the beginning of this document.

11 FUTURE RESEARCH NEEDS

The complexity of vapour intrusion processes and the range of uncertainties and limitations that currently exist lend themselves to the need for further research. Research requirements across modelling, measurement, exposure assessment and population impacts are suggested.

11.1 MODELLING AND MEASUREMENT

In cases where no buildings are involved, model development for:

(a) spills to the water table
(b) plumes below the water table

Factors to be considered include:

- Time dependency.
- Spatial variability and preferential pathways.
- Depth to water table.
- Water table fluctuations.
- Single substances.
- Mixtures – equilibrium of phases and phase partitioning.
- Atmospheric variations – pressure and temperature effects.
- Water movement – Richard's Equation.
- Transport equations.
- Soil moisture.
- Spatial variability of soils – moisture, pressure, capillary fringes.
- Degradation.

In cases where buildings are present additional areas should be investigated including:

- All of the above.
- Interaction of building with soil surface vapour.
- Building structure and entry characteristics.
- Building ventilation characteristics.
- Atmospheric effects on buildings – pressure, temperature, wind.
- Internal spatial distribution of volatiles.
- Temporal changes within buildings.
- Relationships between internal volatile concentrations and variables influencing those changes.

11.2 Exposure assessment and population impacts

Research examining existing population impacts from vapour intrusion combined with improved understanding of inhalation dosimetry is required. Areas of suggested investigation include:

- Epidemiological studies across Australia examining vapour intrusion outcomes for chlorinated hydrocarbons and petroleum hydrocarbons.
- Determining effective dose considering time, duration and inhalation uptake.
- Short-term versus long-term exposures – how could differences lead to adverse pathologies?
- Time dependent versus averaged exposure – what is important to consider and why?
- Matching toxicological outcomes with exposure assessment for volatile substances of interest – what is the latest science?
- What are the worst case settings for confined environments in Australia?
- Which population exposures warrant the greatest concern?
- Development of indoor air sampling methods based on spatial and temporal indoor contaminant distribution.
- Development of non-invasive biological monitoring methods for vapour intrusion assessment.
- Assessment of relationships between inhalation dose and body burden.
- Development of exposure assessment tools aligned to biological markers of body burden.

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13 APPENDICES

Appendix 1

Summary of analytical methods for soil gas, indoor and ambient air samples (extracted from ITRC, 2014)

Table 11: Summary of analytical methods for soil gas, indoor and ambient air samples (from ITRC, 2014, pp236-238)

Parameter	Method	Sample media/storage	Description	Method holding time	Reporting limit
VOCs					
BTEX, MTBE, TPH	TO-3	Tedlar bag or canister/ambient temperature	GC/FID	3 days Tedlar or 30 days for canister	1–3 µg/m^3
Nonpolar VOCs	TO-14A	Canister/ ambient temperature	GC/ECD/FID or GC/MS	30 days for canister	1–3 µg/m^3
Polar & non-polar VOCs	TO-15	Canister/ ambient temperature	GC/MS	30 days for canister	1–3 µg/m^3
Low level VOCs	TO-15 SIM	Canister/ ambient temperature	GC/MS	30 days	0.011-0.5 µg/m^3
Polar & non-polar VOCs	TO-17[3]	Sorbent tube/chilled <4C	GC/MS	30 days	1–3 µg/m^3
VOCs	8021B modified[4]	Syringe, Tedlar bag, glass vial/ ambient temperature	GC/PID	On-site analysis or up to 30 days (depending on container)	10–60 µg/m^3
VOCs	8260B modified[4]	Syringe, Tedlar bag, glass vial/ ambient temperature	GC/MS	On-site analysis or up to 30 days (depending on container)	50–100 µg/m^3
SVOCs					
SVOCs	TO-13A[3]	High volume collection (may require large sample volume; e.g. 300m^3) /PUF/XAD media/Chilled <4C	GC/MS	Extracted within 7 days of collection; analyzed within 40 days of extraction	5–10 µg/sample

Parameter	Method	Sample media/storage	Description	Method holding time	Reporting limit
Low level PAHs	TO-13A SIM[3]	High volume collection (may require large sample volume; e.g. 300m^3) /PUF/XAD media/Chilled <4C	GC/MS	Extracted within 7 days of collection; analyzed within 40 days of extraction	0.5–1 µg/sample
SVOCs to C28	TO-173	Sorbent tube/chilled <4C	GC/MS	30 days	1–3 µg/m3
Pesticides & PCBs					
Pesticides & PCBs	TO-4A[3] or TO-10A[3]	High volume collection (may require large sample volume; e.g. 300m^3) /PUF media/Chilled <4C	GC/ECD	Extracted within 7 days of collection; analyzed within 40 days of extraction	Pesticides: 0.5 –1 µg/sample PCBs: 1 – 2 µg/sample
Fixed gases					
Fixed gases (methane, nitrogen, oxygen)	USEPA 3C	Canister or Tedlar bag/ ambient temperature	GC/FID	3 days for Tedlar bag 30 days for Canister	1000–2000 µg/m^3
Fixed cases (methane, nitrogen, oxygen, carbon dioxide, carbon monoxide)	ASTM D-1946	Canister or Tedlar bag/ ambient temperature	GC/TCD/FID	3 days for Tedlar bag 30 days for canister	1000–2000 µg/m^3
Natural gases	ASTM D-1945	Canister or Tedlar bag/ ambient temperature	GC/FID	3 days for Tedlar bag 30 days for canister	1000–2000 µg/m^3
TPH – alkanes					
C4–C24	8015 mod.	Canister or Tedlar bag/ambient temperature	GC/FID	3 days for Tedlar bag 30 days for canister	10 ppmv
C4–C12	8260	Canister or Tedlar bag/ambient temperature	GC/MS	3 days for Tedlar bag 30 days for canister	1 ppmv[3]

Parameter	Method	Sample media/storage	Description	Method holding time	Reporting limit
C4–C12	TO-15	Canister or Tedlar bag/ambient temperature	GC/FID	3 days for Tedlar bag 30 days for canister	0.1 ppmv

[1] This is not an exhaustive list. Some methods may be more applicable in certain instances. Other proprietary or unpublished methods may also apply.
[2] Reporting 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.
[3] The indicated methods use a sorbent based sampling technique. The detection limits will be dependent upon the amount of air passed through the media.

GC/MS = gas chromatography/mass spectrometry
GC/FID = gas chromatography/flame ionization detector
GC/TCD = gas chromatography/thermal conductivity detector
GC/ECD = gas chromatography/electron-capture dissociation
VOC = volatile organic compounds
PAH = polycyclic aromatic hydrocarbons
SVOC = semivolatile organic compounds

Appendix 2

Advantages and disadvantages of various investigative strategies (extracted from ITRC, 2014)

Table 12: Matrix of recommendations for various evaluation options for vapour intrusion (from ITRC,2014, pp239-241).

Measurement Approaches	Source at depth (>5ft) directly under building				Shallow source (<5ft) under building				Source in vadose zone adjacent to building				Special conditions			
	Undev. Site	Res. w/ basement or slab-on grade floor	Res. w/ dirt floor or crawl space	Comm./ Industrial	Undev. Site	Res. w/ basement or slab-on grade floor	Res. w/ crawl space or dirt floor	Comm./ Industrial	Undev, Site	Res. w/ basement or slab-on grade floor	Res. w/ crawl space or dirt floor	Comm./ Industrial	PHCs	Vapor Migration Routes	Wet basement	Very low permeability soils
Shallow groundwater (near water table)	●	●	●	●	●	○	○	○	○	○	○	○	◒	○	●	○
Deep (>5ft) soil gas	●	●	●	●	NA	NA	NA	NA	●	●	●	●	●	○	NA	NA
Shallow (5 ft) soil gas	●	●	●	●	●	●	●	●	●	●	●	●	●	●	NA	NA
Subslab soil gas	NA	●	NA	●	NA	●	NA	●	NA	◒	NA	◒	●	○	NA	●
Vertical profile of soil gas	○	○	○	○	NA	NA	NA	NA	○	○	○	○	●	○	NA	NA
Indoor air	NA	◒	◒	◒	NA	◒	◒	◒	NA	◒	◒	◒	◒	●	◒	◒
Ambient (outdoor) air	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Passive soil gas sampling	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	○1	◒

Measurement Approaches	Source at depth (>5ft) directly under building				Shallow source (<5ft) under building				Source in vadose zone adjacent to building				Special conditions			
	Undev. Site	Res. w/ basement or slab-on grade floor	Res. w/ dirt floor or crawl space	Comm./ Industrial	Undev. Site	Res. w/ basement or slab-on grade floor	Res. w/ crawl space or dirt floor	Comm./ Industrial	Undev, Site	Res. w/ basement or slab-on grade floor	Res. w/ crawl space or dirt floor	Comm./ Industrial	PHCs	Vapor Migration Routes	Wet basement	Very low permeability soils
Emission flux chambers	○	NA	◓	○	○	NA	◓	○	○	NA	◓	○	○	NA	NA	○
Tracers testing for alpha factor	NA	○	○	○	NA	○	○	○	NA	NA	NA	◓	○	○	NA	○
Tracer testing for ventilation rate	NA	○	○	◓	NA	○	○	◓	NA	○	○	○	○	○	○	○
Pressure differential monitoring	NA	○	○	○	NA	○	○	○	NA	○	○	○	○	○	NA	○
Real-time analyzers	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Meas-urement Approache-s	Source at depth (>5ft) directly under building				Shallow source (<5ft) under building				Source in vadose zone adjacent to building				Special conditions			
	Undev. Site	Res. w/ basement or slab-on grade floor	Res. w/ dirt floor or crawl space	Comm./ Industrial	Undev. Site	Res. w/ basement or slab-on grade floor	Res. w/ crawl space or dirt floor	Comm./ Industrial	Undev, Site	Res. w/ basement or slab-on grade floor	Res. w/ crawl space or dirt floor	Comm./ Industrial	PHCs	Vapor Migration Routes	Wet basement	Very low permeability soils
Meteorological data	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

This rating indicates that each tool can be used for the category lower in the hierarchy
[1]This is dependent on the passive sampler device

Key:

● = Primary investigative tool - data can potentially be used as a principle tool for assessing VI

◒ = Secondary investigative tool - can be used to develop CSM and/or as a line of evidence in support of another line of evidence

○ = Optional investigative tool - may be useful to further define VI pathway or as means to focus primary investigative tools

NA = not usually appropriate as an investigative tool for VI assessment

Appendix 3

Advantages and disadvantages of various investigative strategies (extracted from ITRC, 2014)

Table 13: Advantages and disadvantages of various investigative

Measurement	Advantages	Disadvantages	Comments
Deep soil gas (>5 ft. below slab)	• Existing data may already be available for some sites • Less chance of short-circuiting by atmospheric air • Temporal variations in concentration minimal	• Data may not be representative of soil gas concentrations at shallower depths due to intervening soil layers • Does not account for aerobic biodegradation in shallower soil layers	When combined with other data, deep soil gas data can provide evidence of biodegradation as a function of vertical transport distance. However, deep soil gas sampling is conservative for screening purposes.
Shallow soil gas (e.g., <5 ft. below slab or basement floor)	• Standard equipment and approaches have been developed • Media most likely to intrude into receptors • Data can be collected outside the building	• Rate of vapor transport to the building must be estimated • May not reflect subslab concentrations • Greater temporal variability than deeper soil gas data	Building zone of influence must be taken into consideration in sampling design. Shallow soil gas sampling may not be conservative for screening purposes.
Subslab soil gas	• Provides more representative subsurface data for sites with surface releases (e.g., spills & leaks) • Gives concentrations immediately below building and receptors	• May contain contaminants from interior sources • Highly intrusive; requires building access and drilling through slab/floor • Rate of vapor transport into the building must be estimated • Conservative screening levels	Preferred approach of many regulatory agencies Concurrent determination of slab-specific attenuation factor may be useful to interpret data.
Emission flux	• Measure actual contaminant emissions from subsurface • Takes into account all subsurface processes such as biodegradation, advection, sorption	• Equipment and experienced staff may be difficult to find • Selection of representative sampling locations may be difficult • Biased low results if emission "hot spots" are not sampled	This approach is best suited for evaluating future use scenarios on undeveloped land, houses with dirt floor basements or crawl spaces, and to confirm biodegradation in shallow vadose zone (<3' bgs).

Measurement	Advantages	Disadvantages	Comments
	• Eliminates interpretation using attenuation factor or model	• Not considered by most regulatory agencies	
Soil gas attenuation (α) factors	• Quick and very easy	• Attenuation factors used for this purpose tend to be very conservative (for instance., <<50th percentile) • Empirical attenuation factors may be biased high due to sources other than VI • No agreed upon attenuation factors for many regulatory jurisdictions	Attenuation factors may be based on empirical measurements of concentration ratios at other sites or on assumed Q_{soil} and building ventilation flow rates.
Slab-specific attenuation factor determination (from subsurface tracer)	• Naturally occurring compounds (for instance., Rn-222) can be used in some cases • Provides a direct measure of attenuation across a slab • Typical values often >10 times lower than default values	• Usually requires separate analytical method than that used for target compounds • If radon is used, investigator may find indoor concentrations exceeding health-risk levels • Radon not present everywhere at levels distinguishable from background	Method assumes that the tracer and subsurface contaminants move into the building at the same rate.
Indoor air	• Relatively simple to collect samples • Direct measurement of contaminant concentrations in buildings • May be more convincing to occupants	• Background sources complicate data interpretation • Requires access to indoor space • For residential sites, a building survey prior to sampling is often necessary • Very low reporting limits	Time-integrated samples are typically collected (e.g., 24-hr samples for residential sites and 8-hr samples for industrial sites).

Measurement	Advantages	Disadvantages	Comments
		may be required for some compounds (e.g., TCE) • One time sampling results may not be representative of long-term average concentrations • Poor sample control	
Crawl-space air	• Simple to measure	• Background sources from overlying structure may complicate data interpretation	Most guidance uses an attenuation factor of 1.0 between crawl space and indoor air
Pressure differential	• Relatively simple to measure • Can Provide evidence of direction of vapor transport (in or out)	• Requires subslab port or other subsurface sampling point • Temporal variations complicate interpretation and often requires multiple sampling events	Detection levels down to 1 Pa can be obtained using inexpensive 0 – 0.25” H_2O magnahelic gauge.
Building ventilation rate	• Very simple to measure (standard ASTM method exists) • For many commercial buildings, rate is already known from design specs • Value can be >10 times default parameters allowed in models	• For residences, seasonal variations may be large	Fewer sampling locations are needed if additional mixing of air within building is provided. Most commonly used for commercial receptors.
Forensics	• Can differentiate sources of contaminants	• Typically requires a significant amount of data • Methods still being developed	Forensic approaches are not likely to be used until later rounds of an investigation

Measurement	Advantages	Disadvantages	Comments
		• Background sources can complicate interpretation	
Continuous Analyzers	• Provides large amounts of data • Can help sort out temporal variations and background scatter	• Limited use	Larger data sets allow correlation to other variables such as pressure differentials, wind speed, and HVAC systems.
Soil Physical Properties	• Easy to measure • Enable site-specific values to be used in predictive models • Values can be >10 times default parameters in models	• Data collected near a building may not be representative of zone beneath building • Difficult to get rig near most residential buildings (e.g., lawns, landscaping, trees)	Most sensitive soil physical properties to measure are % water content and permeability.
Groundwater data	• none • Monitoring wells already exist for many sites (previous data) • Acceptable to most agencies • Familiar media to most investigators • Temporal effects minimal	• Look-up values, attenuation factors, or models tend to be extremely conservative, so VI risk often over-estimated. • Existing data may be from a well that is not optimally screened for upper water table	This approach is often used as an initial screen.
J & E model with groundwater or soil gas data	• Quick and easy • Model can account for various site-specific factors • Potential future scenarios can be evaluated	• Default input values to model tend to be very conservative • Pressure differential always assumed to be present (i.e., Q_{soil} assumed to be positive value) • Model does not account for	The accuracy of the model output is best if the pollutant transport distance is at a minimum (i.e., shallow soil gas is better than deep soil gas) and no partitioning calculations are needed (soil gas data are better than groundwater data).

Measurement	Advantages	Disadvantages	Comments
		biodegradation of BTEX or other compounds • Model is designed to evaluate residential scenarios and has some added limitations if used for other scenarios • Regulators may not accept results if depth to groundwater is <5 ft.	
Biodegradation Models	See Appendix H		

Appendix 4

Summary of mitigation methods (Extracted from ITRC, 2014)

Table 14: Summary of Mitigation measures (ITRC, 2014, pp303-305)

Technology	Typical applications	Challenges	Range of installation costs (per ft^2)(1)
Active system			
Subslab depres-surization (SSD)	Most structures; sumps, drain tiles, aer-	Low permeability and wet soils may limit performance, oth-	\$2–\$10/ft^2; residential sys-tems typically in the \$2-4/ft^2

Technology	Typical applications	Challenges	Range of installation costs (per ft²)(1)
	ated floors, and block wall foundations may also be depressurized if present	erwise, highly effective systems; may require a discharge permit	range
Subslab ventilation (SSV) or Crawl space venting□	New and existing structures relies more on influencing air flow over depressurization	Low permeability and wet soils may limit performance, otherwise, highly effective systems; may require a discharge permit	\$2–\$10/ft²; residential systems typically in the \$2-4/ft² range□
Submembrane depressurization (SMD)	Existing structures, crawl spaces	Sealing to foundation wall, pipe penetrations; membranes may be damaged by occupants or trades people accessing crawl space	\$1–\$6/ft²; residential systems typically in the \$1.50–\$2/ft² range
Subslab pressurization (SSP)	Same as SSD; most applicable to highly permeable soils	Higher energy costs (not included) and less effective than SSD; □potential for short-circuiting through cracks	\$1–\$5/ft²
Building pressurization	Commercial structures that are specifically designed	Requires regular air balancing and maintenance; may not maintain positive pressure when building is unoccupied and may have high O&M costs	\$1–\$15/ft²; heavily dependent on size and complexity of structure
Passive barrier			
Asphalt/latex membrane	Typically limited to new construction prior to flooring being installed and crawl spaces; retrofitting a building is possible with the installation of an additional protective barrier	Preventing tears and holes in the liner during installation; may not suffice as a stand-alone technology; must be chemically compatible with the COC	\$3–\$7/ft² for the system which includes liner costs of \$2–\$6/ft² and a passive venting system cost of \$0.75–\$2/ft² *see Note (2)
Thermoplastic liner	Typically limited to new construction prior to flooring being installed and crawl spaces; retrofitting a building is possible with the installation of an additional protective barrier	Preventing tears and holes in the liner during installation; may require seaming and taping; addressing subsurface penetrations; may not suffice as a stand-alone technology; limited vapor resistance testing available; may not suffice as a stand-alone technology	\$2–\$7/ft² for the system which includes liner costs of \$0.50–\$5/ft² and a passive venting system cost of \$0.75–\$2/ft² *see Note (2)
Epoxy floor sealant system	Retrofitting an existing structural slab in which a spray or roll is applied to seal floor	Existing surface preparations (oil and grease free, level, competent); ensuring total or complete coverage; preventing	\$1–\$7/ft² cost varies on the amount of surface preparations and leveling required. System may also

Technology	Typical applications	Challenges	Range of installation costs (per ft^2)(1)
	surfaces	tears, holes by building use; surface wearability and durability depending on application; may require subsurface venting as well as venting during placement	additional costs of a passive venting system cost ($0.75–$2/ft^2)
Passive Venting			
Subslab venting; perforated pipe/low-profile vent and gravel layer	New construction; existing construction would require additional surface protection	Relies on advective flow of air due to wind and heat stack effects; does not continuously operate; air flows and suction typically far less than achieved by active systems; limited regulatory acceptance	$0.75–$5/ft^2 plus the additional cost of an engineered base consisting of sand or gravel
Aerated flooring	New construction, complete floor replacement, or floor overlays	Relies on advective flow of air due to wind and heat stack effects to increase the oxygen; fans may require to achieve additional air flows and suctions; may not be effective for CVI	New construction, $2–$2.75 /ft^2 *see Note (2)
Other			
Indoor air treatment	For marginal or low impacts, immediate response actions to address vapor (short term), and expected short time frames for a completed remedial action	Typically generates a waste disposal stream; effective capture of air contaminants may be difficult; energy-intensive, with significant O&M burden	Costs are highly variable dependent upon the building layout, the number of rooms, contaminant, concentration and overall size in addition to the type of technology employed. $15,000–$25,000 per application is typical for treatment of a single 2,000 ft^2 area.
Sealing the building envelope		May not be effective over the long term	$2.50–$6/ft^2; cost varies depending on surface preparations

Notes:
(1) Costs for many of these technologies may be outside the ranges listed above due to many factors (such as regional contractor rates, regulatory review, access issues, and O&M).
(2) Estimated costs do not include the cost of any required additional protective barriers or construction overlays ($2–$4 /ft^2) not anticipated through normal construction practices.