The Society of Brownfield Risk Assessment

SOCIETY OF BROWNFIELD RISK ASSESSMENT

Vapour Intrusion to Support

Sustainable Risk Based Decision Making

Summer Workshop 2017

PUBLICATION

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PREFACE

The Society of Brownfield Risk Assessment (SoBRA) was established in December 2009 with the principal aim of promoting technical excellence in land contamination risk assessment in the United Kingdom (UK).

As part of achieving this aim, SoBRA undertook to host regular conferences and workshops on technical subjects of interest to UK risk assessors.

SoBRA's first Summer Workshop was held in June 2010 in York where the human health risk assessment of polycyclic aromatic hydrocarbons in soil was considered.

SoBRA's second Summer Workshop was held in June 2011 at the Mechanics Institute in Manchester. It addressed the assessment of the risks associated with lead contamination in soil.

SoBRA's third Summer Workshop was held in June 2012 at Armada House in Bristol. It addressed the assessment of risks associated with petroleum hydrocarbons in groundwater.

SoBRA's fourth Summer Workshop was held in June 2013 at the Priory Rooms in Birmingham. Rather than the usual thematic format established by previous events, the specific aim of the event was to support the Joint Industry Working Group (JIWG) risk assessment chapter. Therefore, the event focussed on the risk assessment aspects of asbestos throughout the CLR11 process.

SoBRA's fifth Summer Workshop was held in June 2014 at the Cathedral Centre in Sheffield. It addressed the assessment of risks associated with chlorinated solvents.

SoBRA's sixth Summer Workshop was held in July 2015 at the Miners Institute in Newcastle. It addressed uncertainty in human health risk assessment.

SoBRA's seventh Summer Workshop was held in June 2016 in the Engineers House in Bristol. It addressed the subject of site investigation and risk assessment for historic landfill redevelopment.

SoBRA's eighth Summer Workshop was held in June 2017 in St George's Hall, Liverpool. It addressed the subject of vapour intrusion to support sustainable risk-based decision making and is the subject of this report.

The aims and objectives of the day were put in context by the SoBRA Chairperson, Alex Lee, after which the delegates heard six presentations from expert speakers on different aspects of the vapour intrusion pathway, with an overall emphasis on improving understanding and practice. The presentations covered the topics of the conceptual site model, issues arising through poor installation of mitigation measures, pitfalls in the use of photo-ionisation detectors as a means of detecting soil vapours, a case study on the impact of the capillary fringe on vapour modelling, the potential to use vertical screening distances for petroleum hydrocarbons, and a consideration of options for the way forward for the investigation and assessment of the vapour intrusion pathway, inspired by current Australian practice and recent case studies. During the afternoon, expert speakers and delegates were divided into groups and participated in four workshops on the themes of: the conceptual site model; site investigation; development of alternative risk assessment techniques based on scientific studies; and how quantitative risk assessment can be used to evaluate mitigation measures.

Ninety delegates registered for the 2017 Summer workshop, including expert speakers and SoBRA Executive Committee members. Feedback provided by delegates after the event was extremely positive with more than 70% of responding delegates rating the event as "excellent" or "good" and over 97% of responding delegates giving positive feedback about the workshop sessions. Overall therefore the 2017 Summer Workshop consolidated SoBRA's commitment to hosting high quality and stimulating meetings on technical topics of relevance to its members.

This report fulfils an undertaking given by SoBRA to produce a formal record of the proceedings of the workshop. It summarises the expert presentations given on the day, records current views on the main technical issues within each subject area and describes the challenges identified by risk assessors in improving investigation and assessment of the vapour intrusion pathway.

Supporting technical excellence and promoting good practice are embedded within SoBRA's core objectives for all members. By publishing this report SoBRA is signalling its strong commitment to upholding the highest possible standards of risk assessment practice in the UK, with the hope and expectation that this will lend much needed support to practitioners, regulators and others who share the same, important objective.

ACKNOWLEDGMENTS

SoBRA wishes to thank the following individuals for their considerable assistance in the successful delivery of the SOBRA 2017 Summer Workshop and associated report.

Alex Lee	WSP	Workshop Chair
Geraint Williams	ALS	Workshop Organiser
Paul Nathanail	University of Nottingham Land Quality Management	Speaker
Jonathan Cundall	NHBC	Speaker and Workshop 4 facilitator
Neil O' Regan	Shawcity	Speaker
Tom Parker	Argentum Fox	Speaker, Workshop 2 facilitator and Editor
Matt Lahvis	Shell	Speaker and Workshop 3 facilitator
James Lucas	EPG	Speaker
Judith Nathanail	Land Quality Management	Workshop 1 facilitator
Sarah Mortimer	EPG	Workshop 1 rapporteur
Ray Watson	RSK	Workshop 2 rapporteur
Paloma Montes	WSP	Workshop 3 rapporteur
Emily Upton	Atkins	Workshop 4 rapporteur
Naomi Earl	Freelance Consultant	Report Main Author and Editor

Special thanks are due to Naomi Earl and Tom Parker who have authored this document, the SoBRA Executive Committee, especially Hannah White (Atkins/ NGP and SoBRA's Treasurer and Vice Chair) who looked after financial matters, David Schofield (Ramboll and SoBRA's Secretary) and David Jackson (Wakefield Council and SoBRA's website coordinator) who coordinated bookings, and again, finally to our Chair for the event, Alex Lee (WSP and SoBRA's Executive Committee Chair) for providing a thought provoking introduction to the event.

Finally, SoBRA wishes to acknowledge the contribution to the overall success of the event made by individual workshop delegates for attending and enthusiastically participating in the day's proceedings.

Workshop delegates are listed in Appendix 1 to this report.

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1 INTRODUCTION

1.1 Chair Person's Thoughts

The 2017 Summer Workshop took place within the beautiful blue and gilt setting of the Concert Hall in St George's Hall, Liverpool. SoBRA's chairperson, Alex Lee, gave the delegates a warm welcome on one of the hottest days of the year, remarking that the venue was one of the first buildings in England to have air conditioning. He explained that the aim of the day was to consider different aspects of vapour intrusion (VI) to support sustainable decision making, all the way through from the Conceptual Site Model (CSM) through to complex risk assessment, stating that the ultimate objective was to promote positive change. He also suggested that we all, as risk assessors, "*individually seek to identify and implement our own small and easy bright spots that may make a difference to the way we operate*".

Alex provided an interesting perspective, referencing Thomas Kuhn's, 1962 work, The Structure of Scientific Revolutions[1] and Kuhn's concept of a "*paradigm shift*". This theory was controversial at the time and contrasted with the traditional Whig interpretation of scientific progress. The latter suggested past researchers, theorists and experimenters had engaged in a long march, if not towards "*truth*", then at least towards an ever-greater understanding of the natural world. Instead, Kuhn postulated that scientific progress was achieved through alternating "*normal*" and "*revolutionary*" phases, with the latter being characterised by a period of "*turmoil, uncertainty and angst*". During the "*normal*" phase, Kuhn argued that scientists and practitioners work on resolving differences between what the paradigm predicts and what is revealed by observation and experiments. Alex quoted Ian Hacking and his preface to the new edition of Structure of Scientific Revolutions that "*Normal science does not aim at novelty but at clearing up the status quo. It tends to discover what it expects to discover.*"

He observed that during this normal phase, Kuhn argued that last thing that people are trying to do is to refute established theories. This continues until it becomes impossible to reconcile observations with the received wisdom, at which point discontent builds until a revolutionary phase is initiated. Thus, for most of the time,

[1] Kuhn , T . *Structure of Scientific Revolutions*: 50th Anniversary Edition, 2012 (original 1962), University of Chicago Press.

normal scientists and practitioners actively avoid refuting the theories embedded in their paradigm.

Alex noted that a contrasting view has been offered by the philosopher Karl Popper, 1963 in the paper "Conjectures and Refutations"[2]. Popper asserted that a good scientist should try to refute, rather than confirm theories, with an emphasis on attacking dominant theories. In the eyes of Kuhn, science could never progress if scientists busied themselves attacking the accepted theories, but Popper emphasised the importance of overthrowing theories that may well prove false for their designers and users.

Alex stated that there was no immediate resolution of these two viewpoints but that there is a middle ground where a scientist should be free to both accept and/ or critically challenge the paradigm. He sought to remind delegates that "*as practitioners we are free to listen, but maybe we should also be critical and formulate our own ideas*". He considered that the objective for the day was for the delegates to play an active role in changing the way that risk assessors think about VI, rather than taking the passive role typical of many conferences. He asked that participants "*listen, formulate, and be willing to challenge the paradigm*", so that the profession could advance. He reminded the audience that no question was a silly question, and that he required them to be "*politely objectionable*", embracing "*any change, turmoil or angst it may bring as simply part of the journey*".

1.2 The SoBRA Workshop

The objectives of SoBRA's Summer 2017 Workshop were to define the current state of good practice for site investigation, risk assessment and assessment of mitigation measures for the VI pathway, to establish how this can be disseminated more widely throughout the profession, and to explore further improvements which could be implemented to ensure that decisions made to mitigate the pathway are robust and sustainable.

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[2] Popper, K. *Conjectures and Refutations: The Growth of Scientific Knowledge*. Routledge Press, 2nd edition, 2002 (original 1963).

The specific aims of the workshop were to:

- Provide high quality speakers who could outline the challenges faced for their topic area that affect the evaluation of the vapour intrusion pathway, including CSM, site investigation, modelling and installation of mitigation measures; and
- Break out into workshop groups to discuss issues pertaining to a topic area in more detail and identify how such issues might be resolved. The four topic areas were:
    - CSM;
    - Site investigation;
    - Development of alternative risk assessment techniques based on scientific studies; and
    - Evaluation of mitigation measures using quantitative risk assessment.

1.3 Structure of the Report

A specific goal of the workshop organisers was to produce a formal workshop output that summarised the proceedings, consolidated the ideas expressed, and made recommendations on the work required to support risk assessment efforts in the future. This report is that written output.

Following this introduction, Section 2 of the report summarises the presentations given by the five expert speakers. These cover the breadth of the technical challenges inherent in the different stages of the assessment of the vapour intrusion, and provide a common background for the afternoon workshop discussions.

Sections 3 to 6 summarise the workshop discussions on each of the four themes.

Section 7 of the report draws on the outcome of the workshop discussions, identifies some common issues and highlights key recommendations.

Reference documents used to support presentations and workshop discussions are shown as footnotes to the text the first time that they occur in each Section (or sub-section where they occur within an expert presentation), and are collated as a complete list in Section 8 of the report.

Appendix 1 gives details of the workshop groups including names of individual participants. Appendix 2 sets out a list of the abbreviations and acronyms used in the report.

2 EXPERT PRESENTATIONS

2.1 Conceptual Site Models for Vapour Intrusion, Investigation, Risk Assessment and Remediation

Professor Paul Nathanail of Nottingham University and Land Quality Management began his presentation by asking the delegates to stop thinking of themselves as scientists and instead remember that they were "*servants of society*", tasked with ensuring that people can "*live in homes which are safe and not killing them*". In addition, delegates should be asking themselves what they had to offer to the people who had ultimately paid for them to spend time in grand venues, such as the Concert Hall, attending conferences. He asked the pertinent question of what was intended by the word "*sustainable risk-based decision making*" within the workshop's title, and whether it was intended to refer to "*defensible decision making*", "*reasonable decision making*", or whether the word "*sustainable*" was simply a seasoning akin to parsley.

Paul introduced his take home messages about VI:

- The Part 2A[3] and Planning regimes require different responses to vapour intrusion uncertainty;
- The CSM needs to reflect the legal context, as it drives the site investigation, informs the risk assessment, and supports remediation option appraisal;
- A VI CSM is no different from any other CSM and should include all contaminants;
- Petroleum hydrocarbons biodegrade within the unsaturated zone, but chlorinated solvents 'do not';
- Soil does not usually come in "*Continuous Horizontal Homogeneous layers*" (CoHHLa);
- Capillary fringe processes are important; and
- Preferential pathways (natural and man-made) are key (vapours are "*lazy*" and will take the path of least resistance).

Paul reiterated that not only are CSMs not optional but they are also very useful, even though there is an inherent problem because ideally CSMs would be four-dimensional,

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[3] Department for Environment, Food and Rural Affairs (Defra), 2012. *Environmental Protection Act 1990: Part 2A Contaminated Land Statutory Guidance.* April 2012.

accounting for changes over time, rather than simply three-dimensional. Formats need to include cross sectional plans, as well as a source-pathway-receptor topological diagram, which should also clarify whether barriers to pathways exist to inform decision making. Explicit inclusion of uncertainties within the CSM is required.

He paraphrased the adage that "*all theories are wrong, but some are useful*", by stating that "*all models are wrong, but some are sometimes useful*". Understanding building design and construction is essential as foundations that are piled or on pads will be fundamentally different. If there is an occupied basement there will be additional pathways through the walls, because they will also be in contact with the soil. Understanding the source term, including whether there is Light Non-Aqueous Phase Liquid (LNAPL) or Dense Non-Aqueous Phase Liquid (DNAPL) provides vital information about the path that a migrating plume is likely to take.

The term VOC (volatile organic compound) covers a broad spectrum of contaminants, including chlorinated solvents, hexachlorobutadiene, and the benzene, toluene, ethyl benzene and xylenes (BTEX) group. The World Health Organization (WHO) categorises *indoor* pollutants (WHO, 1989)[4] as:

- VVOC (very volatile (gaseous) organic compounds) which have a boiling point of <0°C up to around 50-100°C;
- VOC which have a boiling point of around 50-100°C up to 240-260°C; and
- SVOC (semi-volatile organic compounds) which have a boiling point of 240-260°C up to 380-400°C.

The Interstate Technology & Regulatory Council (ITRC) state that "*when contaminant vapors (partition) from contaminated soil and groundwater migrate upward into overlying buildings and contaminate indoor air, the process is known as vapor intrusion*" (ITRC, 2014)[5] and provide a schematic CSM which illustrate the process.

[4] World Health Organization, 1989. "*Indoor air quality: organic pollutants.*" Report on a WHO Meeting, Berlin, 23-27 August 1987. EURO Reports and Studies 111. Copenhagen, World Health Organization Regional Office for Europe, cited within https://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds, accessed on 20th December 2017.

[5] ITRC (Interstate Technology & Regulatory Council). 2014. *Petroleum Vapor Intrusion Fundamentals of Screening, Investigation, and Management*. Interstate Technology and Regulatory (ITRC) PVI guidance (http://itrcweb.org/PetroleumVI-Guidance/) Accessed 20th December 2017

Paul commented that these CSMs still depict soil as continuous horizontal, homogeneous layers, when they will not be and this will add exponentially to the complexity of the CSM.

The legal context is everything when considering CSMs. The existing (or foreseeable) land use, and whether there is a source, receptor and one or more pathway(s) is all important for:

- Part 2A of the Environmental Protection Act, and the question of whether there is "*significant possibility of significant harm*" (SPOSH) or statutory nuisance;
- Environmental Liability Directive[6], transposed into the Environmental Damage Regulations (2015)[7] and the question of whether there is "*damage*" as defined within those regulations.

When considering a planning context, the big questions involve a change in the land use. Clearly changes from one land use scenario to another, for instance a derelict brownfield site being developed for housing, will introduce additional pathways and receptors. However, the construction process itself will result in significant changes within the CSM. The source itself may be removed during changes to site levels, for instance if it is a shallow, discrete hotspot of impacted soil that has not migrated or leached to groundwater. New pathways may be created, for instance by installation of foundations, or horizontal pipe runs. Pathways may also be interrupted during building construction.

Within the broader VOC category, fate and transport within the sub-surface environment varies considerably, especially between chlorinated VOCs (CVOCs) and petroleum VOCs (PVOCs). Screening values, especially those which are based on empirical data reflect this. There is 'no' (*i.e.* very limited) degradation in the unsaturated zone for CVOCs, whereas PVOCs degrade in the unsaturated zone due to

[6] *Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage*, accessed 12th July 2017 http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32004L0035

[7] *The Environmental Damage (Prevention and Remediation) (England) Regulations 2015. No. 810*, accessed 12th July 2017 from http://www.legislation.gov.uk/uksi/2015/810/body/made

their rapid breakdown by microorganisms (ITRC 2007[8], ITRC 2014[9]). However, where there are preferential pathways all VOCs can move along these rapidly before biodegradation can take place.

Paul spoke about how difficult it can be to resolve a VI issue once construction has taken place. He recommended the book Toxic Town, IBM, Pollution and Industrial Risks (Little, 2014)[10], as an unvarnished account of the feelings of the residents of Endicott, where pumps and barriers had been retrofitted as risk control measures for an underlying trichloroethene (TCE) plume, resulting from IBM's industrial operations. Paul used the quote "*mitigated landscape, unmitigated disaster*" and noted that social science needs to be incorporated into mitigation strategy choices.

Paul provided a useful summary of the two stages of the journey that need to happen for the vapour intrusion pathway to be complete - getting out of the soil and getting into the home. Leaving the soil involves passage through the capillary fringe, volatilisation and vapour transport (and the absence of attenuation/ biodegradation). Entering the home may take place via a variety of entry points, including cracks, service pipes, faulty barriers, and tracking back, and may be influenced by the presence of other sources. It is essential to think about where the junctions and joins may be and these will differ according to building construction. A basement with a concrete floor will have different entry points from one with a dirt floor or crawl space, and a house founded on a concrete slab will be different from a mobile home or prefabricated building. However, in every case there are weaknesses and discontinuities within the construction materials, as well as seals where construction materials join or services enter the buildings. Vapours may be carried into a building along with sewer gas, or may enter the groundwater from sewage pipes containing sludge laden with VOCs from industrial sources.

The water profile also plays an important part. In the groundwater within the saturated (phreatic) zone VOCs may be chemically bound, or physically constrained in

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[8] ITRC, 2007 *Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios. A Supplement to Vapor Intrusion Pathway: A Practical Guideline* ITRC June 2007.

[9] ITRC, 2014. *Petroleum Vapor Intrusion Fundamentals of Screening, Investigation, and Management*. Interstate Technology and Regulatory (ITRC) PVI guidance (http://itrcweb.org/PetroleumVI-Guidance/) Accessed 20th December 2017

[10] Peter Little, 2014. *Toxic Town: IBM, Pollution and Industrial Risks*. New York University Press, New York).

unconnected pores within the rock, limiting their volatilisation. To enter the unsaturated (vadose) zone as soil vapour they need to pass through the capillary fringe where they can be retarded by capillary water.

Paul stated that "*openings*" within the soil and rock are key, and it is important to recognize that these vary in size, so risk assessors should challenge the paradigm of treating all soils and rocks as homogeneous. Continuous air spaces within porous soils (primary openings) will differ in volume and number between a poorly sorted and a well sorted sand. Fractures within rocks like granite are an entirely different entity from the caverns within rocks such as limestone, although both are secondary openings.

Simplistic CSMs often show vapours moving vertically through stratigraphic soil and rock sequences. It is, however, much easier for vapours to move along wide horizontal planes along bedding sequences than to find narrow vertical discontinuities. It is essential to understand the stratigraphy, both the overall sequence and whether there are features such as wedges or fingering. On site, there is no substitute for detailed logging, noting faults within the sediment, and ensuring that soils are not described as CoHHLa when this is clearly not the case. While Hazen's rule for permeability works on the assumption that permeability is related to the *D10* particle size, this uses a disturbed sample. Permeability will be much greater within horizontal layers and hydraulic conductivity estimates based on the particle size distribution (PSD) curve of the resulting homogenised sample are likely to be unrepresentative of the *in-situ* hydraulic conductivity.

Sequence stratigraphy is vital. For example, fining upwards is important. This is illustrated by the Reading Formation underlying the London Clay which is described by Ellison and Williamson (1999)[11] as a "*series of fining upwards cycles… each cycle commencing with a bed of cross-bedded sand, grading upwards into sporadically burrowed, thinly laminated silt and sand, and culminating with mottled clays with rootlet traces and nodular calcrete*". Applying Hazen's rule to a disturbed sample of this fining up sequence would not be appropriate. Fractures will have a permeability that is proportional to their length and width.

[11] Ellison, R A and Williamson, I T. 1999. *Geology of the Windsor and Bracknell district - a brief explanation of the geological map. Sheet Explanation of the British Geological Survey. 1:50 000 Sheet 269 Windsor (England and Wales).*

Paul returned to his message of being servants of society, reminding the delegates that although they may sometimes over-remediate, at other times there may be a genuine problem. Everyone should therefore beware of allowing familiarity to breed contempt, as being close to a problem can be blinding. Risk assessors have a duty of care to the people who live on the sites they investigate. Where a problem is identified it is important to face up to it head on, as was done by ICI at Weston Quarry. Paul illustrated this by providing a case history from Bonttdu in Wales, quoted within BS8576:2013[12] where a leakage from a petrol station occurred in 1996, involving more than 30,000 litres of petrol from underground tanks at a service station into the Mawddach river. Villagers complained of petroleum odours to Gwynedd Council and some families were evacuated because the smell routinely resulted in headaches. Paul quoted the MP, Elfyn Llwyd, who spoke of being told by experts at a public meeting that "*the public were safe*" and that "*there was no danger*" continuing, "*a few weeks later, not surprisingly, there was an explosion in one of the houses near the polluted site-a build up of gases and bang. It was safe to assume now that there was a danger to the public*". The MP stated, "*Most people would consider that a danger arises as soon as highly flammable liquid escapes…*"[13] and went on to describe a senior fire officer who, prior, to the explosion, had attempted to alleviate concern and demonstrate the lack of risk by throwing a lighted taper into the ravine at Bonttdu, in fact causing an explosion that caused him to run away. Exploratory investigations established that petrol vapours had migrated beneath a residential property, igniting and causing an explosion. In this case, experts were so comfortable with petroleum as a substance they dealt with regularly, that they had overlooked the inherent danger.

2.2 What can go Wrong with Installed Mitigation Measures On-Site Pitfalls when Measuring VOCs

Jonathan Cundall (National House-Building Council (NHBC)) gave a presentation about NHBC's experience of issues with installed on-site mitigation measures.

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[12] British Standards Institute, 2013. BS 8576:2013, *Guidance on investigations for ground gas. Permanent gases and Volatile Organic Compounds (VOCs)*.

[13] Hansard https://publications.parliament.uk/pa/cm200203/cmhansrd/vo030107/halltext/30107h04.htm, accessed 20th December 2017.

Jonathan began by introducing NHBC, which was established in 1936 as a government initiative to improve the quality of new build, and which operates a non-profit distributing company. He explained that the NHBC is primarily an insurance company, which avoids claims by setting standards and monitoring their implementation. Implementing these standards also enables people to buy safe homes and allows builders to protect and improve their reputations. In 1968 NHBC brought in their ten-year warranty, with an 'Approved Inspector' licence granted in 1985 within England and Wales. Currently 1.6 million homes are warranted under the scheme, and NHBC has an 80 per cent market share. The Council of Mortgage Lenders requires a warranty to be in place before mortgage funds are released, meaning that if a property does not have a warranty, the house-builder will effectively be unable to sell it. NHBC will not release the warranty where:

- Issues remain that would result in a claim;
- Major issues exist that may affect the health and safety of the occupants; or
- There are outstanding issues that would cause significant disruption to the homeowner during rectification.

Jonathan emphasised that occurrences of vapour intrusion meet the above criteria, because they potentially affect the health and safety of residents, and, if retrofitting is required, lead to major disturbance. He explained that since 1998 the Buildmark Warranty had covered contamination of the land on which the house was built, in anticipation of the introduction of Part 2A of the Environmental Protection Act 1990. Regularly revised NHBC Standards, which are designed to exceed building regulation requirements, set out the technical requirements, performance standards and guidance for the design and construction of homes acceptable to NHBC. Chapter 4.1 of the NHBC Standards covers contaminated land and geotechnical issues, providing a framework and laying out expectations for managing ground conditions. Where NHBC is acting as the Building Control Body, they also assess contamination aspects under Part C of the Building Regulations[14]. NHBC's team of surveyors, engineers and geo-environmental engineers assess technical submission, while building inspectors attend on site, where NHBC is appointed for building control. One of the issues that they check for is whether, if a vapour membrane is part of the design, it is of the correct

[14] The Building Regulations (2010), *Part C Site Preparation and resistance to contaminants and moisture*, downloaded from https://www.gov.uk/government/publications/site-preparation-and-resistance-to-contaminates-and-moisture-approved-document-c 18th January 2018.

specification and has been appropriately installed by specialist contractors. The inspection process does not, however, involve supervision of site work, 'snagging' new homes on behalf of purchasers, inspecting every element of construction or guaranteeing that homes are defect-free or fully compliant with the standards. There is an element of trust in professionals.

Jonathan continued his presentation by stressing that for the assessment of gas and vapour risks, as for any other risk assessment, getting the CSM right is the most important step, with many subsequent issues arising from getting it wrong. Important questions to ask include:

- Is there any actual source or an ability to create a risk, and if so is there a valid linkage?
- Has there been sufficient monitoring/coverage to assess the risks adequately and if the site is to be zoned, is the data sufficiently robust to do so? Have other lines of evidence such as RB17 (CL:AIRE, 2012)[15] been considered?
- Does the monitoring truly represent the site and risks? For instance, has protection been recommended because of gas found in one deep well, while no gas has been found in shallow wells? Has the actual risk potential been assessed using the Appendix within NHBC 2007, rather than simply using typical maximum concentrations as a blind trigger?
- Do the proposed mitigation measures take account of the actual construction methods and details, including earthworks proposals, floor and foundation types? Will subsequent changes to the site such as sealing or dewatering cause a change in conditions and hence the risk? Could a pathway be created by building or foundation design? For instance, stepped walls involve wall ties which will penetrate the membrane, and vibro stone columns may create pathways to deeper soils.

Jonathan presented two case studies. The first involved a former colliery, including shafts, and colliery spoil underlying the site to a depth of 5 metres (m). The well spacing was rather low. The five wells were screened to 4 m. Six rounds of monitoring were completed over a seven week period in winter, meaning that a full range of environmental conditions were not observed. The principal findings were a maximum

[15] CL:AIRE, 2012. *Research Bulletin 17, A Pragmatic Approach to Ground Gas Risk Assessment*.

concentration of 2.7% volume/ volume (v/v) methane, and carbon dioxide exceeding 5% v/v for four rounds out of six, with a maximum concentration of 10.3% v/v. Flow rates were low, with a maximum flow of 0.5 litres/hour (l/hr). The gases were present mainly in one area of site, in which there were 21 plots. The CSM that was developed attributed the elevated carbon dioxide to the presence of shallow groundwater, resulting in a pumping effect, although the evidence presented was not conclusive. Amber 1 mitigation measures were proposed, with suspended beam and block and a proprietary gas membrane. This initially appeared reasonable.

However, in the calculations on which the NHBC Traffic System is based, achieving one air change per 24 hour period is critical (NHBC, 2007)[16]. In this case, the installation of level access thresholds limited the inclusion of crank vents, reducing sub-floor ventilation rates. The properties were terraced, only ventilated with one vent brick each at front and rear. They were therefore unable to achieve one air change in the sub-floor per 24 hour period. It is notable that the calculations supporting the NHBC Traffic Light system are for a single 8 m by 8 m dwelling, and are therefore not directly applicable to terraced housing. The lack of sufficient ventilation was flagged by the inspector, but relatively late in the process. With a lack of sufficient ventilation, the gas control measures assumed greater importance. Unfortunately, during the installation the membrane was cut off at the cavity and not sealed around the door thresholds. Moreover, the membrane was not lapped with the cavity tray, resulting in a risk of ingress to the cavity and hence to habitable spaces. Post-construction monitoring in well and sub-floor with GasClam and spot monitoring found methane levels at 41.8 % v/v, and carbon dioxide at 21.5 % v/v with flow rates of 6.6 l/hr in the wells, with methane recorded at 0.15 % v/v in the sub-floor. The site was consequently reassessed as Characteristic Situation 3/ Amber 2. Remedial mitigation was thus required to remedy the deficiencies in the gas protection measures. As the plots had already been constructed, with a 2000 gram (g) membrane installed, the only option was to increase ventilation and limit gas ingress rate to the cavity and sub-floor void. The Remedial measures included excavating a trench around the perimeter, drilling through to the sub-floor, the installation of external vent boxes and preformed cavity closers at door thresholds, and filling the cavity below the tray with foam, which expands to fill the void, limiting gas ingress.

[16] NHBC, 2007. *Guidance on Evaluation Of Development Proposals on Sites Where Methane And Carbon Dioxide are Present*.

There are several lessons to be learned from this case study. Firstly, lack of sufficient gas monitoring over an adequate duration did not provide a realistic representation of the risk; improved monitoring could have proven the high risk at the outset, leading to enhanced gas protection measures. Better design, with due consideration for the ventilation required for terraced housing (ventilation to sleeper/ party walls can be critical for middle terraced properties) and the impact of level access, would have avoided the three month delay, and approximately £200,000 costs to retro fit measures to 21 plots. Poor installation on-site exacerbated the situation. If the remedial work had not achieved the required ventilation, demolition or significant reconstruction would have been required.

The second case study involved a former airfield, with a 0.5 m thick layer of peat and relic topsoil/ alluvium in lenses around the north of the site, and Made Ground to a depth of 2.9 m. There was a good level of site investigation with 66 wells, appropriately spaced to give adequate coverage and screened to target the sources, with twelve monitoring rounds over a ten month period. Across the wider site, elevated gases were found in wells with no obvious source, with methane concentrations up to 71.2 % v/v, carbon dioxide up to 20.5 % v/v, and flows up to 4 l/hr. It transpired that the sand lenses were providing a preferential pathway, leading to the site being zoned for gas mitigation (Green, Amber 1 and Amber 2). The detailing on the gas protection designs was robust, involving vented suspended beam and block floors. The gas measures were installed and inspected by a third party. However, subsequently a change in management resulted in confusion in the instructions given to groundworkers, who removed the shuttering between the internal walls, cutting through the membrane in the process. Remedial measures were required. The screed and internal blockwork around the damage were broken out to expose the gas membrane, which was then overlapped and sealed and patched where necessary. The blocks were replaced and the void filled with closed cell foam, with a liquid membrane used to provide a seal at the surface.

Some important lessons can be learned from this case study. One involves the keeping of detailed records of what takes place on site, such as the information given to follow-on trades who may inadvertently damage or compromise the gas protection. It transpired that only one house type with double internal walls was affected. Only eight plots on the site had this design and only two plots were actually identified with damage. However, in the absence of information, all house type plots needed to be broken out to check; some of these had already undergone plastering. The other key lesson is that gas mitigation design should always be reviewed in the context of the building design, both so that it can be installed easily and to minimise the chance of damage after installation. There was no need for the membrane to go over the internal shuttering for the blockwork. Future plots were consequently designed with the membrane running flat over the block and beam floor, below the internal blockwork.

Jonathan also highlighted the importance of a detailed understanding of topography when designing gas protection measures, with an example of a site where a slope was not considered when designing the membrane seal around the wall ties. In this case a liquid membrane, installed by a specialist contractor, was required.

Jonathan concluded that, other than flaws in the CSM, many cases where NHBC observe inadequate or incorrect gas measures are due to either poor design or poor workmanship. The majority of these instances could be avoided with adequate initial gas monitoring/ characterisation, especially on low risk sites, where mitigation may not even be required if a more detailed assessment, weighing up the lines of evidence, is implemented. This becomes an issue because where mitigation is recommended and poor installation occurs, builders must choose to either carry out interim monitoring to assess if the risk is genuinely present or opt for expensive remedial measures. Most opt for remedial measures due to concerns that monitoring may confirm there is a risk and the remedial work will be required anyway. Thus, good characterisation, design and workmanship obviate many of the issues where NHBC require action.

2.3 Common Pitfalls when measuring VOCs

Neil O' Regan (Shawcity) gave a talk about how to achieve the best results when using a Photo Ionisation Detector (PID) on site and how to avoid the most common pitfalls.

He introduced PIDs by explaining that the general principle was the same across the instruments made by different manufacturers (and indeed the same technology can be embedded in a GasClam). PIDs are a good on-site screening tool for a broad look at whether VOCs are present, so that operatives can make decisions about which soils to target for more detailed analysis. VOCs can be categorised according to their Ionisation Potential (IP), which is the energy required (measured in Electron Volts (eV)) to displace an electron and ionise the gas. If the IP of the contaminant is less than the eV of the energy source, the contaminant will be ionised and detected. On a standard PID, using a 10.6 eV lamp, Ultraviolet (UV) light ionises the VOC gases. The ionised particles are attracted to high voltage plates that create an electrical signal.

PIDs can detect a broad range of VOCs, including both organic and inorganic compounds. Organic compounds include aromatic compounds (*e.g.* the BTEX compounds), ketones and aldehydes, alcohols, saturated hydrocarbons chlorinated hydrocarbons and sulphur compounds (mercaptans). Inorganic compounds include ammonia, arsine, iodine and nitrous oxide.

Table 1 shows some of the IPs for some example VOCs.

Table 1 Example IPs for VOCs

Contaminant	IP
Benzene	9.24
Ethylbenzene	8.76
Toluene	8.82
Xylene	8.56
Ethanol	9.51
Butadiene	9.07
Butane	10.63
Octane	9.82
Acetone	9.71
Methyl ethyl ketone or MEK	9.54
Acetaldehyde	10.22
Diethyl amine	8.01
Ammonia	10.18
Arsine	9.89
Iodine	9.31
Nitrous oxide	9.58
Phosgene	11.55

PIDs cannot measure:

- Radiation;
- Principal gases in air (nitrogen, oxygen, carbon dioxide);

- Water vapour;
- Some toxic gases (carbon monoxide, hydrogen cyanide, sulphur dioxide);
- Natural gas (methane and ethane);
- Acidic gases (*e.g.* hydrogen chloride, hydrogen fluoride, and nitric acid);
- Freons; or
- Ozone.

They also cannot speciate or provide accurate measurements for any single VOC, even when only a single VOC is present; this requires a sample to be analysed using gas chromatography (GC). Neil explained that this is because different contaminants have different correction factors when compared to the calibration gas, isobutylene. For instance, benzene has a correction factor of 0.53 and ethylene of 9.90. Thus, a PID reading of 100 parts per million (ppm) could mean either 53 ppm of benzene or 990 ppm of ethylene.

Neil explained that combustible gases, such as methane, are an issue because high concentrations of methane can 'quench' the PID signal. He illustrated this by showing the effect that different concentrations of methane have on the PID reading for 50 ppm of hexane; at 0.25 % v/v methane the reading will be marginally affected, falling to 49 ppm. However, the effect is non-linear and when concentrations rise to 2.5% v/v methane, only 26 ppm of hexane, only marginally above half the original concentration, is detected. Methane readings should always be taken in conjunction with PID readings.

Traditionally PID detectors are affected by humidity in the atmosphere during measurement because the moisture is conductive. This can result in a false high reading. Ion Science Ltd has developed a third electrode to minimise the effects of humidity, while other manufacturers use compensation formulas built into the software. Conversely, high levels of moisture in the atmosphere can result in a 'false negative' reading, especially if the weather is colder. Instruments which are stored overnight in vehicles or unheated buildings will take a little longer to warm up. If moisture condenses inside units, instruments are likely to give erratic, unstable or false readings.

It is important to select the correct lamp for the VOCs being targeted on site and to recognise a lamp's specific limitations. Most contaminants can be detected using either a standard 10.6 eV or 9.8 eV lamp, both of which will last approximately two years if well maintained. However, some VOCs, such as carbon tetrachloride, methylene chloride and acetic acid require an 11.7 eV lamp. 11.7 eV lamps are very specialist, very unstable, and deteriorate quickly, lasting only two weeks to a month. Neil advised that other alternatives be sought if the presence of these VOCs is suspected.

Neil concluded his presentation by giving users advice on maintenance. Site operatives should clean their lamps (9.8 eV and 10.6 eV) regularly, and not as part of annual servicing, and this is a straightforward process. Cleaning should be done using aluminium powder and a cotton bud (avoiding cross-contamination from clothing or fingers). The polytetrafluoroethylene (PTFE, Teflon) filter should be regularly inspected for obvious defects, kept dust free and changed for every 100 hours use, or less in dusty or moist atmospheres. Customer calibration before use is essential, with calibration by an accredited laboratory on an annual basis. If users need to use extension tubing to connect to a PID, this must also be PTFE. Other materials, such as Tygon and rubber may absorb VOCs, resulting in a lower reading. Tygon tubing, can, however, be used for the initial calibration because it does not sorb isobutylene.

2.4 A case study demonstrating how we model including the effect of the capillary fringe

Tom Parker of Argentum Fox gave a presentation which used real site data (since published as Parker *et al.*, 2017)[17] to highlight the potential impact of the capillary fringe and conceptual model on vapour intrusion. The study site had an unoccupied Victorian-era house with both suspended and solid floors, both of which are of interest in vapour intrusion. Many factors introduced uncertainty. For example, while investigating the difference in behaviour while vapour migrated below, and through, suspended and solid floors was an objective of the study, one uncertainty was whether the close proximity of both floor types meant that they were influencing each other at this site. Another uncertainty was whether stack effects, which sucking vapour into the building, would be reduced with no heating in the building.

The geology of the site was granular Made Ground overlying silty sands and gravels in which groundwater was approximately 1.6 m to 2 m below ground level (mbgl), as shown in cross section. The groundwater concentrations within 2 m of the house were

[17] Parker, T., White, H., Taylor, G., Evans, F., Pearce, M., 2017. Real-world uncertainties during a site assessment of vapour migration into a residential house from soil and groundwater, *Quarterly Journal of Engineering Geology and Hydrogeology*. https://doi.org/10.1144/qjegh2016-129

indicative of free phase hydrocarbon. The house had historic sources of contamination up, and across, groundwater flow gradient. Four groundwater wells were installed around the house, with four separate vapour wells in the unsaturated zone. Two Biotraps were placed in unsaturated soils for three months in areas of elevated soil contaminant concentrations.

Soil was sampled during the installation of wells. Groundwater was sampled four times over a period of 18 months, with soil vapour above the groundwater sampled at the same time. Vapour in the sub-floor voids was sampled at the same time, as was indoor air. Thus, samples along the flow path from the potential soil and groundwater sources to the indoor air receptor were characterised at the same time on a number of occasions to establish a temporal dataset.

The results confirmed some previously observed trends. Soil concentrations at this site provided poor indication of soil vapour concentrations (McAlary *et al.* 2011)[18]. Groundwater concentrations had a slight correlation with vapour phase concentrations, but there were many exceptions as previously noted (Lahvis *et al.*, 2013)[19]. One example was provided on a graph showing benzene vapour concentrations always being lower than toluene despite benzene concentrations exceeding toluene in groundwater. The graph also showed limited variation in groundwater elevation at this site (~100 millimetres (mm)).

The results of soil vapour monitoring in wells outside the house were compared to theoretical soil vapour concentrations derived using soil models (CLEA 1.071)[20] and groundwater models (Risk Based Corrective Action, RBCA)[21]. For benzene, the Contaminated Land Exposure Assessment (CLEA) model over-predicted soil vapour concentrations by a thousand-fold, while groundwater derived models over-predicted benzene concentrations by 400-fold. Inclusion or Screening distance methods as

[18] McAlary, T. A., Provoost, J., Dawson, H. E., 2011. Vapor intrusion. In F. A. Swartjes (Ed.), *Dealing with contaminated sites. From theory towards practical application* (1st ed., Vol. 1, pp. 409–454). Dordrecht: Springer.

[19] Lahvis, M.A., Hers, I., Davis, R.V., Wright, J., and G.E. DeVaull. 2013. Vapor intrusion screening at petroleum UST sites, *Groundwater Monitoring & Remediation*, 33 (2):53-67.

[20] Environment Agency, 2015. CLEA Software Version 1.071.

[21] RBCA Tool kit for Chemical Releases V2.6, Modeling and Risk Characterization package: available from http://groundwatersoftware.com.

developed by the ITRC (2014)[22] from United States Environmental Protection Agency (US EPA) data were also checked. Groundwater in the contaminated well was less (2.3 mbgl) than the clean distance suggested of 3.4 – 4.6 mbgl for NAPL plumes. The benzene concentration was not above the 100 µg/m^{-3} (microgram per cubic metre) target soil vapour concentration, while the toluene concentration was above the target concentration. Therefore, the screening method appears to be appropriate in the United Kingdom (UK), although it may also be over-conservative with respect to benzene.

The factors that may be causing this conservatism are associated with the capillary fringe. Provoost *et al*. (2009)[23] suggested that volatilisation could be limited by the diffusion rate through pore water or by temperature. The highest indoor air concentration at this site occurred in June 2015 when temperature was highest, though whether this was due to higher stack effects in the shallow subsurface or within the house was another uncertainty. Another possible factor at the capillary fringe was biodegradation. Biotrap data was a line of evidence that there were many microbes with functional genes capable of petroleum hydrocarbon degradation in the unsaturated zone at this site.

Experience at other UK sites was then highlighted. At a Part 2A (Defra 2012)[24] site, modern houses with large sub-floor voids and air bricks were found to have ventilation rates more than enough to dilute potential fluxes from the ground. Another site with supersaturated groundwater immediately outside a basement caused elevated concentrations inside the house. A cottage with an earth floor and benzene at 1 mbgl outside the house contained elevated vapour concentrations. These disappeared three months after remediation was completed. At a further site that was difficult to model because of fractures, measuring soil vapour around the houses in conjunction with attenuation factors showed that there was not a risk to residents.

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[22] ITRC, 2014. *Petroleum Vapor Intrusion Fundamentals of Screening, Investigation, and Management*. Interstate Technology and Regulatory (ITRC) PVI guidance (http://itrcweb.org/PetroleumVI-Guidance/) Accessed 20th December 2017.

[23] Provoost, J., Reijnders, L., Swartjes, F., Bronders, J., Seuntjens, P., Lijzen, J., 2009. Accuracy of seven vapour intrusion algorithms for VOC in groundwater. *Jeroen J Soils Sediments* (2009) 9:62–73.

[24] Department for Environment, Food and Rural Affairs (Defra), 2012. *Environmental Protection Act 1990: Part 2A Contaminated Land Statutory Guidance.* April 2012.

The presentation concluded that standard UK models do not deal with the capillary fringe and the required data for modelling the capillary fringe are not typically collected. However, measuring the vapour phase next to, or beneath, the house eliminates capillary fringe modelling issues and is perhaps a more robust approach. The importance of a robust CSM, lines of evidence and a temporal dataset was reinforced. A final thought was that one air reading in the house was only a tenth of soil vapour outside the house with nothing beneath the house. Guo *et al.* (2015)[25] identified preferential pathways (*e.g.*, sewers) as critical factors in vapour intrusion assessments and this is another aspect that is not currently investigated in typical UK vapour intrusion projects.

2.5 Update on Vertical Screening Distances for Petroleum Vapour Intrusion Risk Assessment at Underground Storage Tank Sites

Matthew Lahvis (Shell Global Solutions (US) Inc) gave a presentation about the research undertaken by Shell and others to support a new methodology for screening petroleum vapour intrusion sites based on vertical separation between a vapour source in soil or groundwater and a building foundation that incorporates biodegradation. Referencing Alex Lee's Chair's introduction, he suggested that this represents a paradigm shift, given that conventional methods are based on the use of concentrations or risk-based screening levels (RBSLs)[26] in soil and groundwater and do not factor in biodegradation. He stated that in the US, lots of soil vapour data were being collected at petroleum underground storage tank (UST) sites because RBSLs in soil or groundwater for indoor air, based on the Johnson and Ettinger (1991)[27] model

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[25] Guo, Y. *et al.*, 2015. Identification of Alternative Vapour Intrusion Pathways Using Controlled Pressure Testing, Soil Gas Monitoring and Screening Model Calculations. *Environmental Science and Technology*, 49 (22), 13472–13480.

[26] Risk Based Screening Levels (RBSLs) is US terminology for generic assessment criteria and has been retained.

[27] Johnson and Ettinger, 1991. *Users Guide for the Johnson and Ettinger (1991) Model for Subsurface Intrusion into Buildings*, accompanied by original version of the model available from available from https://rais.ornl.gov/johnson_ettinger.html. Accessed 18th January 2018. Updated version *Johnson and Ettinger Model Spreadsheet Tool, Version 6.0*, available from https://www.epa.gov/vaporintrusion/epa-spreadsheet-modeling-subsurface-vapor-intrusion. Accessed 18th January 2018.

were almost always exceeded. However, this did not translate into observed risk, as measured vapour concentrations were generally more than an order of magnitude less than predicted. Aerobic biodegradation in the unsaturated zone is a critical process affecting potential vapour intrusion at petroleum release sites. At some distance above a vapour source in soil or groundwater, conditions in the unsaturated zone can become aerobic. If this occurs, an interface will develop where hydrocarbon vapour concentrations decrease by several orders of magnitude within a short vertical distance. The location of the interface above a petroleum vapour source will vary depending on whether the source is LNAPL or dissolved phase. This behaviour is amenable to screening sites based on source-building separation distance. This observation has led Shell and others to question the usefulness of traditional generic assessment criteria (GAC), such as RBSLs, for petroleum hydrocarbons and to suggest that distance is a better and simpler way to screen sites. and minimise the collection of unnecessary soil vapour data[28]. For benzene, which is often one of the major risk drivers at UST sites, there is a wealth of soil gas and groundwater data to validate screening distances. Analysis of empirical soil vapour data showed that vertical screening distances were longer for benzene than other hydrocarbons. Benzene was thus used to define the vertical screening distances of 1.5 m – 2 m for dissolved phase sources and 5 m for LNAPL sources.

Matthew was careful to emphasise that vertical screening distances are not an appropriate tool for the assessment of some substances, such as chlorinated solvents, the risks from which are far more closely aligned with those predicted by modelling. He also pointed out that the database used to derive vertical screening distances for LNAPL and dissolved phase sources did not include information on the lead scavengers ethylene dibromide (EDB) and 1, 2 dichloroethane (1,2-DCA), which can be still be found at petroleum sites, even though they were largely phased out of petrol by the mid-1990s. Matthew stated that EDB and 1,2-DCA are both toxic, and are also volatile, with effective solubilities and saturated vapour concentrations around an order of magnitude less than those for benzene. They are both also highly persistent in the environment, due to the strength of the halogen bonds. EDB has a half-life of days up to weeks in an aerobic environment, and of months within an anaerobic

[28] Matt Lahvis referred to 'soil-gas data' as this is the terminology in use in the USA, and in much of the scientific literature. As the term 'soil vapour' is more commonly used within the UK, to make a distinction from permanent gases, it has been used to replace "soil-gas" throughout the account of this presentation and the report in general.

environment. 1,2-DCA has a half-life varying between days and years in an aerobic environment, and between months and years in an anaerobic environment with methanogenic conditions. Lead scavengers therefore pose high risk for vapour intrusion. Upon investigation, EDB concentrations above the limit of detection are relatively common within the groundwater in the US. US EPA (2008)[29] found that 40% or more of UST sites had EDB above the GAC. EDB was found to drive the risk over benzene at approximately 25% of sites investigated (Wilson and Adair, 2008)[30]. Findings for 1,2-DCA were similar, with approximately a third of the US states surveyed finding more 1,2-DCA than EDB above the standard. It is therefore clear that lead scavengers have the potential to still be present in groundwater at concentrations that exceed RBSLs. Detection limits for EDB and 1,2-DCA in groundwater and soil vapour by conventional analytical methods are generally well above RBSLs. Separate analytical methods are thus required to assess the vapour intrusion risk of these contaminants. Interference from BTEX compounds can also raise the detection limits of EDB and 1,2-DCA and compound this problem. There is therefore a concern that risks from lead scavengers could be overlooked. Although vapour intrusion guidance issued by the ITRC (2014)[31] and US EPA (2015a)[32] lists lead scavengers as a "*precluding factor*" preventing the use of vertical screening distances, the California

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[29] United States Protection Agency (USEPA) 2008, *Phase 2: Natural Attenuation of the Lead Scavengers 1,2-Dibromoethane (EDB) and 1,2 Dichloroethane (1,2-DCA) at Motor Fuel Release Sites and Implications for Risk Management,* EPA/600/R-09/107, USEPA, Washington DC, 2008.

[30] Wilson, J., and C. Adair, 2008. *Recent Findings in EPA's Lead Scavenger Evaluation*. State Fund Administrators' Conference, Charleston, South Carolina, June 10, 2008.

[31] ITRC, 2014. *Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management.* Interstate Technology and Regulatory Council, Vapor Intrusion Team, Washington, D.C. October. http://itrcweb.org/PetroleumVI-Guidance

[32] USEPA, 2015a. *Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites.* Report# 510-R-15-001. US Environmental Protection Agency, Office of Underground Storage Tanks, Washington, D.C. June 2015.

https://www.epa.gov/sites/production/files/2015-09/documents/pvi-guide-final.pdf

Low-Threat Tank Closure Policy (CalEPA, 2012)[33] does not. Hence, there is the possibility of screening out sites with actual vapour intrusion risks from lead scavengers. To try to address this issue, soil vapour data from 9056 sites in the California GeoTracker database were evaluated. Although lead scavengers were often sampled for in groundwater, only 8% of the 9056 sites had corresponding soil vapour data where these contaminants were analytes. Of these sites, there were few which had detections (*e.g.*, 1% of sites for EDB and 15% of sites for 1,2-DCA). Only 0.1% of all 9056 sites had paired groundwater and soil vapour data necessary to derive screening distances. Where there were paired data, the soil vapour concentrations for 1,2-DCA were non-detect at source separation distances greater than 2 m, even for relatively high groundwater concentrations, exceeding 100 milligrams per litre (mg/l), suggesting that the benzene vertical screening distance of 5 m is probably protective. However, given the relative lack of data and the high limits of detection in soil gas, it is difficult to conclude this definitively.

No EDB was detected in any of the 126 samples with soil vapour measurements. However, in all cases the limits of detection were above the RBSL. Again, although, the non-detects within soil vapour appeared to indicate a general lack of vapour intrusion risk, lower method detection limits and reporting levels are necessary to confirm this.

Some additional modelling to try to derive vertical screening distances from the Geotracker data was undertaken using the BioVapor model that considers biodegradation. Aerobic first order rate constants were estimated within the model by calibrating against measured soil vapour concentrations, where these were available. Source vapour concentrations were estimated using measured groundwater concentration, Henry's Law Constants and a default attenuation factor of 0.1. The vadose zone was assumed to be homogeneous and isotropic. The key findings of the modelling were that aerobic biodegradation rates for 1,2-DCA are usually approximately two orders of magnitude lower than benzene, consistent with literature values. This resulted in a vertical screening distance for 1,2-DCA of around 5 metres, assuming median biodegradation rates, which again would have the implication that the vertical screening distance for benzene is protective. Due to the lack of data, an

[33] Cal EPA, 2012. Low-Threat Underground Storage Tank Case Closure Policy. California Environmental Protection Agency State Water Resources Control Board, Sacramento, California. http://www.swrcb.ca.gov/ust/lt_cls_plcy.shtml

EDB field study is currently being undertaken by the American Petroleum Institute in Sobieski, Minnesota, using high resolution vapour measurement.

Risks from Total Petroleum Hydrocarbons (TPH) (fractions and bulk) also remain an "*emerging issue*" for petroleum vapour intrusion within the US. US EPA (2016)[34] recently decreased Regional Screening Levels (RSLs) for soil vapours by an order of magnitude or more for certain TPH fractions, due to the lowering of toxicological reference concentrations for some fractions. TPH vapour intrusion risk assessment is challenging for several reasons, including variability in fuel composition, analytical uncertainty and uncertainties within the fate and transport and toxicological data. TPH is ubiquitous in the environment and the presence of background sources means that it is hard to interpret bulk TPH measurements because these may be representative of background sources, rather than just petroleum. In addition, Brewer (2013)[35] found that bulk TPH drives the risk from vapour intrusion for petroleum over benzene in 24% of the US EPA (2013)[36] soil gas database, especially when diesel, middle distillates and low content benzene fuels are involved. Work by Golder Associates (2008)[37] and Lahvis and Hers (2013)[38] demonstrates that bulk TPH bulk soil concentrations are not a good predictor of TPH soil vapour concentrations, resulting in over-predictions that

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[34] Regional Screening Levels (RSLs) (US EPA, 2016) **Post-Workshop Editorial Note-RSLs were updated in November 2017**

[35] Brewer, R., Nagashima, J., Kelley, M., Heskett, M., and M. Rigby, 2013. Risk-based evaluation of total petroleum hydrocarbons in vapor intrusion studies. *Int. J. Environ. Res. Public Health,* 10, 2441-2467.

[36] US EPA, 2013. *Evaluation Of Empirical Data To Support Soil Vapor Intrusion Screening Criteria For Petroleum Hydrocarbon Compounds* (EPA 510-R-13-001). http://www.epa.gov/oust/cat/pvi/PVI_Database_Report.pdf

[37] Golder Associates, 2008. *Report on evaluation of vadose zone biodegradation of petroleum hydrocarbons: Implications for vapour intrusion guidance, Research study for Health Canada and the Canadian Petroleum Products Institute,* Report 06-1412-130, Golder Associates Ltd., Burnaby, British Columbia, July, 2008: pp. 94.

[38] Lahvis, M.A., and I. Hers. 2013. Evaluation of Source-Receptor Separation Distances as a Screening Methodology for Petroleum Vapor Intrusion Risk Assessment. *The 2nd International Symposium on Bioremediation and Sustainable Environmental Technologies*. Jacksonville, Florida, June 10-13, 2013.

could result in unnecessary sampling and analysis. Vertical screening distances for TPH and common indicator compounds for specific TPH fraction (n-hexane and naphthalene) are assumed to be much less than the 2 m and 5 m screening distances recommended by ITRC (2014) and the US EPA (2015a) for application at petroleum UST sites with dissolved phase and LNAPL sources, respectively. This assumption is based on the US EPA (2013) finding that TPH fractions, n-hexane, and naphthalene concentrations in soil gas decreased below soil vapour RBSLs at vertical source-separation distances > ~1 m. Actual screening distances for the TPH fractions remain somewhat uncertain, however. This is because these distances were derived from a relatively small dataset (*i.e.*, eleven petroleum UST sites) and using soil vapour RBSLs that are nearly an order of magnitude higher than those recently published for relatively similar TPH carbon ranges by US EPA (2016).

Further work has therefore recently been undertaken to derive TPH vertical screening distances, focusing on UST sites with NAPL sources (between 31 and 35 sites and between 175 and 204 soil gas samples), dependent on constituent(s), using methods previously applied by US EPA (2013) and Lahvis *et al.* (2013). At most sites, the TPH source was mainly petrol (gasoline) containing either methyl tert-butyl ether (MTBE) or ethanol. The general finding was that individual TPH fraction concentrations in soil gas generally attenuate below generic soil gas RBSLs within two or three metres of LNAPL sources at petroleum UST sites, although there was considerable variability. The results for n-hexane indicated vertical screening distances essentially equivalent to those for benzene, while those for naphthalene were much shorter, except in regulatory jurisdictions (US states) that impose very low RBSLs for soil vapour. Thus, when the results for individual TPH fractions, n-hexane, naphthalene and bulk TPH were all evaluated, and statistical evaluation was conducted using the statistical methods of Kaplan and Meier (1958)[39], the overarching conclusion was that the vertical screening distance for benzene of approximately 5 m was protective of bulk TPH, individual TPH fractions, n-hexane and naphthalene. There were good correlations between both individual TPH fractions and bulk TPH in soil gas, when compared to benzene in soil gas, showing that benzene can be a predictor of TPH risk at petroleum UST sites.

[39] Kaplan, E.L. and Meier, P. Nonparametric Estimation from Incomplete Observations. *Journal of the American Statistical Association,* Vol. 53, No. 282 (Jun., 1958), pp. 457481 Published by: American Statistical Association.

Matthew postulated that models that incorporate biodegradation should be used to support petroleum vapour intrusion risk assessment. The models could be of benefit in predicting the location of the aerobic biodegradation interface (*i.e.*, vapour intrusion risk), especially at sites intended for future development. The Biovapor model, available from the American Petroleum Institute (API)[40] is one such model. Other models include the US EPA PVI Screen, which allows Monte Carlo modelling of inputs and should be available shortly, and a 2-D model (PVI-2D) published by Yao *et al.* (2015)[41].

Matt concluded his presentation by stating that there was increasing uptake of the use of vertical screening distances within regulatory guidance, starting with the Cooperative Research Centre for Contamination Assessment and Remediation (CRC CARE) in Australia in 2013[42], with the US following with ITRC in 2014, and US EPA (Office of Underground Storage Tanks) (US EPA 2015a) in 2015. Vertical screening distances cited in these items of guidance vary between 15 and 26 feet (approximately 5 m - 8 m) for LNAPL sources and between 5 and 6.5 feet (1.5 m – 2 m) for dissolved phase sources.

2.6 Vapour Intrusion – What are the Options Going Forward? What can we learn from Australia?

James Lucas (EPG Ltd) gave a presentation about the Australian guidance framework, the derivation of vapour screening criteria for petroleum and chlorinated contaminants of concern, and the Australian approach to vapour intrusion site investigation, illustrated by case studies. James introduced his presentation with the cautionary tale

[40] API 2012. *Biovapor – A 1-D Vapour Intrusion Model with Oxygen-Limited Aerobic Biodegradation (version 2.1)* Washington DC: American Petroleum Institute.

[41] Yao, Y., Wu, Y., Wang, Y., Verginelli, I., Zeng, T., Suuberg, E.M., Jiang, L., Wen, Y., and J. Ma, 2013. A petroleum vapor intrusion model involving upward advective soil gas flow due to methane generation, *Environ. Sci. Tech*., 49, 11577- 11585.

[42] CRC CARE 2013, *Petroleum Hydrocarbon Vapour Intrusion Assessment: Australian guidance, CRC CARE Technical Report* no. 23, CRC of Contamination Assessment and Remediation of the Environment, Adelaide, Australia

of the legal case of Barkley Street-Premier v. Spotless[43]. Spotless was a dry cleaner and there was no contamination sign-off before redevelopment of the site. Subsequently, there was found to be a groundwater plume with high concentrations of perchloroethene (tetrachloroethene, tetrachloroethylene, PCE) and trichloroethene (trichloroethylene, TCE) beneath the site. The development was subsequently demolished, extensive groundwater remediation took place and millions of dollars were spent on lawyers' fees.

The key Australian framework guidance document is the National Environment Protection Measures (NEPM) for the Assessment of Site Contamination, amended in 2013 and now incorporating vapour guidance[44]. The vapour assessment criteria are based on a combination of the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE, 2013)[45] and the US EPA approach, with conservative attenuation factors taken from the US EPA database (US EPA, 2012)[46]. Many of the environmental assessments in Australia involve clients paying for both a site assessor and an environmental auditor, who work together before a report is submitted to the State Environment Authority. The auditor is appointed under the State environmental legislation but privately employed and liable for decisions made, with potential punishments including fines and jail time. This

[43] Australasian Legal Information Institute, Premier Building and Consulting Pty Ltd v Spotless Group Limited & Ors [2007] VSC 377 (5 October 2007), available at www.austlii.edu.au, accessed 24th January 2018.

[44] National Environment Protection (Assessment of Site Contamination) Measure 1999 as amended 2013, https://www.legislation.gov.au/Details/F2013C00288 accessed 11th January 2017.

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

[46] USEPA (2012) Office of Solid Waste and Emergency Response (OSWER) EPA 530-R-10-002, *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings*, U.S. Environmental Protection Agency Washington, DC 20460, https://www.epa.gov/sites/production/files/2015-09/documents/oswer_2010_database_report_03-16-2012_final_witherratum_508.pdf, accessed 11th January 2018.

system leads to a hand in hand approach between the auditor and the assessor, resulting in robust and transparent vapour assessments.

The vapour intrusion investigation approach is based on the concept of assessors being able to reduce conservatism, as more detailed investigation reduces the uncertainty about conditions on site and the fate and transport of contaminants. Even for screening assessment, a solid underpinning CSM is essential. However, increasing complexity in modelling and fate and transport assumptions require a multiple lines of evidence approach to support the vapour intrusion CSM, particularly for chlorinated solvents due to their persistence. This approach is driven by the need to make reasonable decisions that incorporate feedback about how empirical measurements in sub-surface and indoor air relate to model predictions. James referred to empirical data that showed that Johnson and Ettinger modelling based on depth to groundwater and soil type could both significantly over-predict and under-predict. Thus, a multiple lines of evidence approach should take account of temporal and spatial variability, foundation types, and preferential pathways, including the likely dilution factors. Screening values, Johnson and Ettinger modelling and databases of attenuation factors are additional considerations, rather than tools upon which to place reliance. James referred to a case study in Utah of a house over a dilute chlorinated solvent plume (Holton *et al.* 2014)[47]. Four years of intensive monitoring showed unexplained temporal variation of three to four orders of magnitude. It eventually transpired that a land drain was venting into the basement and providing a preferential pathway.

NEPM Health Screening Levels, which have been derived using the Johnson and Ettinger model, are available for the constituents found in a 'typical' petroleum mixture[48]. TPH fractions are represented by two 'collapsed' fractions, and there are separate Screening Levels for BTEX compounds and naphthalene. Screening Levels are available for different soil types (sand, silt, clay) and different depths (<1 m, 1-2 m, 2-4 m, >4 m), for soil, groundwater and vapour and for residential, commercial, and open space land uses. There is an applicability checklist for users meaning that further consideration is required if:

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[47] Holton *et al.* 2014. Lessons-Learned from Four Years of Intense Monitoring of a House Over a Dilute Chlorinated Hydrocarbon Plume. *AEHS/USEPA VI Workshop*, March 2014.

[48] CRC CARE, 2011. Technical Report No. 10*: Health Screening Levels for Petroleum Hydrocarbons in Soil and Groundwater*. Parts 1-5, 2011.

- NAPL is present;
- There is shallow groundwater present (<2 m depth);
- There is fractured rock; or
- There is a non-petroleum mixture.

Users may incorporate biodegradation/ bioreduction factors, if they can demonstrate that the following conditions are met:

- There is oxygen greater than 5 % at depths not influenced by atmospheric ingress (greater than 1.5 m);
- The slab footprint does not exceed 15 m in width; and
- The source is greater than 2 m depth.

Further information that users may consider include screening distances, management limits, direct contact, odour thresholds and explosive limits (CRC CARE 2013). To provide a point of reference, James compared the Screening Levels for BTEX in groundwater with the SoBRA (2017)[49] generic assessment criteria for groundwater to protect human health and noted that in general the SoBRA residential GAC were lower than the NEPM residential values, except where NEPM values were based on effective solubility, but the commercial ones were higher. He also noted that the depths used within the modelling were different, as was the solubility value used for toluene.

There are also Interim Health Investigation Levels for CVOCs, which are available only for vapour beneath the sub-slab. These are designed to evaluate risks from vapours between 0 and 1 m beneath the slab. These values have been derived using an attenuation factor (AF) between sub-slab and indoor air based on the recommended AF for residential buildings within the Office of Solid Waste and Emergency Response (OSWER) technical guidance (US EPA 2015b)[50]. This, in turn, was derived by using on

[49] SoBRA 2017. *Development of Generic Assessment Criteria for Assessing Vapour Risks to Human Health from Volatile Contaminants in Groundwater*.

[50] US EPA 2015b. Office of Solid Waste and Emergency Response (OSWER) *Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air.* OSWER Publication 9200.2-154, June 2015, accessed from https://www.epa.gov/sites/production/files/2015-09/documents/oswer-vapor-intrusion-technical-guide-final.pdf, 11th January 2018.

box and whisker plots to summarise the AFs found within the US EPA 2012 empirical database.

James continued by summarising good practice within vapour intrusion investigation from desktop study through to measurement of vapour concentrations within sub- slab and indoor air. He emphasised that at all stages the focus is on being able to reduce the uncertainty to an acceptable level for decision making.

During a desktop study, the potential for vapour intrusion from on-site and off-site VOC sources to occur should be evaluated, to target soil and groundwater investigation appropriately. Sources of desktop information specific to the State of Victoria include publicly available Environmental Audits from surrounding sites, the Priority Sites Register, and Groundwater Quality Restricted Use Zones (GQRUZs), which show neighbourhood groundwater plumes identified via the Environmental Audit system.

During the soil and groundwater investigation, the aims are to build up the CSM, narrow down the sources of uncertainty and screen out VOCs if possible. Soil bores should be logged by an environmental scientist. The logs should include detailed descriptions of odours including the type and strength (the Australian Standard provides a description), and systematic PID readings to look for trends, which may be indicative, for instance, of a smear zone or preferential pathway, whether via underground services or more permeable lithologies. When VOCs are suspected, soil auguring is not a preferred technique. This is because the potential mixing involved and heat generated mean that results can be unreliable.

Laboratory analysis should include a minimum VOC screen, regardless of whether a source is suspected. At this stage, modelling vapour intrusion from a soil source is overly conservative and not recommended. For groundwater, low flow or passive methods should be used; bailing or system purge methods are not commonly accepted for VOC investigations. Again, laboratory analysis should always include a minimum VOC screen. Modelling from groundwater concentrations is less conservative than for soil because partitioning between soil and groundwater does not need to be estimated. Quality Assurance/ Quality Control (QA/QC) procedures are very important and may take up to 25 % of the analytical budget. Protocols should include duplicates, splits, field blanks, rinsates, and trip blanks.

For vapour installation, direct push methods such as probe and augur are preferred, because air percussive or rotary coring methods can significantly disturb the vapour equilibrium ground conditions for months after installation. The diameter of vapour wells should be much smaller than for groundwater, with a diameter of 50 mm the maximum, as stated within BS8576[51]. The installation should be Teflon with a stainless-steel screen. The screened interval should ideally be targeted within 0.5 m and at depths no less than 1.5 mbgl, to minimise atmospheric ingress. To evaluate the plume and attenuation, wells should either be nested or clustered at different depths, with the number of locations based on the CSM. Vapour should not be sampled from a landfill gas or groundwater well due to the typical long screened intervals and possibility of being in direct contact with contaminated groundwater.

There is much that can go wrong when vapour sampling and experience is essential. There is useful information within BS8576 but points to bear in mind include:

- Stabilisation times (some sites may not equalise for a long period of time);
- Sampling frequency (taking care to sample in both summer and winter);
- Environmental conditions leading up to the sampling event (including rainfall and atmospheric pressure);
- Purge volume and purge rate (a lower purge rate may be required to avoid creating a vacuum which could desorb sorbed VOC);
- Vapour well integrity testing;
- Vacuum; and
- Sampling Method.

Again, QA/QC is critical and it is advisable to take duplicates and splits at a rate of one in ten samples or one per sampling day, rather than the one in 20 adopted by BS8485[52]. PID readings can provide another valuable line of evidence. The use of a tracer gas to perform a vapour well leak test provides an instant QC check for leakage, potentially saving time and money.

Taking vapour samples from the crawl space and/ or indoor air allows the assessment of air quality closer to the breathing space of the receptor, and avoids issues of subsurface variability, but there are additional complications, such as background sources in the soil and indoor air (even including chlorinated drinking water). Evaluating temporal variability is essential for the assessment of chronic risk. Spatial

[51] British Standards Institute, 2013. BS 8576:2013, *Guidance on investigations for ground gas. Permanent gases and Volatile Organic Compounds (VOCs)*.

[52] British Standards Institute, 2015. BS 8485:2015 *Code of practice for the design of protective measures for methane and carbon dioxide ground gases for new buildings*.

variability should also be considered, when selecting sampling locations. Ideally, sampling should be by both active and passive methods. When determining the appropriate number of sampling rounds and reviewing the general level of comfort in a vapour risk assessment, it is useful to implement the Margins of Safety approach, by looking at the ratio of target risk or air concentration to the measured risk or air concentration (CRC, 2013).

Where vapour risk mitigation is required, Australian practice mirrors practice in the UK, with reference to British Standards and CIRIA[53]. The most common method is passive venting, in conjunction with a membrane which has a low permeability to VOCs. The verification plan should be written by the designer, working alongside the developer and architect. Vapours beneath the membrane may be sampled as part of the verification to assess the level of mitigation being achieved. The requirement for post-verification monitoring is increasing, in part driven by the auditor system. The duration of verification should be based on the vapour risk and reliance on the mitigation system, and is typically observed to be between one and six months.

James concluded his presentation with a case study for a site called Clovelly Park in South Australia (Fyfe, 2014)[54], involving a co-sourced chlorinated solvent groundwater plume, arising from a chemical manufacturing facility and a former motor manufacturing plant. Following an owner reporting a problem to the EPA in 2008, unacceptable concentrations of TCE were detected in 19 apartments in 2009, resulting in the residents being relocated, triggering community uproar and a detailed vapour intrusion investigation and risk assessment involving 124 hectares and 1400 homes. The investigation involved 66 groundwater wells, which identified three separate chlorinated plumes within the aquifer. The site was underlain by clays and silty clays with the groundwater between 9 mbgl and 13 mbgl. Soil vapour probes were installed at 103 locations to evaluate the vapour source. Soil vapour was measured at varying depths, beneath the slab and within the indoor air. Underground services were targeted. Background concentrations were also measured. All this data was then incorporated into a two-tiered screening process.

[53] CIRIA, 2009. *The VOCs Handbook Investigating, assessing and managing risks from inhalation of Volatile Organic Compounds (VOCs) at land affected by contamination*, CIRIA Report C682, London 2009.

[54] Fyfe, 2014. *Clovelly Park/Mitchell Park Environmental Assessment FINAL REPORT* Volume 1. Prepared for the EPA, South Australia. December 2014.

The first screening assessment involved screening the shallow soil vapour data against the Interim Health Investigation Levels for CVOCs. In the second tier of assessment, multiple lines of evidence were used to build up the CSM and parameterise and calibrate the subsequent Johnson and Ettinger modelling. These lines of evidence included vertical and horizontal vapour gradients, the correlation between the groundwater plume and the vapour plume, evidence of lateral soil vapour migration along the sewer and storm water mains, and the correlation between indoor air samples and sub-slab sampling. The Johnson and Ettinger model was then used to predict indoor air concentrations for both slab-on-ground and crawl space residential buildings.

The predicted indoor air concentrations were then cross-referenced to the indoor air samples collected from within the selected buildings to provide another line of consideration, thereby reducing the model uncertainty. The predicted and actual indoor air TCE concentrations were then used to determine the required site-specific response, based on acceptable levels which were derived between South Australia Health and the South Australia EPA. Responses ranged from 'No Action' (no TCE detected) through to a requirement for Validation to confirm the property was 'safe' (above detection, below 2 µg/m^3), through Investigation (no immediate health concerns, further assessment necessary, between 2 µg/m^3 and 20 µg/m^3), Intervention (potential health risk, between 20 µg/m^3 and 200 µg/m^3) and Accelerated Intervention (health risk, above 200 µg/m^3). The majority of the 1400 homes (1352) fell into the 'No Action' category, with eight in the 'Intervention' category and none in the 'Accelerated Intervention Category'.

3 CONCEPTUAL SITE MODEL (WORKSHOP GROUP 1)

3.1 Introduction

The development of a robust CSM is critical when considering potential risks associated with VI. This section summarises the thoughts of Group 1, whose discussions were focussed on the development of the CSM for VI. The attendees of this group are listed in Appendix 1. The group was led by the facilitator, Judith Nathanail (Land Quality Management), accompanied by the rapporteur, Sarah Mortimer (EPG Ltd).

3.2 Key documentation and tools

The group, comprising a combination of consultants and regulators, was initially asked to provide a list of documents which provide guidance on the development of CSMs and/ or the assessment of VI risks. Collectively, the group cited the following documents as being useful reference tools (albeit noting that this list is not exhaustive). The full references have been included within the references at the end of the report:

- Defra and Environment Agency, 2004, CLR 11[55]
- Department of Environment (DoE) Industry Profiles (47 No. published in 1995)[56]
- CIRIA (2009), The VOCs Handbook[57]
- BS 8576:2013[58]

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[55] DEFRA and the Environment Agency, 2004. *Model procedures for the management of land contamination* (2004), R&D Report CLR 11, United Kingdom.

[56] Department of Environment (DoE) *Industry Profiles* (47 No. published in 1995), as scanned and PDF'd by DEFRA. Held on the CL:AIRE webpage https://www.claire.co.uk/useful-government-legislation-and-guidance-by-country/76-key-documents/198-doe-industry-profiles accessed on 24th January 2018.

[57] CIRIA, 2009. *The VOCs Handbook Investigating, assessing and managing risks from inhalation of Volatile Organic Compounds (VOCs) at land affected by contamination*, CIRIA Report C682, London 2009.

- ITRC (2014)[59], Petroleum Vapour Intrusion – Fundamentals of Screening, Investigation and Management.
- CRC CARE (2013), Petroleum hydrocarbon vapour intrusion assessment: Australian guidance[60]

The group were then asked to name any VI risk assessment tools of which they were aware. The following were the principal VI tools which delegates had knowledge of (although again, this list is not exhaustive);

- Johnson and Ettinger Model for Subsurface Vapor Intrusion into Buildings [61],[62];
- The Modular Approach to Johnson and Ettinger (Wilson, 2008)[63];
- BioVapor (API, 2012)[64];
- The Risk-Based Corrective Action Method, RBCA Toolkit[65];

[58] British Standards Institute, 2013. BS 8576:2013, *Guidance on investigations for ground gas. Permanent gases and Volatile Organic Compounds (VOCs)*.

[59] The Interstate Technology & Regulatory Council Petroleum Vapour Intrusion Team (ITRC) 2014, *Petroleum Vapour Intrusion – Fundamentals of Screening, Investigation and Management*, Washington DC.

[60] CRC CARE, 2013, *Petroleum Hydrocarbon Vapour Intrusion Assessment: Australian Guidance, CRC CARE Technical Report no. 23*, Co-operative Research Centre of Contamination Assessment and Remediation of the Environment, Adelaide, Australia

[61] Original Version available from https://rais.ornl.gov/johnson_ettinger.html, together with Users Guide for the Johnson and Ettinger (1991) *Model for Subsurface Intrusion into Buildings*. Accessed 18th January 2018.

[62] Updated version "*Johnson and Ettinger Model Spreadsheet Tool, Version 6.0*", together with Documentation for EPA's Implementation of The *Johnson And Ettinger Model To Evaluate Site Specific Vapor Intrusion Into Buildings* Available from: https://www.epa.gov/vaporintrusion/epa-spreadsheet-modeling-subsurface-vapor-intrusion Accessed 18th January 2018.

[63] Wilson S. 2008. Modular approach to analysing vapour migration into building in the UK. *Land Contamination and Reclamation*, 16 (3) pp223-236.

[64] API 2012. *Biovapor – A 1-D Vapour Intrusion Model with Oxygen-Limited Aerobic Biodegradation (version 2.1)* Washington DC: American Petroleum Institute.

- RISC5 (previously referred to as BP RISC)[66];
- CLEA version 1.071 (Contaminated Land Exposure Assessment Model)[67]; and
- SoBRA's Generic Assessment Criteria for the assessment of chronic health risks from the inhalation of vapours arising from groundwater (GACgwvap) (SoBRA, 2017)[68].

3.3 Objective

The objective of this group was to identify critical aspects of the CSM when considering risks associated with VI. Specifically, Group 1 was tasked with responding to the following questions:

- How do practitioners identify potential sources of vapour phase contamination?
- What are the main pathways for migration of vapour phase contamination?
- What is the influence of foundation types on the vapour intrusion CSM?
- Is there too much UK focus on the assessment of vapour intrusion risks via soil and groundwater sampling?
- With respect to vapour intrusion, what are the challenges of the sector and how can we overcome these (in terms of scientific research)?
- Should practitioners be using the CSM to design and construct monitoring wells?

Responses to the stated objectives, arising from the active discussions of Group 1, are set out beneath.

3.3.1 How do practitioners identify potential sources of vapour phase contamination?

The group considered that knowledge of the historical uses of a site and the surrounding area is critical when assessing the potential for VOCs to be present.

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[65] RBCA Tool kit for Chemical Releases V2.6, Modeling and Risk Characterization package: available from http://groundwatersoftware.com

[66] RISC5, *Human Health & Ecological Risk Assessment for Contaminated Sites*: available from http://groundwatersoftware.com

[67] Environment Agency, 2015. *CLEA Software Version 1.071.*

[68] SoBRA 2017. *Development of Generic Assessment Criteria for Assessing Vapour Risks to Human Health from Volatile Contaminants in Groundwater*.

Specifically, the group cited that an understanding of the physical processes which have been completed on the site is important, ideally including the site's historical layout and the potential contaminants associated with previous activities. The importance of completing a reconnaissance visit to the site and surrounding area was stressed, notably because this gives practitioners the opportunity to collect anecdotal evidence from local people.

With respect to the physical characteristics of a contaminant source, delegates considered the following to be fundamental considerations with respect to the CSM for VI:

- What is the lateral extent of the contamination plume?
- What is the vertical extent of the contamination plume?
- Is the contamination extensive, localised, or discrete?
- Is the source located on-site or off-site? Is there evidence of on-site and/or off-site migration?
- Are contaminants present as LNAPL, DNAPL, residual NAPL, dissolved in groundwater, adsorbed onto the soil matrix or a mixture of these media?
- What type of contamination is present (*e.g.* petroleum hydrocarbons or chlorinated compounds)?
- What is the mobility and associated volatility of the anticipated compounds?
- How old is the anticipated contamination – is it residual or from a potentially replenishing source?
- What chemical changes may have occurred/ be occurring? Will petroleum hydrocarbon compounds be affected by natural biodegradation processes? Could chlorinated solvent degradation be underway and is there potential for more toxic daughter compounds to be present?
- What are the physical concentrations of the compounds present in the ground?
- Is there potential for a 'cocktail' of contaminants to be present – could risks to receptors be increased by additive effects?

Throughout the group discussions delegates became increasingly cognisant of the complexities of developing a CSM for VI. Whilst delegates acknowledged that there is always potential for a missing (unexpected) source to be identified, one of the key discussion points was ensuring that the CSM remained relevant by always assessing if a potential source was valid, *i.e.* credible.

3.3.2 What are the main pathways for migration of vapour phase contamination?

Broadly, the group concluded that potential pathways associated with VI could be influenced by three distinct considerations:

- The physical ground conditions of the site;
- Temporal effects; and
- The physical characteristics of the proposed/ existing building.

The physical ground conditions of the site

- The isotropy of the ground – Is there horizontal layering? What is the composition of the ground? Is the ground homogeneous or heterogeneous? What is the grain size and grain size variability?
- What is the depth to the contamination, *i.e.* the distance between the source and the receptor? Where is the capillary fringe?
- What is the depth of the vadose (unsaturated) zone?
- Is there potential for preferential migration of vapour phase contamination via fissuring and/or fractures, *e.g.* in rock?
- What is the organic content of the ground?
- Are ground conditions indicative of aerobic or anaerobic degradation?
- Specifically, in relation to DNAPL, if this is vertically constrained on top of unproductive strata, with negligible permeability, is there potential for migration of the NAPL to preferentially follow the topography of the underlying low permeability unit – as opposed to the direction of groundwater flow?

Temporal effects

- Does the depth to groundwater vary? Is there any tidal influence? What is the direction of groundwater flow? What are the infiltration rates at the site (will these vary as part of the development)? Is there any influence from nearby boreholes?
- Will atmospheric pressure changes potentially influence the vapour regime? Is barometric pumping possible?
- Will vapour phase contamination be subject to temporal effects? Is summer / winter sensitivity a consideration?

The physical characteristics of the proposed / existing building – (see also discussion within Section 3.3.3)

The group concluded that one of the main risks associated with VI was that "*you don't know what you don't know*". Specifically, delegates discussed preferential pathways (*e.g.* vibro stone columns, utility service trenches *etc.*) and the potential for these to influence pathways associated with VI. On new developments, risks associated with preferential pathways can be mitigated, if they are identified by risk assessors and considered as part of the CSM. However, particularly with regard to existing buildings (*e.g.* potentially those being inspected under Part 2A of the Environmental Protection Act 1990)[69], there is a risk that unknown preferential pathways could be present, and this uncertainty needs to be considered carefully within the CSM.

3.3.3 What is the influence of foundation types on the vapour intrusion CSM?

The physical characteristics of a building's construction are critical when developing a CSM for VI. Delegates identified a number of key questions when assessing the influence of the built environment on the CSM for VI.

For new sites these were:

- What are the development proposals?
- What is the proposed floor slab/ foundation design?
- Is a basement proposed? If so, what is the design standard for the basement engineering? What waterproofing grade will be adopted? Could the basement effectively remove the source?
- Will the extent of hard-standing relative to soft landscaping be altered as part of the development (if so, will this affect VI risk)?
- Is there a risk that the development will introduce preferential pathways which could alter on-site or off-site VI risks (*e.g.* by the construction of vibro stone columns, utility service trenches etc.)?

For existing sites, all of the considerations for new sites apply but delegates acknowledged that there may be very little information pertaining to the physical construction of existing properties, which could make assessment of this critical part of the CSM particularly complex and necessitate site-specific investigations to reduce uncertainty.

[69] Department for Environment, Food and Rural Affairs (Defra), 2012. *Environmental Protection Act 1990: Part 2A Contaminated Land Statutory Guidance.* April 2012.

Discussions between practitioners indicated that some risk assessors may not fully understand detailed design drawings, which provide invaluable information on the CSM. These include, amongst others:

- Architectural plans;
- Structural sections;
- Waterproofing specifications; and
- Reinforcement detailing.

These are fundamental considerations when developing a CSM for VI and risk assessors should be mindful of this – recognising the limits of their expertise and knowing when to consult wider members of the project design team for assistance.

3.3.4 Is there too much UK focus on the assessment of vapour intrusion risks via soil and groundwater sampling? Should we consider vapour sampling to be more 'the norm'?

Based on the presentations provided as part of the conference one delegate summed this up as follows;

"There is poor correlation with soil data and VI risk. There is weak correlation with groundwater data and VI risk. Therefore, it is hard to argue that vapour phase sampling should not be used more."

It was agreed generally that the decision to implement vapour phase sampling should be based on the development of a robust CSM. Only if there is a potentially credible VI source and pathway should vapour monitoring wells be installed to enable collection of vapour phase samples. This approach is consistent with the UK's approach to the monitoring and assessment of permanent gas risks. However, it was also noted that not all risks associated with vapour phase contamination will be driven by chronic inhalation risks – in some cases acute risks and/or exceedance of odour thresholds may be the main risk driver.

It was concluded that if there was a credible VI source and pathway, then obtaining soil vapour data should be more the norm.

3.3.5 With respect to vapour intrusion, what are the challenges of the sector and how can we overcome these (in terms of scientific research)?

With respect to the CSM, the overriding issue was predicting likely preferential pathways, both in the sub-surface and in the building itself.

The problem of where to measure vapours remains. For example, vapours could be measured in the ground by using tubes and canisters – but this will not necessarily reflect the vapours which would enter the building. However, indoor air monitoring can be affected by other sources inside the building.

A clear challenge associated with VI is the applicability of the distance screening approach to the UK, specifically relating to UK building types and prevailing ground conditions. In terms of scientific research, it would be helpful if a similar study could be completed to the one undertaken by the ITRC (2014) within the USA.

3.3.6 Should practitioners be using the CSM to design and construct monitoring wells?

The group acknowledged that the CSM provides a mechanism for risk assessors to capture the key site features and consider the factors which influence VI risks at that site. Although the CSM is unlikely to provide all the answers for a site's assessment, it should highlight any uncertainty associated with VI. The risk assessor can then use their expertise to assess if the uncertainty will make a material difference to the evaluation of VI risks. It is this uncertainty, and any requirement to resolve it, that should dictate the design and construction of vapour monitoring wells (if required), thus permitting refinement of the CSM. This is consistent with the fundamental principles of CLR11 (Defra and Environment Agency, 2004), whereby the assessment of risk is an iterative process.

3.4 Conclusions

The types of information needed for the VI CSM are reasonably well understood – and not that dissimilar to the information recorded on CSMs in general.

However, collecting site-specific information to populate the CSM is more difficult; in particular:

- Identifying and characterising the preferential pathways for inclusion in the CSM; and
- Understanding the types of foundation/building design and their impact on VI.

Separately, there was interest in whether the distance screening approach could be used in the UK.

3.5 Recommendations

The group did not make explicit recommendations, but issues arising from the discussion for consideration include:

- Provision of mechanisms to ensure the industry considers VI at every site where there is a credible VI source;
- Provision of mechanisms to ensure the industry understands the importance of preferential pathways to the VI pathway;
- Provision of mechanisms to promote vapour phase monitoring, given that estimation of the VI risk based on soil and (to a lesser extent) groundwater data is poor;
- Provision of further guidance on best practice for vapour intrusion assessment, to include:
    - methods to collect soil vapour samples;
    - where to collect soil vapour samples; and
    - CSMs for VI which address preferential pathways.
- Provision of guidance summarising the physical characteristics of a building's construction and its impact on VI;
- Increased emphasis on a lines of evidence approach to assess risk from VI; and
- Collection of data to inform a distance screening approach for the UK.

4 SITE INVESTIGATION (WORKSHOP GROUP 2)

4.1 Introduction

This section summarises discussions by Group 2 on the topic of site investigation in vapour intrusion projects. The group attendees are listed in Appendix 1 and were led by facilitator, Tom Parker (Argentum Fox), and rapporteur, Ray Watson (RSK). The workshop group comprised environmental and engineering consultants, with some representation from laboratory and equipment suppliers and regulators.

4.2 Objective

The objective for this group was to look at key issues associated with site investigation techniques and laboratory analysis for vapour intrusion projects. The group focussed on the intrusive techniques required to develop the CSM and inform subsequent detailed quantitative risk assessments (DQRA).

4.3 Key Issues

The key themes identified by the group are:

- Specification of data quality objectives (DQO);
- Soil and groundwater assessment practices for delineation of VOCs;
- Correct monitoring well installation procedures from dedicated soil vapour wells;
- The relative advantages and disadvantages of different investigation (sampling) techniques;
- Assessment of preferential pathways and the pitfalls of indoor air assessment;
- Addressing temporal variations;
- Vapour sampling quality control issues; and
- Other issues

The discussions on each of these key themes have been summarised under the sub-headings below.

4.3.1 Specification of data quality objectives (DQO)

The main foci of the group discussions were:

- Ensuring that the correct level of data is acquired for the project scope and purpose, for instance recognising that there are different data requirements and thresholds to demonstrate SPOSH for Part 2A[70], versus "*suitable for use*" under planning;
- Ensuring that acquired data is used appropriately, for instance recognising that soil vapour measurements from deep screened wells may be suitable for delineation purposes, but not for direct comparison with risk-based vapour screening levels developed for shallow soils. Similarly, wells installed during initial site characterisation may not be suitable for soil vapour sampling, following source delineation and development of CSM. Non-dedicated wells (*e.g.* groundwater monitoring wells) are unlikely to be suitable.

There was consensus among the group that vapour sampling could sometimes be perceived as a 'last resort' option, and is therefore often only conducted late in the project lifecycle, when soil and groundwater analysis have not proved sufficient lines of evidence to a regulator. With a well-developed CSM and DQO it is noted that timely and appropriate soil vapour assessment could reduce project costs/ timescales by reducing uncertainty.

Early determination of how the investigation strategy will account for variability was considered important – examples given included variability associated with anisotropic soils, fractured rocks and/ or preferential pathways.

4.3.2 Soil and groundwater assessment practices for delineation of VOCs

The group held a wide-ranging discussion on appropriate techniques for characterisation of VOCs during soil and groundwater investigation. The following aspects were discussed:

- Drilling technique selection to allow suitable assessment of VOCs from soil samples, for instance the collection of sample from sample liners is considered preferable to amalgamated samples from augers;
- Use of shallow driven probes as a sampling conduit may allow effective quick site coverage, although health and safety consideration (*e.g.* underground utilities) may preclude their use;

[70] Department for Environment, Food and Rural Affairs (Defra), 2012. *Environmental Protection Act 1990: Part 2A Contaminated Land Statutory Guidance.* April 2012.

- Pro-active use of in-situ monitoring – using PIDs for soil source delineation on-site, and correct, consistent methods for taking sample headspace readings;
- The use of geotechnical soil testing (*e.g.* PSDs to provide additional information to support the CSM with respect to vapour migration);
- The use of QA/QC samples to ensure the veracity of laboratory analysis (discussed further later in this section);
- Groundwater sampling technique selection to ensure suitable samples obtained for VOC analysis; purging methods disturb the water column and may result in loss of volatiles. Suitable techniques were considered to be low-flow sampling following water quality parameter stabilisation, or passive/snap samplers. Low disturbance is key when assessing stratification;
- Consideration of appropriate direct push technologies to delineate volatiles *e.g.* a membrane interface probe (MIP) for soils or Waterloo profiler for high resolution vertical aquifer profiling;
- Forensic analysis of any NAPL may provide further information on the likely source character and inform the selection of contaminants to test for in other phases;
- Where required, ensuring that the investigation targets DNAPL, so that an evaluation can be made as to whether this could be a viable source of VOCs to the receptor being assessed; and
- Separate wells should target LNAPL and DNAPL sources, with appropriate screened sections.

4.3.3 Correct monitoring well installation procedures from dedicated soil vapour wells

The most important factors related to the installation of soil vapour wells were considered to be:

- Ensuring installation above the water table;
- Ensuring a short-screened section at a suitable depth profile – informed by the CSM and site observations;
- Installation techniques involving minimal soil disturbance are preferable – a suitable period must be left following installation to allow conditions to re-equilibrate, especially for high disturbance methods *e.g.* vacuum excavation;
- Narrow diameter wells may be used, reducing the required purging volume and time – *e.g.* 19 mm standpipe or 4 mm tubing;

- Ensuring a suitable bentonite and/ or cement seal on well. Bentonite grout is preferable for achieving a suitable seal, though where pellets/ chips are used they must be adequately hydrated;
- Multipoint installations must be given due planning and consideration to ensure suitable vertical separation and seals between sampling horizons; and
- Well headworks should allow ease of sampling access.

Short circuiting of monitoring wells to atmosphere was highlighted as a common problem (either through surrounding ground or via the standpipe gas/ tap connection). Suitable assessment methods were considered to be:

- Use of bulk gas analyser to allow comparison with atmospheric concentrations (considered a minimum requirement);
- Leak testing from within a shroud surrounding the monitoring set-up containing helium (although use of helium was noted by a delegate not to be a sustainable option), with subsequent helium analysis of the sample to assess any ingress into the sampling train; and
- Leak testing using isopropyl alcohol (IPA)/ shaving foam on a cloth surrounding the wellhead, with subsequent IPA analysis of the sample to assess any draw through.

4.3.4 The relative advantages and disadvantages of different investigation (sampling) techniques

This aspect formed the largest part of the discussion. Extensive reproduction of the pros and cons of all sampling techniques is outside the scope of the discussion, and can be found in the relevant sections of BSI (2013)[71] and the CIRIA document produced by CIRIA (2009)[72]. Relevant practitioner experience of various techniques is summarised below:

- Evacuated canister whole air samples – these allow more than one analysis. High volume canisters can achieve lower limits of detection (LODs), providing they are

[71] British Standards Institute (2013), *Guidance on investigations for ground gas – Permanent gases and Volatile Organic Compounds (VOCs)* (BS8576:2013).

[72] CIRIA, 2009. *The VOCs Handbook Investigating, assessing and managing risks from inhalation of Volatile Organic Compounds (VOCs) at land affected by contamination*, CIRIA Report C682, London 2009.

suitable for the project scope. Flow restrictors can be used to achieve time weighted averages (TWA) – consideration should be made of the averaging period used;

- Manually pumped sample vessels (*e.g.* 'Gresham' tubes) also collect whole air samples and are simple to operate, although they may be restrictive in terms of sample volume;
- Sorbent tubes – these can be used either passively or to obtain a pumped sample. Different sorbents are used for different suites of chemicals, and therefore more than one tube type may be needed.
    - Pumped samples can become saturated by high vapour concentrations, though sampling in series can monitor breakthrough. Higher pumped volumes allow achievement of specific or low LODs because a TWA is calculated;
    - Passive methods allow longer averaging periods. Outdoor passive sampling is useful for assessment of background concentrations, although it can be affected by moisture;
- Real time monitoring, for instance using in-situ PID/ GasClam devices – this is good for assessing temporal variation but cannot discriminate between compounds;
- Flux boxes – practitioners considered these to be difficult to install and operate correctly, and placed low confidence in the results.

A common theme arising from the discussion was the ability of the chosen technique to reach challenging analytical limits of detection for more toxic compounds. It was agreed that early consultation with laboratories would provide the best chance of appropriate sampling protocols (technique and required sampling volumes) being specified.

4.3.5 Assessment of preferential pathways and the pitfalls of indoor air assessment

A frank discussion was held on the inherent difficulties associated with indoor air sampling including the impact of trace VOC concentrations associated with household products/ processes and occupational factors. The group expressed a strong disinclination to undertake indoor air sampling unless absolutely required. Delegates discussed the sensitivities around engagement with residents and the potential alarm/ perception of blight on property that indoor sampling can elicit. It was agreed that the local authority can have a positive role in assuring residents of the purpose of works, and that the SNIFFER (2010)[73] guidance booklet on risk communication is a helpful reference tool. The group discussed alternative preferred assessment options to achieve their DQOs without the need for indoor air assessment:

- Sub-slab sampling through a thin diameter sampling port / vapour-pin installed within a drilled hole;
- Sealing air bricks and laying sampling tubing within sub-floor voids;
- Use of sorbent tubes beneath floor boards;
- VOC GasClam/ fixed PID installed beneath floor/through the floor slab; and
- Direct assessments targeted towards service corridors / entry points/ voids and confined space.

4.3.6 Addressing temporal variations

Discussion included observations on the importance of considering temporal variation, and the type and level of assessment needed to achieve the DQOs, which should be aligned to the work purpose. The management context within which the data is being collected should inform decisions about whether extra work is required to confirm whether concentrations are consistently low, or whether the absence of elevated concentrations is due to temporal variability.

Delegates noted that in some instances, for instance small-scale developments, the proactive use of membranes or other design mitigation may be more cost efficient/practical than attempting to demonstrate the effects of temporal variability. Other potential issues discussed included seasonally variable 'stack' effects (advective flow) into buildings, the effects of seasonal soil moisture variations, or ground gases acting as carriers.

4.3.7 Vapour sampling Quality Control issues

The group discussed QA/QC issues on vapour sampling projects, highlighting existing practices, including:

- Use of sampling tubing blanks as an equipment blank;
- Use of hydrogen filled trip blank canisters; and

[73] SNIFFER (2010), *Scotland and Northern Ireland Forum For Environmental Research (SNIFFER) UKLQ13 Communicating Understanding of Contaminated Land Risks*

- Use of split samplers to allow duplicate sampling using canisters or diffusion tubes.

Obtaining a minimum of one duplicate QA/QC sample per sampling event was recommended. For soil and groundwater samples, the importance of appropriately packed, chilled, rapid transport to the laboratory was emphasised to adhere to sample holding times and preservation guidelines.

4.3.8 Other issues

There was also a wide-ranging discussion around a number of other areas, with a focus on sub-standard/ non-standard sampling and assessment practices that practitioners had encountered. Workshop participants noted that there are often commercial barriers to high quality technical performance. These include fixed price contracts, which discourage amendment of work specifications, and a lack of understanding of vapour intrusions issues and the requisite cost and quality of work required from some clients. It was agreed that consultants can emphasise the potential cost savings to be gained by technically sound early investigation, rather than later remobilisation/ repeat work/ retrofitting.

4.4 Conclusions

The industry needs to keep a focus on accurately defining our DQO at project inception, and ensuring these are developed/re-appraised through the project life cycle alongside the CSM, and that the level and type of data collected are suitable for the project scope/ site scenario;

- Early consultation with stakeholders can ensure the correct assessment methods are selected; and
- Those in consultancy roles need to be proactive in not being unduly led by cost or contractual issues.

4.5 Recommendations

No specific recommendations were agreed, aside from the need for increased consultancy staff awareness and training in vapour assessment protocols.

5 DEVELOPMENT OF ALTERNATIVE RISK ASSESSMENT TECHNIQUES BASED ON SCIENTIFIC STUDIES (WORKSHOP GROUP 3)

5.1 Introduction

This section summarises the discussion held by Group 3 in relation to the current data gaps and uncertainties in the assessment of exposure to vapours associated with petroleum and chlorinated hydrocarbons. Group attendees included representatives from local authority, contaminated land consulting and industry. The attendees of this group are listed in Appendix 1. The group was led by the facilitator, Matt Lahvis (Shell), accompanied by the rapporteur, Paloma Montes (WSP).

The Group 3 discussion was held following a presentation by Matt Lahvis (see Section 2.5) on screening PVI sites based on vertical separation between a vapour source in soil or groundwater and a building foundation. The screening criteria take account of a large body of empirical data from the USA, Canada and Australia.

5.2 Objective

The objective for this group was to discuss the issues associated with the techniques available for VI risk assessment in the UK and whether a distance screening approach would be relevant for consideration of PVI in the UK, specifically focussing on:

- Typical approaches used in the UK;
- Availability of modelling tools both in the UK and those available internationally;
- Agreement of the differences that should be considered when modelling petroleum hydrocarbon and chlorinated solvent risk assessments;
- Differences between the CSM used for an international distance screening approach and that typically used within the UK (*i.e.* CLEA approach); and
- Identifying solutions to resolve the differences identified in CSM, with the aim of developing PVI; and
- Discussion of the potential use of distance screening criteria for the UK (*e.g.* additional research or building surveys).

5.3 Key Issues

The group identified the key issues as:

- Availability of modelling tools;
- Requirement for additional guidance;
- Applicability of the screening distance approach within the UK;
- Empirical database requirements;
- GAC for Soil Vapours;
- Preferential Pathways; and
- Building parameters.

The group discussions on these key issues are summarised in turn in the sub-sections below.

5.3.1 Availability of modelling tools

At the time of the workshop, the Johnson and Ettinger (J&E) model was no longer directly available for download from the US EPA website. The absence of the tool was considered to present a key issue given the UK screening values are based on the J&E model. Although consultants have derived GAC for soil, soil vapour and groundwater to facilitate generic quantitative risk assessment (GQRA), there are still situations where modelling is needed. The need for an appropriate publicly available modelling tool was raised. **[Post meeting note: the model has since been substituted by an US EPA-developed Excel based tool (Johnson & Ettinger Model Spreadsheet Tool V6.0, September 2017) for supporting assessments of the vapour intrusion (VI) pathway.]**[74],[75]

It was discussed that the Environment Agency CLEA Workbook v1.071[76] is appropriate for the derivation of soil GAC and possibly vapour GAC. However, it was considered likely to be overly conservative for the derivation of groundwater GAC due to the

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[74] Original Version available from https://rais.ornl.gov/johnson_ettinger.html, together with *Users Guide for the Johnson and Ettinger (1991) Model for Subsurface Intrusion into Buildings*.

[75] Updated version "*Johnson and Ettinger Model Spreadsheet Tool, Version 6.0*", together with "*EPA's Implementation of The Johnson And Ettinger Model To Evaluate Site Specific Vapor Intrusion Into Buildings*", 2017.

[76] Environment Agency, 2015. *CLEA Software Version 1.071.*

inability of the CLEA model to include a capillary fringe (*i.e.* partially saturated zone), which may significantly retard vapour migration (compared with unsaturated zone soils). Groundwater GAC calculated by practitioners using the RBCA model (incorporating the capillary fringe)[77] are therefore less conservative than those calculated using the CLEA model (*e.g.* SoBRA GAC_{gwvap})[78].

Models, such as J&E, RBCA and CLEA that do not take account of bio-attenuation in unsaturated zone soils tend to be significantly over conservative for petroleum hydrocarbons, but less conservative for chlorinated compounds that do not undergo rapid aerobic degradation. BIOVAPOR[79], a model used internationally, is a modelling tool that can take account of biodegradation of petroleum hydrocarbons. Therefore, this model may be used to assess the potential mitigating effects of bio-attenuation if there is sufficient evidence that this is occurring in the unsaturated zone on site. **[Post meeting note: BIOVAPOR is available as an add-on within the RBCA model (v 2.6)]**.

5.3.2 Requirement for additional guidance

The degree of understanding of vapour investigations and vapour inhalation risk assessments appeared to vary across the group. The majority of the group recognised that CIRIA C682 VOC Handbook (CIRIA 2009)[80] was a very useful guidance document. It was, however, considered that a more prescriptive guidance might be useful. The group considered that the Australian guidance CRC CARE Technical Report 23 (CRC

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77 RBCA Tool kit for Chemical Releases V2.6, Modeling and Risk Characterization package: available from http://groundwatersoftware.com

78 SoBRA 2017. *Development of Generic Assessment Criteria for Assessing Vapour Risks to Human Health from Volatile Contaminants in Groundwater*.

79 API 2012. *Biovapor – A 1-D Vapor Intrusion Model with Oxygen-Limited Aerobic Biodegradation (version 2.1)* Washington DC: American Petroleum Institute.

80 CIRIA, 2009. *The VOCs Handbook Investigating, assessing and managing risks from inhalation of Volatile Organic Compounds (VOCs) at land affected by contamination*, CIRIA Report C682, London 2009.

CARE, 2013)[81] provides a clear decision framework for VI assessments and is a useful source of information for the design of vapour investigations.

There was a consensus in the group that there should be more focus on soil vapour assessments. At sites where the CSM indicates a VI pathway is present, soil vapour investigation and assessment should be undertaken to provide additional lines of evidence, rather than relying solely on modeling using soil and/or groundwater results, as this is likely to be inherently conservative for petroleum hydrocarbons. If undertaken correctly, soil vapour measurements may take account of bio-attenuation (as well as soil- and soil water-phase partitioning) in the unsaturated zone, thereby removing the conservatism related to over-reliance on soil and groundwater GAC. Ideally, a soil vapour profile is required. It was agreed that remediation criteria for VI should never be based solely on an assessment using soil and/or groundwater VI GAC. In such cases the collection of appropriate soil vapour samples is essential, prior to consideration of remediation criteria (except possibly in acute risk scenarios). It was noted that Part 2A investigations would typically require indoor air and/or soil vapour monitoring, irrespective of the outcome of the DQRA that utilised soil and/or groundwater data alone.

The group considered that it would be useful if SoBRA developed a guidance document, including a framework and flowchart to help consultants identify sites where soil vapour data should be collected and used to refine the CSM.

The difference in the behaviour of petroleum and chlorinated hydrocarbons in soil vapour was also discussed. The group consensus was that the key differences centred around aerobic degradation in the unsaturated zone, which in turn affects the concentrations in the sub-surface beneath a property.

The group was in favour of collection of sub-surface data paired with indoor air concentration data at sites impacted with chlorinated solvents. It was also raised that a review for chlorinated compounds has been undertaken by the Netherlands (RIVM, 2006)[82]. The group was less certain about the absolute need for similar data collection

[81] CRC CARE, 2013, *Petroleum Hydrocarbon Vapour Intrusion Assessment: Australian Guidance, CRC CARE Technical Report no. 23*, Co-operative Research Centre of Contamination Assessment and Remediation of the Environment, Adelaide, Australia

[82] Van Wijnen, H.J. and Lizjen, J.P.A., 2006. Validation of the VOLASOIL model using air measurements from Dutch contaminated sites. Concentrations of four chlorinated compounds. RIVM report 711701041/2006

for petroleum hydrocarbons where vapour sources are delineated and there are sufficient lines of evidence to inform the CSM. However, they recognised this may help demonstrate whether a screening distance tool is appropriate within the UK, as discussed within Section 5.3.3. It was therefore agreed that collection of paired sub-surface and indoor air data from across the UK for both petroleum hydrocarbons and chlorinated solvents, following the US approach, would be useful. It was noted that the datasets for the two different types of VOC should be kept separate.

5.3.3 Applicability of screening distance approach within the UK

Soil vapour investigations are generally driven by the exceedance of either soil or groundwater GAC, which are inherently conservative for petroleum hydrocarbons due to the lack of consideration for biodegradation in unsaturated zone soils, which may provide significant Petroluem VI (PVI) attenuation To address this issue, screening distances were developed using empirical data collected at hundreds of petroleum UST sites spanning a range of environmental conditions and geographic regions over a 16-year period (Lahvis *et al.* 2013)[83] in Australia, USA and Canada (CRC CARE, 2013). It was, however, highlighted that the CSM upon which the screening distances are based was ITRC driven. Thus, the US EPA would not accept the use of screening distances in Superfund sites. Further details in the use and application of vertical screening distances are described in Lahvis et al. 2013, CRC CARE 2013 and ITRC 2014[84].

There was an interesting discussion in the workshop sub-group about the applicability of the screening distances in the UK, given the variability of site specific conditions between countries. The main issues raised with the use of screening distances in the UK are detailed below:

- A significant number of sites in the UK have shallow/ perched water as opposed to typically deeper groundwater in the USA;
- Property foundations and other construction differences may exist and will be an important part of the VI CSM. One example discussed was the implications of new

[83] Lahvis M., Hers I., Davis R., Wright L., DeVaull. 2013. Vapour intrusion screening at Petroleum UST sites. *Groundwater Monitoring and Remediation* 33 (2), pp53-67.

[84] ITRC, 2014. *Petroleum Vapor Intrusion Fundamentals of Screening, Investigation, and Management*. Interstate Technology and Regulatory (ITRC) PVI guidance (http://itrcweb.org/PetroleumVI-Guidance/) Accessed 20th December 2017

build techniques in the UK on vapour intrusion, in particular the move to more air-tight buildings with mechanical ventilation;

- Many UK sites have a thick layer of Made Ground that may not be a suitable medium for biodegradation, due to the potential absence of a suitable medium and/or sufficient soil moisture to support viable populations of aerobic bacteria.

The group also raised concerns that the vertical screening approach did not account for the potential presence of preferential pathways, while acknowledging this is the same with current modelling approaches. They also recognised that the soil type and moisture content were critical to the significance of preferential pathways, with the significance often increasing where cohesive ground conditions prevail.

The group discussed how these issues could be addressed. The majority of the discussion focussed on what inputs would be required, should an empirical database be set up in the UK.

5.3.4 Empirical database requirements

The group noted the lack of a robust dataset in the UK upon which the screening distances tool could be validated. The other concern was whether sufficient vapour investigations are undertaken and thus, whether sufficient data is available for collation in such a database.

The group identified the key risk driving compounds for vapour intrusion that would be required within an empirical data collection exercise as:

- Naphthalene;
- Aliphatic hydrocarbons;
- Trimethylbenzenes;
- Benzene; and
- Chlorinated compounds.

In addition to soil and foundation type, the database would also need to be created to answer questions such as:

- Percentage of investigated sites that have shallow water; and
- Characterisation of Made Ground that does not support biodegradation.

The following measurements were considered necessary to improve the understanding of the conditions resulting in potential for petroleum hydrocarbon biodegradation:

- Oxygen;

- Methane;
- Carbon dioxide; and
- Soil moisture content of unsaturated zone soils.

It was considered that soil microcosm studies might provide additional useful information.

5.3.5 Generic assessment criteria for Soil Vapours

Soil vapour and sub-slab vapour GAC have been derived by a number of consultancies. However, it was observed this was not common practice due to the lack of resources amongst smaller consultancies and other contaminated land practitioners. It was noted that consultancies were using approaches that, although all valid and in accordance with the Environment Agency published guidance and relevant international guidance, incorporated slight differences which could lead to different outcomes. The absence of published soil vapour/ sub-slab vapour GAC was considered to be an important issue that could be resolved by SoBRA, potentially using existing approaches used by consultancies. The recently published SoBRA GAC_{gwvap} (SoBRA, 2017) could be used as a starting point for the derivation of new vapour GAC for a groundwater source. It was noted that the limitations of the CLEA model (no groundwater source or capillary zone) would result in over-conservatism that would, in many cases, limit their practical use. Nevertheless, the group considered that the derivation of SoBRA vapour GAC would encourage consultants to undertake vapour investigations. This is because they would provide insight into the VI CSM and clarity on the importance of considering VOC in groundwater as a human health risk. This would also subsequently increase the VI dataset in the UK.

It was also discussed that it would be useful to assess the different models / approaches used by consultants to derive in-house GAC in order to select the most suitable approach, thus reducing the number of uncertainties and levels of conservatism. Models such as BioVapor could be considered as potential tools for the derivation of GAC for petroleum hydrocarbons, although the assumption that biodegradation is occurring without actual site-specific evidence, is likely to limit this model for GQRA assessment.

5.3.6 Preferential pathways

It was highlighted that the CSM should incorporate both vertical and lateral migration of vapours and the existence of potential preferential pathways, such as higher air porosity soil layers and underground services/ trenches. Potential for off-site risks must be included in the assessment (*i.e.* horizontal migration), together with an understanding of potential preferential VI routes, such as unsealed service entries into buildings. The group was not aware of modelling approaches to assess vapour intrusion risks associated with the transport of vapours through such preferential pathways. Consequently, the group considered a robust CSM supported by soil vapour data was the most appropriate method of VI assessment.

The group identified that there is the potential for shallow groundwater levels in the UK to give rise to a non-typical pathway for vapour intrusion, where contaminated groundwater is in direct contact with the building foundations. In this instance, the building fabric is impacted; migration occurs more readily and more irreversibly through building materials. However, no UK guidance has been identified to account for direct contact intrusion. Australian guidance proposes the use of a seepage model in CRC CARE Technical Report 23 (CRC CARE, 2013). The Virginia Department of Environmental Quality (VDEQ) proposes the use of a model based on mass transfer equations (VDEQ, 2016)[85]. In the event LNAPL is in direct contact with foundations international guidance recommends collecting indoor air quality data.

5.3.7 Building parameters

The group also discussed the potential involvement of NHBC and the Sustainability Institute in the derivation of GAC, as they could provide information on building construction and ventilation rates for different type of buildings. It was also raised whether lessons could be learnt from studies undertaken for radon ingress.

It was discussed that there is not sufficient empirical data in the UK to derive Qsoil (*i.e.* soil gas volumetric flow rate into the building through the floor slab) and comments were made regarding some risk assessors using incorrect assumptions relating to Qsoil rates for sandy versus sandy loam soils (see Qsoil discussion in SR3 [86]). Other countries have derived Qsoil based on empirical sub-slab to indoor air attenuation factors.

[85] VDEQ, 2016. *Virginia Unified Risk Assessment Model, VURAM User's Guide for Risk Assessors*, Virginia Department of Environmental Quality (VDEQ), 2016.

[86] Environment Agency, 2009. *Updated technical background to the CLEA model*, Science Report SC050021/SR3. Bristol: Environment Agency.

5.4 Conclusions

The group concluded:

- Use of soil and groundwater data alone (and comparison with relevant GAC) for vapour intrusion assessment is often unreliable;
- Soil vapour investigations are rarely conducted in the UK. Whilst the reasons for this are uncertain, it was considered that a clear protocol documenting when soil vapour sampling is required to reduce the conservatism of basing VI risk conclusions on soil and/ or groundwater data would raise awareness. If soil vapour GAC were available this would help practitioners with data interpretation;
- The potential for biodegradation in the unsaturated zone as a significant attenuation mechanism for PVI requires more consideration, along with the collection of supporting site data (soil moisture and oxygen, carbon dioxide and methane concentrations) and undertaking vertical soil vapour concentration profiling; and
- Evaluation of the applicability of vertical and lateral screening distances in the would be useful. This would start with a detailed review of the conceptual site model in the UK versus that used to prepare the existing screening distance criteria, followed by creation of an empirical database, similar to that created by the US, Canada and Australia.

5.5 Recommendations

The group recommended that SoBRA should establish a sub-group (or various sub-groups) to engage with relevant stakeholders and to prepare:

- User friendly, concise guidance (*i.e.* a practitioner's guide) with flowcharts, decision and a specific framework for vapour intrusion assessment in the UK. This would also identify differences in existing models to help practitioners make an informed decision;
- Vapour GAC, which would also encourage the collection of empirical data. This would also necessitate a review of the suitability of the available models for both GAC for groundwater and soil vapour and approaches to inform the methodology;

Input parameters needed for an empirical database that would inform UK validated screening tools. This would necessitate a review in the difference in CSM for properties in the UK by comparison to existing screening distance tools to ensure appropriate input parameters were collected.

6 RISK ASSESSMENT TECHNIQUES AND HOW WE CAN PROACTIVELY MANAGE 'WHEN THINGS DON'T GO TO PLAN' (WORKSHOP GROUP 4)

6.1 Introduction

The group comprised primarily consultants but regulators and representatives from local authorities were also present. The group attendees are listed in Appendix 1 and were led by the facilitator, Jonathan Cundall (NHBC), and rapporteur, Emily Upton (Atkins).

6.2 Objective

The objective of this group was to look at the key issues associated with the risk assessment options available for vapour intrusion projects and how they can be proactively managed 'when installation doesn't go to plan'.

6.3 Key Issues

The key issues that were identified and discussed by the group were:

- Inadequate site data;
- Inadequate initial risk assessment;
- Incorrect vapour membrane installation; and
- Over-reliance on vapour membranes.

Summaries of the discussions regarding the above issues are presented in turn in the sub-sections below. Generally, there was consensus amongst the group on the issues discussed.

6.3.1 Inadequate site data

A comment was made that modelling and risk assessment are only as good as the data collected on site. The subsequent discussion focussed on the need to install vapour-specific monitoring wells on sites to assess the risk from vapour sources competently, where identified. Vapour wells should target the ground above the capillary fringe to avoid an underestimation of the vapour concentrations, and careful consideration should be given to vapour well locations and depths. When sampling vapours in buildings, consideration should be given to sources within the building, such as building materials, paints, cleaning products, electrical items and cigarettes.

A standard PID should only ever be used as a preliminary assessment tool to characterise the extent of the source zone, and to indicate whether further vapour data monitoring or sampling is therefore required in or beneath the building[87].

6.3.2 Inadequate initial risk assessment

Inadequate initial risk assessment may be the cause of installation not going to plan, or regulators may not approve proposed remedial measures. Regulators in the group cited a parallel example of permanent gas monitoring and gas protection mitigation measures being carried out at some sites where no gas source has been identified, and commented that consultants or developers sometimes show a lack of understanding of BS8485[88]. The group discussed the idea of updating the CIRIA vapour handbook (CIRIA, 2009)[89] to provide more detail. An understanding of the way vapour behaves, how to incorporate this into the CSM, and then how best to adapt a modelling tool to reflect the CSM, is vital. Modelling requirements become more complex if the risk assessment is being carried out post-construction. It was suggested that SoBRA could organise training sessions in the correct use of the J&E model, as some members of the group believed it to be commonly misunderstood. Some members of the group were also concerned that risk assessors do not understand the role and mechanisms of vapour diffusion rather than advection. Limitations of the CLEA model for modelling vapours were highlighted, including:

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[87] Editorial Note: A standard PID with a detection limit of ppm would not be sensitive enough to detect some common contaminants of concern at hazardous concentrations within a building with any certainty, especially given the additional uncertainties introduced by moisture and background effects. A PID with a detection limit within the ppb range may be used as a preliminary assessment tool to detect preferential entry points for vapour within a building, if combined with a technical examination of the structure. However, a PID combined with thoron or a tracer gas gives a higher chance of detecting intrusion pathways (Hvidberg, B, 2013 Detecting intrusion pathways of soil gas to indoor air. A presentation to the RSC/ SoBRA 2013 Christmas Conference)

[88] British Standards Institute, 2015. BS 8485:2015 *Code of practice for the design of protective measures for methane and carbon dioxide ground gases for new buildings*.

[89] CIRIA, 2009. *The VOCs Handbook Investigating, assessing and managing risks from inhalation of Volatile Organic Compounds (VOCs) at land affected by contamination*, CIRIA Report C682, London 2009.

- Limited floor type options, which do not necessarily represent all buildings in the UK;
- Over-conservatism in the estimation of hydrocarbon vapour concentrations; and
- Lack of an option to represent preferential pathways.

The group discussed the possibility of creating an updated and more concise database of building parameters for buildings in the UK. They also considered the question of whether data on hydrocarbon vapour activity in the vadose zone could be collected from studies conducted in the United States and Australia, if considered relevant to the UK, in order to create an updated modelling database. Questions raised by the group included:

- Could a SoBRA sub-group derive vapour generic assessment criteria, based on data in the vadose zone?
- Should the effect of changing the ground cover (for example, from soft cover to hard-standing) may have on the oxygen content in the ground, and hence the degradation rate of VOCs be explicitly incorporated into risk assessments? and
- Are the effects of pressure, temperature and weather on VOC concentrations understood?

6.3.3 Incorrect vapour membrane installation

Protection can be rendered ineffective by the incorrect selection of and/ or incorrect installation of a membrane. There is no standard way to install a membrane; it can be installed above or below the floor screed. The group agreed that better training and certification of staff installing and verifying the membranes would be beneficial. Additionally, uniform methods of testing membranes by manufacturers is required, as at present there is an inconsistent approach by manufacturers to reporting data on their membranes.

6.3.4 Over-reliance on vapour membranes

The group agreed that undue reliance should not be placed on vapour membranes to provide total mitigation to ingress of vapours. Robust risk assessment should be carried out, and sub-floor voids and ventilation systems should be appropriate to the CSM. Ideally, as much of the source as possible should be removed. There is not yet an appreciation of the lifespan of vapour membranes, and there is no guarantee that inhabitants or users of buildings containing vapour membranes will not compromise them in the future. It was recognised that some developers install vapour/ gas membranes as a 'precaution' without carrying out a robust risk assessment first. There is a risk that other sources and pathways may be missed in these circumstances, and a robust site investigation is always preferable. Vapour membranes should always be considered as the last line of defence, and communication with local authorities in the risk assessment and design phases is recommended.

6.4 Conclusions

In conclusion, issues can arise due to:

- inadequate site investigation data;
- inadequate risk assessment;
- inadequate membrane installation; or
- poor mitigation design/over-reliance on vapour membranes.

Where a vapour source is identified on site, robust site investigation targeting vapours is required, with thorough risk assessment carried out by competent risk assessors who have a good understanding of vapour behaviours and the conceptual site model. All models have limitations which the users should be aware of, and models should be adapted to incorporate as many site-specific parameters as possible. Installation of appropriate sub-floor voids and vents is a vital vapour mitigation measure, and vapour membranes should be installed and verified by competent, certified staff.

6.5 Recommendations

Members of the group offered the following suggestions:

- Vapour-specific monitoring wells should be used more frequently for vapour risk assessments, and sufficient monitoring should be undertaken;
- Vapour membranes should be considered as the last line of defence.
- Vapour membrane installers and validators should be 'competent', with consideration given to an industry definition of competency;
- Vapour membrane suppliers should provide greater standardisation within the testing regime for their products;
- SoBRA should consider organising training sessions to provide a much-needed enhanced understanding of vapour modelling, particularly the J&E model;
- SoBRA should consider setting up a sub-group to develop soil-vapour GAC; and
- Industry should consider producing an update to the CIRIA C682 vapour handbook.

7 CONCLUDING REMARKS

7.1 Key Issues and Recommendations

The SoBRA Summer Workshop 2017 identified many areas where the practices relating to the conceptualisation, investigation, assessment and evaluation of mitigation of the vapour intrusion pathway could be improved.

Several more general recommendations relating to implementation of existing good practice are presented within the recommendations for each workshop, with significant consensus between Workshops. These can be summarised as:

- Improvement of general practice within the industry so that VI is always considered at sites where this is a credible source and pathway;
- Improvement of the recognition of the importance of preferential pathways within the VI pathway across the industry;
- Promotion of collection of soil vapour data from appropriately designed installations, rather than reliance on soil and groundwater data and increased emphasis on a lines of evidence approach;
- Vapour membranes should be considered as a final option, rather than a 'catch all' and should be installed and validated by 'competent' individuals; and
- Vapour membrane suppliers should provide greater standardisation within the testing regime for their products.

Other, more specific recommendations of the Summer Workshop were:

- Collection of empirical paired sub-surface and vapour measurements, together with data on soil conditions to develop a database and inform a vertical distance screening approach for the UK.
- Development of improved guidance and protocols to build on existing good practice for vapour intrusion assessment, to include: investigation design, vapour sample collection, CSMs for VI including considering building construction and addressing preferential pathways;
- Development of training material to improve investigation and assessment of the vapour intrusion pathway, including DQRA; and
- Development of freely available Vapour GAC.

7.2 Delivering the Recommendations

SoBRA's 2017 Summer Workshop produced several recommendations that members believe would improve UK risk assessment practice for the VI pathway. Some require reaching out to and working with other organisations in order to deliver solutions.

A number of the recommendations involve further research and the development of guidance, building on the work of the previous Vapour Intrusion Sub-group, which successfully delivered GAC and accompanying guidance for groundwater GAC for human health risks from vapour. A new vapour Intrusion Sub-group has therefore been set up by the Executive Committee to consider these recommendations. Further information can be found on the SoBRA website (www.sobra.org.uk).

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APPENDIX 1

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WORKSHOP 3: DEVELOPMENT OF ALTERNATIVE RISK ASSESSMENT TECHNIQUES BASED ON SCIENTIFIC STUDIES

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WORKSHOP 4: RISK ASSESSMENT TECHNIQUES & HOW WE CAN PROACTIVELY MANAGE 'WHEN THINGS DON'T GO TO PLAN'

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APPENDIX 2 ABBREVIATIONS/ACRONYMS

1,2-DCA	1,2-dichloroethane
AF	Attenuation Factor
API	American Petroleum Institute
bgl	Below ground level
BSI	British Standards Institution
BTEX	Benzene, toluene, ethylbenzene and xylenes
CLEA	Contaminated Land Exposure Assessment
CoHHLa	Continuous Horizontal Homogeneous Layers
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation
CSM	Conceptual Site Model
CVOC	Chlorinated Volatile Organic Compounds
DNAPL	Dense Non-Aqueous Phase Liquid
DQO	Data Quality Objective
DQRA	Detailed Quantitative Risk Assessment
EA	Environment Agency
EDB	Ethylene dibromide (1,2-dibromoethane)
eV	Electron Volt
g	gram
GAC	Generic Assessment Criteria/Criterion
GC	Gas Chromotography
GQRA	Generic Quantitative Risk Assessment
GQRUZ	Groundwater Quality Restricted Use Zone
IP	Ionisation Potential
IPA	Isopropyl alcohol
ITRC	Interstate Technology and Regulatory Council
l/hr	litres per hour
LNAPL	Light Non-Aqueous Phase Liquid

LOD	Limit of Detection
m	metre
mg/l	milligrams per litre
mm	millimetre
MIP	Membrane Interface Probe
MTBE	Methyl tert-butyl ether
NAPL	Non-Aqueous Phase Liquid
NEPM	National Environment Protection Measures
NHBC	National House-Building Council
OSWER	Office of Solid Waste and Emergency Response
Part 2A	Part 2A of the Environmental Protection Act 1990
PCE	Perchloroethene (perchloroethylene, tetrachloroethene)
PID	Photo Ionisation Detector
ppb	Parts per billion
ppm	Parts per million
PSD	Particle Size Distribution
PTFE	Polytetrafluoroethylene (Teflon)
PVI	Petroleum Vapour Intrusion
PVOC	Petroleum Volatile Organic Compounds
QA/QC	Quality Assurance/ Quality Control
RBCA	Risk Based Corrective Action
RBSL	Risk Based Screening Levels
RSL	Regional Screening Level
SNIFFER	Scotland and Northern Ireland Forum For Environmental Research (now simply SNIFFER, but acronym used in previous reports)
SoBRA	Society of Brownfield Risk Assessment
SPOSH	Significant Possibility of Significant Harm
SVOC	Semi-Volatile Organic Compound

TCE	Trichloroethene (trichloroethylene)
TPH	Total Petroleum Hydrocarbons
TWA	Time-Weighted Average
UK	United Kingdom
US	United States
USA	United States of America
US EPA	United States Environmental Protection Agency
UST	Underground Storage Tank
UV	Ultra-Violet
VOC	Volatile Organic Compound
v/v	volume/ volume
VDEC	Virginia Department of Environmental Quality
VVOC	Very Volatile Organic Compound
WHO	World Health Organization
$\mu g/m^3$	microgram per cubic metre