SoBRA
The Society of Brownfield Risk Assessment

SOCIETY OF BROWNFIELD RISK ASSESSMENT

Vapour Intrusion – Guidance Notes for Assessment in Contaminated Land Scenarios in the UK

Note 1A: Conceptual site model development for the assessment of vapour intrusion linkages in the UK

Version 1.0

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PUBLICATION

This series of reports and tools is published by the Society of Brownfield Risk Assessment (SoBRA). It presents work undertaken by a SoBRA sub-group composed of volunteers listed in the acknowledgments below. This publication is part of a series of work packages designed to address various issues in data collection and evaluating risks associated with vapour intrusion.

The Society of Brownfield Risk Assessment (SoBRA) has produced a series of accessible and concise practitioners' guides to support informed decision making with respect to vapour intrusion (VI) risk assessment within the UK. In the context of these paper, “VI” is defined as:

“Vapour intrusion occurs when there is a migration of vapor-forming chemicals from any subsurface source into an overlying building” (US EPA).

These guides follow on from the publication of the SoBRA Groundwater Vapour Generic Assessment Criteria (GAC_{gwvap}) and from the recommendations of the SoBRA Summer 2017 workshop.

It is acknowledged that there is already an extensive portfolio of existing industry guidance available both within the UK and internationally in relation to VI risk assessment, nevertheless, these practitioners’ guides aim to provide high level summaries of the existing guidance, covering key aspects of VI risk assessment and include signposting to the relevant published industry documents for more detailed information, where required.

The topics covered by the SoBRA practitioners' guides published so far comprise:

1A. Conceptual site model development for the assessment of VI contaminant linkages in the UK (this publication);

1B. Benefits of soil vapour sampling for assessment of VI risks; and

1C. VI data collection considerations.

This first document in the series focusses on the development of conceptual site models (CSM) for assessment of VI linkages in the context of UK building types, including consideration of relevant contaminant linkages, preferential pathways and associated uncertainties. As the first document in the series, this also provides a useful reference list of key sources of guidance in relation to VI assessment.

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1. INTRODUCTION

This guidance note provides an overview of the development of a CSM for VI in the UK and considers the two prevalent classes of volatile organic compounds (VOCs) that commonly drive VI risks, namely:

- **Petroleum hydrocarbons (PHCs)**: such as tars, petrol, diesel or jet fuel (composed of complex mixtures of hundreds of individual compounds such as benzene, toluene and butylbenzenes). These hydrocarbons are typically neutral to Light Non-Aqueous Phase Liquids (LNAPL) and have dissolved-phase and vapour-phase aerobic degradation rates that can limit VOC flux and the potential for VI risks.
- **Chlorinated hydrocarbons (CHCs)**: solvents such as dry-cleaning chemicals (e.g. tetrachloroethene) and degreasing solvents (e.g. trichloroethene). These chlorinated VOCs may more often be present with a large predominance of a single chemical, although mixtures of the parent compound and biodegradation daughter products are common. CHCs are typically Dense Non-Aqueous Phase Liquids (DNAPL), with lower rates of aerobic degradation in both groundwater and the vadose zone.

Note: There is differing terminology commonly used to represent the presence of VOCs in the soil vapour phase. The terms “soil vapour” and “soil vapour-phase VOCs” are used throughout this paper and are synonymous with other terms such as “soil gas VOCs”.

Throughout the subsequent sections of this paper CHCs and PHCs are identified by the colours purple and orange to assist the reader.

2. KEY ELEMENTS OF THE VI CSM

Where a site is, or is suspected, to be impacted by VOCs, the migration of VOCs into buildings is likely to be the pathway with the greatest potential to result in exposure of human receptors. Therefore it is crucial to understand the source characteristics and the numerous pathways by which VI could occur. In simplistic terms, the main elements of the VI CSM comprise:

- Presence of a VOC source in soil and / or groundwater;
- Partitioning of those VOCs from the soil and / or groundwater source into soil vapour;
- Migration of soil vapour (via diffusion) through the vadose zone, from the source area to beneath the building, with varying degrees of biodegradation potentially occurring along the migration pathway; and

- Further migration of soil vapour (via advection and diffusion) into the building through floor cracks, service entries etc. and mixing with indoor air.

A CSM where PHCs are present will differ from a CSM where CHCs are present, due to differences in biodegradation of these two groups of VOCs in the typically aerobic shallow soils of the vadose zone. PHCs can attenuate rapidly in the vadose zone due to aerobic degradation, yielding nontoxic degradation products including carbon dioxide, water and occasionally methane. CHCs on the other hand degrade at a much slower rate, and primarily only via anaerobic processes - hence their potential for degradation in the aerobic vadose zone is very limited. Furthermore where CHCs are able to degrade, they can generate degradation daughter products which are also toxic, such as vinyl chloride and dichloroethene.

A summary VI CSM is provided in diagrammatic form in Figure 1 – not all sites will have all aspects of this overall CSM, but they are nonetheless important to consider in each instance.

The source-pathway-receptor aspects of the CSM shown on Figure 1, including key uncertainties, are discussed in the following sections of this paper.

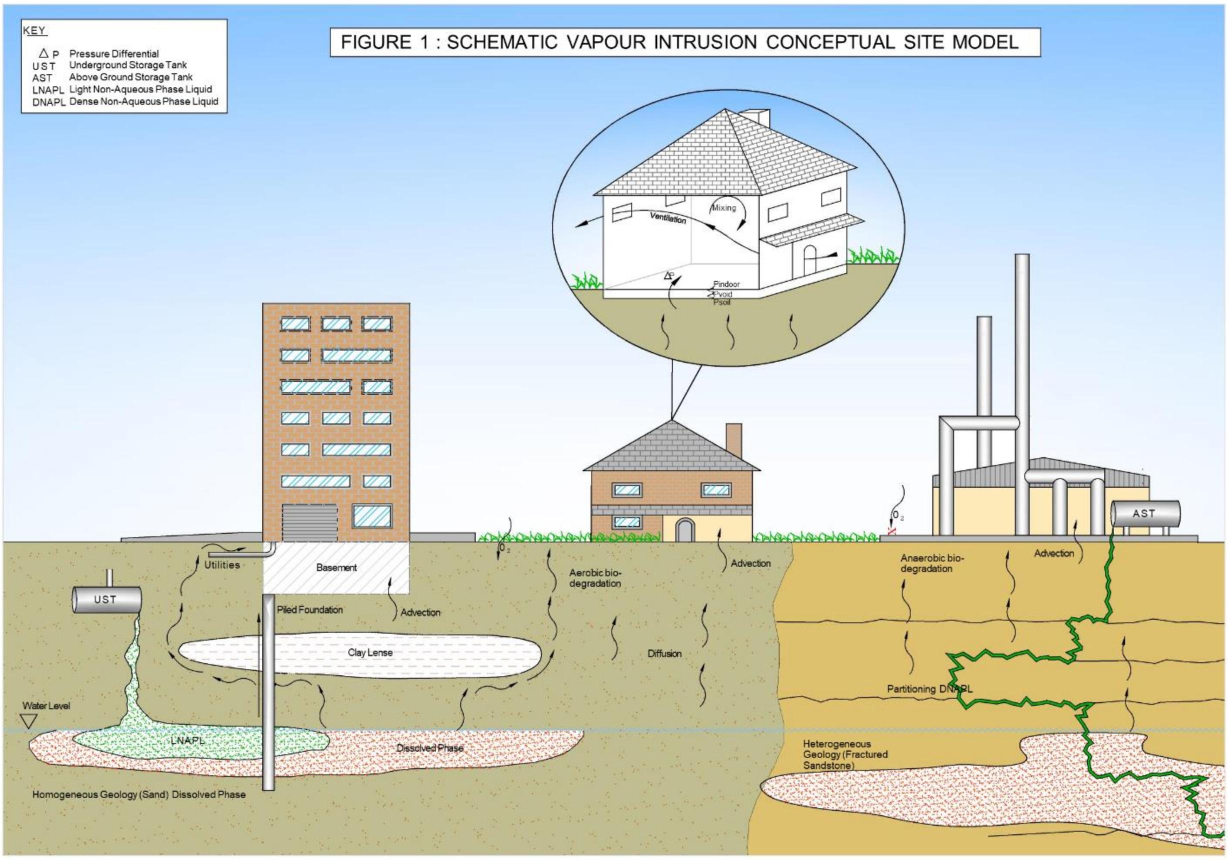

Figure 1: Schematic Vapour intrusion (VI) conceptual site model (CSM)

2.1 CSM Uncertainty

The assumptions made in an initial CSM will drive future investigations and assessments for VI (and any other relevant potentially complete contaminant linkages), with each subsequent phase of work having its own inherent areas of uncertainty associated with it.

With regards to the initial CSM, assumptions need to be made on the potential sources, pathways and receptors, with these assumptions being refined as further investigations improve the understanding of conditions on or off site. Some of the commonly occurring uncertainties that can be associated with the various aspects of the CSM, and that can have a substantial effect on the assessment of VI risks, are identified in the relevant sections below.

Note: The uncertainties listed in relation to each of the CSM elements are not an exhaustive list and the reader should consider uncertainty in each CSM developed on a site-by-site basis.

2.2 Sources

There are numerous potential sources of soil vapours in the subsurface, which can include primary sources (tanks, fuel lines etc.) and secondary sources (e.g. NAPL, VOCs sorbed to soil and VOCs in the dissolved-phase present in porewater and / or groundwater).

Potential sources include:

- Leaking below ground tanks, which could include underground storage tanks (UST) or backfilled below ground tanks potentially containing tars, NAPLs and contaminated water (e.g. former gasholder tanks);
- Surface spills including those from above-ground storage tanks (AST);
- Wastes within landfills and / or infilled ground;
- Drains and sewers where contaminated material has been disposed or accumulated;
- NAPL including the main NAPL plume, residual NAPL in soil pores, and NAPL within the groundwater smear zone; and
- Dissolved-phase VOCs in groundwater.

2.2.1 Factors affecting VOC behaviour in the source area

Ground conditions

The ground conditions will affect source distribution, with highly permeable geology allowing easy vertical migration of source liquids. Conversely, low permeability geology may limit vertical migration, or else may facilitate vertical migration along higher permeability preferential pathways such as fractures, sandy lenses or man-made features such as drainage runs.

Density relative to water

Typically, PHCs are less dense than water, so they do not tend to penetrate to any significant depth vertically beyond the water table, unless driven by vertical groundwater flow.

Conversely, CHCs are typically more dense than water and therefore will continue to 'sink' through the saturated zone where pathways are available.

The differing density-driven extremes of behaviour exhibited by PHCs versus CHCs are critical considerations when compiling a CSM for VI risks. Failure to consider these contrasting behaviours at the CSM stage can lead to inappropriately scoped intrusive investigations and inadequate assessments of potential VI risks.

2.2.2 Physicochemical processes affecting VOC behaviour in the source area

Partitioning

VOCs will partition into three phases in the vadose zone (sorbed, vapour and dissolved phase), and into two phases (dissolved and sorbed phase) in the saturated zone.

Partitioning of VOCs is controlled by:

- Contaminant specific parameters such as Henry's Law, K_{oc} or K_{ow};
- Soil properties such as water / air filled porosity, bulk density and soil organic matter; and
- Compound mixtures as defined by Raoult's Law.

For groundwater sources, the capillary fringe – controlled by soil properties – influences vapour concentrations immediately overlying the saturated zone.

Biodegradation

Source area biodegradation can occur through aerobic or anaerobic processes depending on the ground conditions. There is a fundamental difference between the potential for PHCs to degrade in the ground compared to CHCs: PHCs readily degrade under aerobic conditions and CHCs degrading at a much slower rate, and primarily only via anaerobic processes (hence their potential for degradation in aerobic soils is very limited).

In terms of source term characterisation, the significant point to note with respect to biodegradation is the differing degradation products arising from PHC and CHC degradation, and how this can change the VI CSM with time. PHCs degrade to produce oxygen, water and methane which pose a lower risk to receptors in the context of VI (although the explosive nature of methane should be considered). Conversely, the breakdown products of CHCs can include daughter compounds which are sometimes more toxic (and therefore of a higher risk in the context of VI) than the original parent CHCs compound, although CHCs may eventually break down to ethene, ethane and carbon dioxide. Biodegradation of CHCs can therefore cause the proportional mix of the specific CHCs present to change with time, with concentrations of some contaminants declining and others increasing.

2.2.3 Uncertainty considerations: Source

- Source location and distribution – Defining the lateral edge of a soil source area or contaminant plume is often not known with the same degree of certainty as the vertical delineation. Investigations of lateral extent are usually conducted over a scale of several metres, compared to centimetres when delineating vertically.
- Consideration of whether the source is in direct contact, or has the potential to come into direct contact, with the building fabric (discussed further in Section 2.2 - Pathways);
- Groundwater levels – if LNAPL is present on the surface of the groundwater as a secondary source of soil vapour, then variation in groundwater levels can have implications for the current understanding of the CSM and may require potential risks to be reassessed;
- Accuracy of theoretical partitioning coefficients; and
- Soil heterogeneity and soil sampling to characterise VOC source concentrations – intrusive site investigations typically provide very limited characterisation of the sub-surface. Estimated soil concentrations (e.g. VOC loss during and after sample collection), theoretical partitioning and capillary fringe effects result in high

uncertainty when estimating vapour concentrations from soil and groundwater data.

- Appropriate best practise guidance should be considered when designing a site investigation and recovering soil samples for VOC analysis (e.g. BSI 10176:2020) but ultimately, direct soil vapour sampling will inevitably produce more reliable estimates of soil vapour sources (see SoBRA Note 1B – When soil gas sampling is beneficial).

2.3 Pathways

In the context of VI CSM, a VI pathway is the route by which vapours migrate towards and into a building. Migration can occur vertically or laterally and can be influenced by many factors, as identified in Figure 1 and described below. Migration pathways can be considered under three general sub-groups, namely:

- Conventional pathways: the migration of vapours through the vadose zone and building foundations;
- Preferential pathways: the migration of vapours along a higher permeability subsurface feature, that can act as a conduit allowing easier entry of vapours into buildings; and
- Direct contact / infiltration: the source may be in direct contact or may have the potential to come into direct contact, with the building fabric.

2.3.1 Conventional pathways

In the UK, there are three typical modern foundation types which will each facilitate VI in different ways, and which have implications for the VI CSM. The three foundation types are shown schematically in Figure 2 and comprise:

1) Beam and block with a ventilated sub-floor void commonly supported by strip or pad foundations (analogous to suspended timber floors in older housing stock);
2) Cast in-situ slab with sub-floor void; and
3) Cast in-situ ground bearing slab.

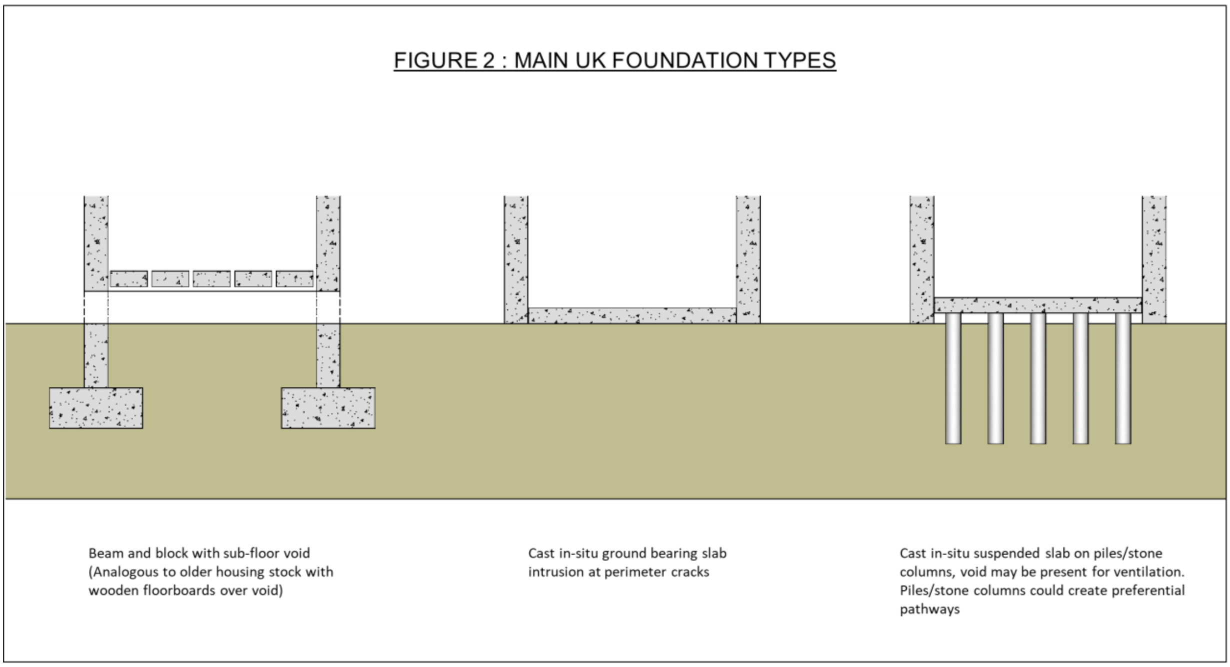

Figure 2: Summary of the three main foundation type most commonly used in the UK

Cast in-situ slabs may be supported by piled foundations, or stone columns (or similar) may also be used to improve the ground. Pile or stone column foundations form potential preferential pathways from deeper sources direct to the base of the building floor.

When considering buildings with basements, these foundations may have various constructions. Older residential basements may potentially comprise simple brick walls and earth floors, and more modern basements may comprise cast in-situ ground bearing slab and walls with varying levels of waterproofing.

Other less common modern methods of construction can include prefabricated buildings that may be raised off the ground, or buildings with under-croft car parks etc. In both cases, the presence of an underlying, freely ventilated air space will help to reduce potential risks associated with VI.

As well as the foundation construction type, consideration of the foundation depth is also important in characterising conventional VI migration pathways with respect to the offset between the base of the foundations and the underlying water table and any LNAPL that may be present on the water table. The shallower the groundwater level beneath a building, the shorter the vapour migration pathway through the vadose zone and the less opportunity there is for attenuation to occur within the vadose zone. Similarly, the deeper the groundwater level is beneath the foundations, the greater the opportunity for attenuation of soil vapours. Where LNAPL is present in close proximity to the foundations then it may migrate vertically up into the foundations via capillary action (See later section on "Direct infiltration of building fabric" for further discussion).

Potential VI into buildings of typical construction (as set out in CIRIA C682, 2009) comprises migration through:

- Cracks and openings in solid concrete;
- Construction joints / openings at wall-foundation interface with ground slab (if not sealed);
- Cracks in walls below ground level;
- Gaps and openings in suspended block and beam floors and / or punctures / damage to damp proof membranes;
- Gaps around service pipes / entries and / or ducting; and
- Cavity walls voids.
- When considering the CSM for VI, it is also important to note that VI risks associated with lateral migration of soil vapours are most more likely where there is a confining layer (such as hardstanding cover or clay) over a more permeable horizon.

2.3.2 Physicochemical processes affecting VOC behaviour along conventional migration pathways

Diffusion

Diffusion is the migration of vapours driven by a concentration gradient – the vapours migrate from areas of high soil vapour concentration to areas of lower soil vapour concentration.

Parameters that will affect diffusive vapour migration and intrusion include:

- Contaminant diffusion coefficient (in air and in water) – compound-specific property;
- Source area;
- Diffusive path length i.e. depth of source, distance of source from building (as per the screening distances approach discussed in ITRC, 2014);
- Porosity of soil;
- The size of the cracks and gaps in foundations; and
- Effective diffusivity of soil and of the air / dust present in foundation cracks and gaps.

Advection

Advection, generally considered the predominant VI force, is controlled by the pressure differential between the air inside the building and soil gas pressure in the ground.

Advection is the bulk movement of soil gas induced by this pressure differential, with vapours migrating towards the area of lower pressure. This pressure differential is caused by a number of factors:

- Stack effect due to temperature differences in buildings which affects air density and pressure, which is usually increased for taller buildings; and
- Venturi effect which causes a pressure differential by drawing air out of a building to the leeward side where pressure is lower due to air / wind motion. Soil gas may be drawn into lower pressure buildings through entry points in the foundations.

Parameters that will affect advective vapour migration and intrusion include:

- Barometric pressure differences;
- Pressure differences between the ground and building interiors;
- Soil air permeability (intrinsic permeability);
- Soil saturated hydraulic conductivity; and
- Pathway dimensions (area and length).

Overpressure in the ground, caused by for example significant methane generation in a source area, may also contribute to the generation of a pressure differential which in turn drives advective migration, but this is a less common scenario.

Biodegradation

As discussed in the Section 2.1.2, biodegradation is a key differentiating factor between how we consider PHCs and CHCs in a VI CSM, primarily due to their differing susceptibility to degradation as well as the issue of "daughter" products (in the case of CHCs). In the context of considering the influence of vapour migration pathways on the potential VI risk, PHCs typically biodegrade readily under aerobic (oxygenated) environmental conditions which can limit the potential for migration and VI, whereas CHCs typically biodegrade much more slowly, and primarily under anaerobic conditions in the subsurface.

When considering biodegradation in relation to VI migration pathways, the following factors can have implications for the degree of biodegradation that may occur, whether we are considering PHCs or CHCs:

- Availability of oxygen (e.g. type of surface coverings etc.);
- Moisture content of soils;
- Nutrient availability for soil microbes;
- Soil temperature; and

- Presence of additional contaminants that may inhibit biodegradation (e.g. heavy metals which can be toxic to microorganisms).

Given that shallow soils in the vadose zone are commonly oxygenated, an aerobic biodegradation zone will form around the periphery of a PHC soil vapour and / or dissolved phase plume, with resultant natural microbial activity degrading the PHC via aerobic processes, thus limiting the overall extent of the PHC contaminant plume. Whilst this aerobic microbial activity may subsequently cause depleted oxygen levels within the core of the plume, the aerobic biodegradation zone around the periphery is maintained via replenishing oxygen transport either from the atmosphere or from oxygenated groundwater.

Subsurface conditions therefore often favour the rapid and complete aerobic degradation of PHCs, rather than the slow and incomplete anaerobic degradation of CHCs. This in turn can lead to a greater prevalence of CHC VI risks compared to PHCs, and CHC plumes that often extend over a much wider area compared to PHC plumes (for soil vapour and dissolved phase).

Re-partitioning

As soil vapours migrate along a vadose zone pathway, they may re-partition to soil if horizons overlying the source area have higher soil organic carbon contents. Estimates of soil vapour-phase concentrations, based on source partitioning alone, could therefore overestimate actual soil vapour concentrations.

Mixing and dilution

Mixing and dilution occur as vapours migrate from the soil into a sub-floor void (if present), and again from sub-floor void to the indoor air within the building.

The processes of mixing and dilution are affected by:

- The flow rate of outdoor air into the sub-floor void or building (the air exchange rate), which can be influenced by receptor behaviour in an occupied building; and
- Outdoor air or indoor air background VOC concentrations.

2.3.3 Preferential pathways

A preferential pathway is a pathway that provides an easier route for vapours to travel into buildings, and therefore resulting in greater exposure of the receptor, than might be expected based on typical ground conditions. Preferential pathways typically increase the risk of significant VI and can potentially result in greater than expected concentrations in buildings. Preferential pathways can be both natural and anthropogenic. Examples of preferential pathways include:

- Natural ground conditions: Fractured bedrock, gravel lenses / channels, naturally occurring voids – may lead to atypical gas flow, in some cases opposite to groundwater flow direction; and
- Artificial / engineered conditions: Utility features (e.g. conduits, drains, sewers, heating and ventilation ducts and lift shafts etc.) or ground engineering (e.g. historic mine workings, tunnels, piles, stone columns etc.)

Identification and assessment of preferential pathways can be problematic, as they are not generally targeted by a traditional intrusive site investigation.

2.3.4 Direct infiltration of building fabric

In some instances, the source may be in direct contact, or may have the potential to come into direct contact, with the building fabric. Where this occurs, the VOC source (either LNAPL or contaminated groundwater) may permeate into and saturate the fabric of the building via cracks in the foundations or via basement structures.

Owing to the absence of the vadose zone migration pathway (and the associated attenuation that can occur along the vadose zone pathway), these situations can result in increased vapour concentrations reaching indoor air than would otherwise have been associated with the same source where it was not in direct contact with the building. Mitigation and / or remediation of such scenarios is also more problematic than with conventional pathways scenarios.

2.3.5 Uncertainty considerations: Pathways

- The significance of advection and diffusion in the vadose zone – these processes are affected by soil moisture (which is in turn controlled by soil type, rainfall, presence / absence of hardstanding), atmospheric pressure, soil type and degree of heterogeneity, preferential pathways (e.g. fractures and sand horizons) and confining layers (e.g. clay bands preventing vertical migration in certain areas);
- Degree of biodegradation – this is heavily influenced by the oxygen content of the sub-surface and is likely to be a significant attenuating mechanism for PHCs vapours, and less so for CHCs. The soil organic matter content is also an important factor is considering the potential degree of biodegradation – for biodegradation to occur, the soils must be "biologically active";
- Floor construction type and influence of sub-floor voids (if present);
- Slab thickness and extent of open cracks / joints in concrete slab and in walls below ground level;
- Building parameters such as air exchange rate;
- Operation of heating, ventilation and air conditioning (HVAC) climate control systems can significantly alter VI rates into buildings;

- Changes to site conditions during redevelopment – such as the removal of hardstanding or other confining layers – which can alter the existing CSM and affect the assessed level of VI risk; and
- Creation of preferential pathways with respect to VI:
  - Via piling or ground improvement such as vibro replacement stone columns; and
  - Via service pipes/entries, ducting/service corridors, historic mine workings or other sub-surface infrastructure.

2.4 Receptors

The receptors in the VI CSM in the context of this guidance note are the occupants of onsite building(s) in question, either proposed or existing. Typically, this could include:

- Residents in residential buildings, which could include low rise housing or apartment blocks;
- Workers in commercial or industrial premises;
- Visitors to residential or commercial / industrial buildings; and
- Regular maintenance workers in centrally serviced buildings or sub-surface confined spaces.

Although this paper focusses on receptors located onsite, the same principles apply when considering offsite receptors from a potential VI risk perspective, particularly where potential preferential offsite migration pathways exist (i.e. service conduits) or where PHCs or CHCs are present in groundwater and groundwater is migrating offsite and potentially beneath offsite buildings.

The most important receptor characteristics and behaviours determining the degree of risk from VI include:

- Breathing rate relative to body weight (i.e. rate of intake of contaminant per unit weight)
- Exposure duration (i.e. number of years receptor resides or works in the building)
- Exposure frequency (i.e. hours per day and days per year that receptor occupies the building)

For the purposes of a precautionary assessment, in the UK these parameters are typically based on a female child aged 0-6 years for residential exposure, and a female adult aged 16 – 65 (i.e. 49 years exposure) for commercial / industrial exposure, as defined within Environment Agency Science Report – SC050021/SR3 (Environment Agency, 2008).

2.4.1 Uncertainty considerations: Receptors

- Demographic of the residents and workers – what is the critical receptor for the CSM?;
- Use and occupation of the building by the receptors that can be highly variable and can affect factors such as ventilation, air exchange rates and resulting exposure; and
- Variability in receptor physical and physiological characteristics and receptor behaviour on an individual basis (both of which are subject to assumptions where assessment criteria are modelled for generic land uses) – albeit this is more likely to be considered as part of a VI detailed quantitative risk assessment, such as to support a Part 2A assessment under the Environmental Protection Act 1990, rather than a more routine VI assessment.

3. CONCLUSIONS

This note provides a summary of the key elements to be considered when developing a VI CSM for contaminated land risk assessment. These include:

Sources

VOC sources can exist in the sub-surface as NAPL, sorbed to soil, in the vapour phase, and in the dissolved phase. Delineation of the source area and identification of source concentrations can have high uncertainty, particularly horizontally, given the practical limitations of many intrusive investigations. Partitioning occurs between the different phases and can be a key uncertainty in the VI CSM. The soil type and organic carbon content of the soils strongly influence how much of the compound partitions to the vapour phase. Consideration should be given to incorporating vapour monitoring in any intrusive investigation to help characterise the VI source and reduce uncertainty with theoretical partitioning.

PHCs and CHCs have very different characteristics that are critical to developing an appropriate VI CSM:

- PHCs more typically exist as complex mixtures of different compounds whereas CHCs are more likely to be present as single compounds, or as a small group of compounds associated with a parent compounds and degradation product daughter compounds.
- PHCs are LNAPLs and therefore do not tend to penetrate to any significant depth beneath the water table. CHCs are DNAPLs and can therefore migrate vertically down through the water column where geological conditions allow.

It is critical to take the density difference of CHCs and PHCs into account when developing the understanding of the VOC source area.

- PHCs degrade readily in aerobic conditions and degrade to low toxicity compounds: this means that the vapour phase of PHC sources will often be of limited extent. **Screening of PHC sources using the 'screening distance' approach should be considered.** CHCs degrade slowly and mainly under anaerobic conditions often producing equally or more toxic daughter products: this means that CHC vapour plumes are likely to be more persistent and the proportion of the parent/daughter compounds is likely to change with time. **The changing source profile through time should be considered when developing the VI CSM for CHCs.**

Pathways

Pathways are grouped into three key areas:

- Conventional pathways
- Preferential pathways
- Direct contact

Conventional pathways involve the migration of vapours through the vadose zone by advection and diffusion, with entry through foundations and into the indoor air within buildings driven by a pressure differential between the inside of the building and the sub-surface. The main factors affecting the migration pathway include:

- Distance from source to building;
- Soil porosity and permeability;
- Soil moisture content; and
- Pressure differential.

Biodegradation is an important process acting on VOCs during migration along conventional pathways. For PHCs, aerobic biodegradation can often cause relatively rapid decreases in vapour concentrations across short distances. Assessment of PHC sources using 'screening distance' approaches may be appropriate in many situations where aerobic biodegradation is likely to be occurring. Biodegradation of CHCs tends to anaerobically and more slowly with the creation of daughter compounds that may be more toxic than the parent compound.

Preferential pathways include migration of vapours along natural features such as fractures, joints and dissolution features as well as along man-made features such as mine workings, stone columns and utility corridors. **Migration along preferential pathways can be rapid and difficult to characterise**.

Standard vapour intrusion assessment models are not well suited to dealing with preferential pathways and more direct measurements may be needed if they are of concern.

Vapours typically enter buildings from the sub-surface through cracks, joints and gaps in building floors, as well as through service penetrations and cavity walls. The three standard foundation types typically considered in the UK include suspended floor (block and beam), ground bearing concrete slab, and suspended concrete slab with sub-floor void. Older buildings with basements may have earthen floors and brick walls, whilst modern basements are likely to be constructed of cast in-situ concrete with waterproofing.

Within the building, mixing and dilution are key processes, with the building volume and ventilation rate being key parameters. Larger volume buildings with higher ventilation rates pose a relatively lower VI risk.

Though rare, direct contact pathways involve a NAPL / impacted soil / impacted groundwater source being in direct contact with a building foundation. Due to the absence of migration through the vadose zone this scenario can result in higher indoor air concentrations than might be expected from standard vapour intrusion models.

Receptors

The receptors in the VI CSM are the occupiers of any building subject to VI. Within the standard UK assessment framework, these are usually assumed to be characterised by:

- Residents in residential buildings, with the most sensitive receptor assumed to be a female child aged 0 to 6 years; and / or
- Commercial / industrial workers, with the most sensitive receptor assumed to be a female adult aged 17 to 59 years.

In both cases the key factors affecting VI risk are the breathing rate, the number of days per year exposure, and the number of hours per day exposure. If site specific knowledge can be used to adjust these parameters (particularly the exposure frequency and duration) this can have a large effect on the estimated risk.

For other receptors such as maintenance workers in confined spaces standard exposure scenarios are less common and site-specific considerations may be required.

4. GUIDANCE DOCUMENTS

A summary of several of the key guidance documents which may assist the reader in developing and refining the VI CSM applicable to a site in the UK are summarised in Table 1, based on those available at the time of preparing this Note.

Table 1: Summary of key published guidance documents currently available

Title	**Key elements**
UK Guidance	
CIRIA, 2009. CIRIA C682 - The VOCs Handbook. Investigating, assessing and managing risks from inhalation of VOCs at land affected by contamination.	This document provides guidance on investigating, assessing and managing risks from vapours in the UK. Particular sections relevant for the CSM are: • Sections 4.4 to 4.8 deals with the development of the CSM for vapour intrusion. • A checklist for developing a vapour intrusion CSM is provided in Appendix A4 of this document. • A building survey checklist identifying building information relevant to vapour risk assessment is provided in Appendix A5. • A case study showing how a preliminary risk assessment and CSM may be developed for vapour intrusion is provided in Appendix A6 of this document.
Wilson, S, 2008. Modular approach to analysing vapour migration into buildings in the UK. Land Contamination & Reclamation, 16 (3); 223-236.	The paper discusses the Johnson and Ettinger approach for modelling vapour migration into buildings and highlights key factors that may invalidate the use of the model for many of the new buildings being constructed in the UK. The paper then goes on to propose a simplified, “modular” approach to model vapour phase partitioning, transport and dilution mechanisms. The proposed modular method may be more applicable to new UK housing stock because it can take account of ventilated sub-floor voids, and it does not assume the presence of a basement (unlike the Johnson and Ettinger approach). The modular approach is also consistent with the approach adopted by the NHBC with respect to assessing ground gas migration into buildings in the UK.

Title	**Key elements**
Wilson, S, Card, G, Mortimer, S, and Roberts, J, 2018. Basement waterproofing and ground gas. Ground Gas Information Sheets, Sheet No. 4.	The paper provides a simple framework for designing waterproof basement structures such that they also provide adequate gas (and therefore also soil vapour) resistance. Covers the assessment of gas or soil vapour phase migration within the vadose zone. The framework is based around a flow chart design process that considers two situations; a more generic design (where VOCs are not of concern) and a design supported by a comprehensive detailed quantitative risk assessment which is applicable to more complex / higher risk ground gas situations (>CS3) and / or where VOCs are present.
International Guidance	
ITRC, 2007. Technical and Regulatory Guidance, Vapor Intrusion Pathway: A Practical Guideline, VI-1 (January 2007).	This document primarily focusses on chlorinated vapour intrusion and does not specifically address the differences between chlorinated versus petroleum vapour behaviour in the sub-surface. The document contains 4 chapters covering an overview of VI, preliminary screening of sites, site investigation considerations and mitigation options. The document also includes a useful CSM checklist and lists quality assurance considerations.
ITRC, 2014. Petroleum Vapor Intrusion, Fundamentals of Screening, Investigation and Management, PVI-1 (October 2014). [Otherwise known as the "screening distance approach"]	Follows on from the 2007 ITRC guidance document (above). Focuses on petroleum VI, with the fundamental differentiating factor between chlorinated and petroleum VI being biodegradation. The guidance aims to address the need for guidance on effective screening, investigation and management of petroleum VI sites. The guidance presents a method of screening petroleum contaminated sites for potential VI and provides the tools and strategies with which to evaluate the VI pathway.
ASTDR, 2016. Evaluating Vapour Intrusion Pathways. Guidance for ATSDR's Division of Community Health Investigations. October 31 2016.	This document was written to assist ATSDR health assessors to evaluate risk from VI. It includes checklist of factors that may be considered when performing risk assessments. It recommends multiple lines of evidence approach and provides a 12-step approach to evaluation of vapour site for public health.
USEPA, 2012a. Office for Underground Storage Tanks (OUST) - Petroleum Hydrocarbons and Chlorinated Solvents Differ in their Potential for Vapor Intrusion, March 2012.	This document was written to summarise the key concepts with respect to petroleum VI, and also describes how PHCs' behaviour in the subsurface differs fundamentally from the behaviour of CHCs. The paper goes on to discuss the implications for VI resulting from these differing behaviours, and how the behaviours need to be considered when assessing potential VI risks associated with PHC.

Title	Key elements
USEPA, 2015b. OSWER Technical Guidance for Assessing and mitigating the vapour intrusion pathway from subsurface vapour sources to indoor air, OSWER publication 9200.2-154, June 2015.	This document presents the current technical guidance from the USEPA for vapour risk assessment. It provides a flexible science-based approach to vapour risk assessment and covers the various phases from preliminary analysis, detailed investigation to clean up. Chapter 2 presents the conceptual model of vapour intrusion and identifies 5 conditions that need to be met for a VI pathway to be confirmed as present.

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6. GLOSSARY

Acronyms	Description
AST	Above-ground storage tanks
BS	British Standard
CHCs	Chlorinated hydrocarbons
CIRIA	Construction Industry Research and Information Association
CSM	Conceptual site model
DNAPL	Dense non-aqueous phase liquids
GAC	Generic assessment criteria
HVAC	Heating, ventilation and air conditioning
ITRC	Interstate Technology and Regulatory Council
LNAPL	Light non-aqueous phase liquids
NAPL	Non-aqueous phase liquids
PHCs	Petroleum hydrocarbons
SoBRA	Society of Brownfield Risk Assessment
USEPA	United States Environmental Protection Agency
UST	Underground storage tanks
VI	Vapour intrusion
VOCs	Volatile organic compounds

LIMITATIONS

This publication has been developed by members of the SoBRA VI sub-group acting in a voluntary capacity, and details the views of the individual members, not those of their employers. It is provided freely on the SoBRA website to help promote discussion on what should constitute good practice in assessing the potential health risks associated with vapour intrusion into buildings in the UK. Users of the paper must satisfy themselves that the content is appropriate for the intended use and no guarantee of suitability is made.

FEEDBACK

Feedback on this publication is welcomed and should be submitted to SoBRA at info@sobra.org.uk.