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The VOCs Handbook

Investigating, assessing and managing risks from inhalation of VOCs at land affected by contamination

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Summary

Considerable advances have been made in the assessment of risks associated with land contamination over the past decade that have been incorporated into recent regulatory guidance. The focus has been on developing an overall risk-based assessment framework, reflecting statutory requirements under Part 2A of the Environmental Protection Act 1990.

This publication is intended to provide clear and flexible guidance on the investigation, assessment and management of risks associated with Volatile Organic Compounds (VOCs) at land affected by contamination in the UK, primarily relating to inhalation by people. The handbook has been prepared to be consistent with existing UK regulatory guidance on land contamination and is also intended to complement CIRIA C665 *Assessing risks posed by hazardous ground gases to buildings* (Wilson *et al*, 2007).

Mitigating the risk to human health is the main principle of this guidance. Where an immediate risk to human health is known, or suspected, it recommends that direct action should be taken.

A phased and iterative approach has been developed to complement the three stages of risk assessment used in the UK, namely:

1 Preliminary risk assessment.

2 Generic quantitative risk assessment.

3 Detailed quantitative risk assessment.

The guidance highlights the importance of developing and refining a conceptual site model (CSM), with a checklist provided to help users develop an initial CSM. Several screening mechanisms are incorporated throughout the publication to indicate exit points in the assessment process. This includes knowledge of the volatility and toxicity of a compound to screen it from further consideration, and a question-based flow chart to guide the user through the assessment process.

The nature, occurrence, fate and transport of VOCs in the environment are discussed in detail. Guidance is provided on the development of investigation strategies, alongside a description of several different exploratory and analytical techniques and their relative advantages and disadvantages.

This publication provides information on how existing generic assessment criteria, such as Soil Guideline Values (SGVs), can be appropriately applied, and explores the development of alternative screening methods and assessment criteria.

The handbook guides the user towards a framework for applying a range of alternative investigation and assessment techniques, where a more detailed assessment of the migration of VOCs in the environment is required. This includes several different modelling tools that can be partly used to develop site-specific assessment criteria for different environmental media.

The final stage in the assessment process is developing a strategy and carrying out a remediation plan. *The VOCs Handbook* provides the user with an overview of remediation considerations specific to the migration of VOCs in the environment.

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Foreword

The risk-based approach to land contamination is well established in the United Kingdom. Historically, metals contained within made ground were originally the main focus of attention. Although these contaminants can create risks of pollution to controlled waters by leaching, the risks to human health can largely be resolved by the use of simple cover systems. However, the explosions at Loscoe and Abbeystead brought the risks associated with hazardous soil gas to the fore.

Through a series of guidance documents produced over the last 15 years, CIRIA has provided advice on the nature of these hazards, a programme that culminated in the CIRIA publication by Wilson *et al* (2007). Throughout this process, the importance of evaluating soil gases other than methane and carbon dioxide has been highlighted. The nature of our industrial past has left a major legacy of VOCs in the ground, all of which have the potential to migrate and pose significant risks to both controlled waters and human health that, in most cases, are very difficult to assess and resolve.

This document is the first attempt to provide standardised guidance on the subject of assessing risks to human health, primarily through inhalation of VOCs, for the land contamination practitioner. It describes the nature and sources of VOCs, how they behave both physically and chemically in the ground and gives a detailed review as to how they can be reliably measured. This is done in the context of the regulatory approach to land contamination in the UK and the associated model procedures (Contaminated Land Report 11). It then describes the process of preliminary, generic and detailed quantitative risk assessment, with a summary of remediation considerations. By highlighting all the technical issues and providing a review of the good practice approach, it will assist the professional community seeking to restore our industrial past in a consistent, safe and cost-effective way.

Peter Witherington
Group Deputy Chairman
RSK Group Plc

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RICS

CIRIA Core members

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Glossary

Acute exposure	Exposure/contact with a substance that occurs once or over a short period (up to 14 days), often referred to as short-term exposure.
Acute health effects	An instantaneous health effect that is observed in a matter of hours or days. Also referred to as acute toxicity effects.
Advective flow	Movement of chemical constituents in a fluid (including liquid and air) down a pressure gradient.
Aerobic	A process that involves oxygen.
Air spaces	A general term used to describe a space where VOCs could accumulate.
Ambient air	Typically used to describe air present in an open environment, rather than in an indoor air space.
Anaerobic	In the absence of oxygen.
Analytical technique	The methods to quantify the presence and size of contamination.
Borehole	A hole drilled into the ground that can be used to obtain samples.
Brownfield sites	A term generally used to describe previously developed land, which may or may not be contaminated.
Carrier gas	A soil gas that may be naturally occurring (for example methane or carbon dioxide) that could increase the migration rate of VOCs (or lower volatility compounds) through the unsaturated zone.
Chlorinated solvent	A general term used to describe halogenated hydrocarbons that contain chlorine, such as tetrachloroethene and trichloroethene.
Chronic exposure	Exposure/contact with a substance that occurs for longer than a year, often referred to as long-term exposure.
Chronic health effects	A health effect that occurs over a longer period, typically months or years, as opposed to acute health effects. Also referred to as chronic toxicity effects.
Conceptual site model	A representation of the characterisation of a site in diagrammatical and/or written form that shows the possible relationships between the contaminants, pathway and receptors. This helps to evaluate the potential risks that the site poses given the intended operations and future use of the site.
Development	Works of construction, which may be buildings or civil engineering structures above or below ground, and including ancillary works, installations and open spaces associated with the structures.

Diffusive flow	Movement of chemical constituents in response to (or down) a chemical concentration gradient.
Direct push	A method of advancing a probe or other investigative tool into the ground, typically using both static force and percussion.
Exploratory technique	A methodology used to collect or investigate a sampling location.
Flammable	A substance capable of supporting combustion in air.
Flux	Movement of gas, usually expressed as volume of gas, per unit of time.
Gas	One of three states of matter, characterised by very low density and viscosity (relative to liquids and solids), with complete molecular mobility and indefinite expansion to occupy with almost complete uniformity the whole of any container.
Gas chromatography	An analytical technique, which can be used in conjunction with suitable detector instrumentation (for example, flame ionisation detector, electron capture detector or mass spectrometry), to identify and quantify substances according to their relative rate at which they separate out when passed through a specific medium.
Hardstanding	A man-made surface (such as concrete or tarmac) that can typically support the weight of a range of transport vehicles.
Halogenated hydrocarbon	A compound containing hydrogen, carbons and one or more of the halogens (fluorine, chlorine, bromine and iodine).
Hazard	A property or situation that in particular circumstances could lead to harm or pollution (Defra and EA, 2004a).
Hazardous ground gases	A general term describing gas generated from the ground that can adversely affect human health, structures and the environment (including through explosion). Typically applied to gases generated from landfill waste, including methane and carbon dioxide, with the potential to adversely affect structures or human health via asphyxiation.
Indoor air	Air within a building envelope, including residential properties and commercial/industrial buildings.
Intermediate exposure	Exposure/contact with a substance that occurs for more than 14 days but less than one year. Often referred to as medium-term exposure.
Intrinsically safe	Of an instrument (or equipment) that does not generate an ignition source within the gas atmosphere being monitored (usually indicated by BSI accreditation).
Johnson & Ettinger (1991) model	Also known as the Johnson & Ettinger vapour intrusion model (J&E model)
Landfill	Waste or other materials deposited into or onto the land.

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Landfill gas	Gas generated from licensed, unlicensed, operating or non-operating landfill sites. Includes gas generated by biodegradation of the deposited waste, and that produced purely by volatilisation.
Made ground	Ground where there are deposits that have not been formed through natural geologic processes. These may comprise a combination of natural deposits together with products and materials, and man-made waste.
Near-slab	Used to refer to a near-surface (sub-hardstanding) soil gas sampling location that is close to, but not under, the foundation of a building.
Occupational	Associated with the working environment/ workplace.
Oxidation	Reaction of species with an oxidant normally, but not necessarily, oxygen from the air.
Partitioning	The distribution of a substance between two or more media (for example, between soil phases or between soil and outdoor air).
Passive control	The control of gas emission by provision of engineered venting pathways (for example, wells and vent trenches) without mechanical aid.
Pathway	A route or means by which a receptor could be, or is exposed to, or affected by a source (adapted from Defra and EA, 2004a).
Permeability	A measure of the ability of a medium to allow a fluid (gas or liquid) to pass through it.
Petroleum hydrocarbon	A compound containing carbons and hydrocarbons only, that have been made from feedstock derived from petroleum or natural gas.
Photo-ionisation	The ejection of an electron from an atom by quantum of electromagnetic energy.
Pollutant linkage	The relationship between a source (in this guide, VOCs), pathway and a receptor (Defra and EA, 2004a).
Receptor	A general term, in this guide primarily used to refer to people that could be adversely affected by a source (VOCs).
Risk	A combination of the probability, or frequency of a defined hazard occurring and the size of the consequences of the hazard (Defra and EA, 2004a).
Sampling	Collection of a portion of material for experimentation. The material taken is representative of the whole.
Soil gases	Gases present between soil particles or other sources that are generated from man-made and naturally occurring sources. In this publication, soil gases have been used to describe all potential gases present in the subsurface. VOCs where present as a constituent in soil gas are referred to as "VOCs in soil gas" throughout the document.
Solubility	The ability of a substance to form a solution with another solution. In this guide, solubility refers to the

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	maximum amount of a chemical that will dissolve in water under stated conditions of temperature and pressure.
Source	A general term, in this guide primarily used to refer to VOCs that are in, on or under the land and have potential to cause harm to health.
Sub-slab	Used to refer to a soil gas sampling location just below the foundation slab of a building, within the unsaturated zone.
Surface emission rate	Volume of gas escaping from a unit area of ground in a unit of time. In the UK, following Environment Agency guidance, expressed as mg (of gas of interest)/m²/s.
Trace component	Chemical constituents present in soil gas or air at trace levels derived directly from materials present in waste materials in the subsurface or but also from degradation of waste
Tracer gas	A gas or compound that can be used to trace the (potential) presence or migration of another chemical constituent in the environment. Also known as a marker compound.
Vapour	A general term used in this publication typically to describe VOCs in gaseous phase when present in an air space (as opposed to within the ground). Also used in other guidance documents to refer to VOCs in gaseous phase in the ground, which should be seen as interchangeable with the terminology used in this publication (VOCs in soil gas).
Vapour emission	A general term used to describe the process by which VOCs migrate from the ground surface or an excavation into atmospheric conditions (often into an outdoor air space).
Vapour intrusion	A general term used to describe the process by which VOCs migrate into a structure from the subsurface.
Vapour release	A general term used to describe an instantaneous release of VOCs, typically into atmospheric conditions, due to physically disturbing the soil structure.
VOCs	Volatile Organic Compounds. In this publication considered to comprise organic compounds that are volatile under normal environmental/atmospheric conditions. They may also be found in the ground in the solid, liquid and dissolved phase form as well as in gaseous phase.
Void space	The space between solid particles, occupied by a gas.
Volatile compound	A general term referring to compounds (organic or inorganic) that are volatile under normal environmental/atmospheric conditions, although they may be found in the ground in the solid, liquid and dissolved phase form as well as in gaseous phase (for example, elemental mercury).

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Volatility	How easily a chemical constituent transfers/moves from a liquid to gaseous phase.
Volatilisation	The transfer/movement of a chemical constituent from a liquid to gaseous phase.
Workplace exposure limits	Limits relating to personal exposure to substances hazardous to health in the air of the workplace.
Zone of influence	The volume of ground surrounding a soil gas investigation installation that can be, or is being, influenced by the use of control of that installation.

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Abbreviations

ADE	Average daily exposure
API	American Petroleum Institute
ASTM	American Society for Testing of Materials
ATSDR	Agency for Toxic Substances and Disease Registry
BRE	Building Research Establishment
BS	British Standard
BTEX	Benzene, toluene, ethylbenzene, xylenes
BTEXT	Benzene, toluene, ethylbenzene, xylenes and trimethylbenzenes
CIEH	Chartered Institute for Environmental Health
CIRIA	Construction Industry Research and Information Association
CLEA	Contaminated land exposure assessment
CLR	Contaminated land report
COC	Committee on Carcinogenicity of Chemicals in Food, Consumer Products and the Environment
COMAH	Control of Major Accident Hazards
CSI	Chemical Substances Inventory
CSM	Conceptual site model
DELCD	Dry electrolytic conductivity detector
Defra	Department for Environment, Food and Rural Affairs
DNAPL	Dense non-aqueous phase liquid
DQO	Data quality objectives
EA	Environment Agency of England and Wales
FID	Flame ionisation detector
FPD	Flame photometric detector
FSA	Food Standards Agency
GAC	Generic assessment criteria
GC-MS	Gas chromatography-mass spectrometer
HCV	Health criteria value
HDPE	High density polyethylene
HELA	Health and Safety Executive/Local Authority
HPA	Health Protection Agency
HSE	Health and Safety Executive
HVAC	Heating, ventilating and air conditioning
ID	Index dose
ITRC	Interstate Technology and Research Council

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J&E model	Johnson and Ettinger vapour intrusion model (also known as Johnson & Ettinger (1991) model)
LIF	Laser induced fluorescence
LNAPL	Light non-aqueous phase liquid
MCERTS	Environment Agency of England and Wales' monitoring certification scheme
MDL	Method detection limit
MIP	Membrane interface probe
MSDS	Method safety data sheet
MTBE	Methyl tert-butyl ether
NAPL	Non-aqueous phase liquid
NHBC	National House Building Council
NICOLE	Network for Industrially Contaminated Land in Europe
PID	Photo ionisation detector
PPE	Personal protective equipment
QA/QC	Quality assurance/quality control
RBCA	Risk-based corrective action
RBDM	Risk-based decision making
REACH	Registration, evaluation, authorisation and restriction of chemical substances
SEPA	Scottish Environment Protection Agency
SGV	Soil guideline value
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
SPOSH	Significant possibility of significant harm
SSAC	Site-specific assessment criteria
TDI	Tolerable daily intake
TPH	Total petroleum hydrocarbons
u-PVC	Unplasticised poly vinyl chloride
USEPA	United States Environmental Protection Agency
v-DQRA	Detailed quantitative risk assessment for vapour intrusion/ emission pathways
v-GAC	Generic assessment criteria for vapour pathways
v-GQRA	Generic quantitative risk assessment for vapour intrusion/ emission pathways
v-PRA	Preliminary risk assessment for vapour intrusion/emission pathways
VE	Vapour emission
VI	Vapour intrusion
VOCs	Volatile Organic Compounds
WEL	Workplace exposure limit
WHO	World Health Organisation

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1 Introduction

1.1 BACKGROUND

The Department for Environment, Food and Rural Affairs (Defra), its predecessor departments and the Environment Agency (EA) have produced a series of guidance documents that provide a general framework and approach for investigating, assessing risk and remediating land contamination. However, the complexities involved in investigating and assessing several pathways by which people can be exposed to contaminants have highlighted the need for more detailed guidance for specific exposure pathways. One such pathway is the inhalation of volatile compounds that have migrated in a vapour phase from the subsurface. There has been a rapid emergence of technical and practical guidance for this in several countries over the past five years. This document provides guidance on the investigation, assessment and management of risks associated with the inhalation of Volatile Organic Compounds (VOCs) at land affected by contamination in the UK.

This publication has been prepared to be consistent with existing UK guidance on land contamination, particularly with Contaminated Land Report 11 (CLR11) (Defra and EA, 2004a) and more recent documents (such as EA, 2009a and b). It is also intended to complement CIRIA publication C665 (Wilson *et al*, 2007).

1.2 LEGISLATIVE AND REGULATORY FRAMEWORK

This publication provides technical guidance in an area where there is a complex mix of documentation related to legislative, statutory guidance and non-statutory technical guidance. It is not the purpose of this publication to describe in detail all regulations. However, it is important to recognise the context that this guidance should be employed into. Several main pieces of legislation are discussed here.

Part 2A of the Environmental Protection Act 1990 (inserted by Section 57 of the Environment Act 1995) created a regime for the identification and remediation of contaminated land. Section 78A(2) of the Environmental Protection Act 1990 defines contaminated land for the purposes of Part 2A as:

> *"any land which appears to the local authority in whose area it is situated to be in such a condition, by reason of substances in, on or under the land, that*
>
> *(a) significant harm is being caused or there is a significant possibility of such harm being caused*
>
> *(b) pollution of controlled waters is being, or is likely to be caused."*[1]

Part 2A considers a wide range of receptors (including people, other living organisms, controlled waters and buildings). This guide focuses on one particular receptor type, ie people.

Notes:

1 Definition to be amended to "significant pollution of controlled waters is being caused or there is a significant possibility of such pollution being caused" under the Water Act 2003.

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The UK Government set out the following policy objectives about contaminated land (Defra, 2006):

- to identify and remove unacceptable risks to human health and the environment from contaminated land
- to reduce the pressure on greenfield land and to encourage the reuse of land that may have been subject to potentially contaminative uses
- to seek to ensure a proportionate, manageable and economically sustainable approach to the cost burdens faced by individuals, companies and society.

These objectives support the suitable for use approach that the UK Government considers is the most appropriate way to achieve these goals. This approach is based on the principles of risk assessment, including the concept of a pollutant linkage between a contaminant, and a receptor, via a pathway. Developing a conceptual site model is vital for assessing land contamination using a risk-based framework, and it can take many forms such as a graphical representation or as a flow chart.

Statutory guidance on the interpretation and use of Part 2A legislation in England is given in the Defra Circular 01/2006 (Defra, 2006). Similar guidance has also been provided for Wales (Welsh Assembly Government, 2006) and Scotland (Scottish Executive, 2006). Further guidance on applying the definition of contaminated land in respect of risks to human health has also been published (Defra, 2008). Where the local authority determines the land to be contaminated land, a remediation notice can be served to ensure the unacceptable risk is managed appropriately.

Land contamination is a material consideration within the planning regime. A planning authority has to consider the potential implications of contamination both when it is developing structure or local plans (or unitary development plans) and when it is considering applications for planning permission. Planning Policy Statement 23 (England), in the granting of planning permission for new development including permission to carry out remediation, states that remediation must remove unacceptable risk and make the site suitable for its intended use (ODPM, 2004). Similar considerations are provided by the Welsh Assembly Government (2002) and the Scottish Executive (2000). As a minimum, after development and at the start of its use, the land should not be capable of being deemed contaminated land under Part 2A.

The Building Regulations for England and Wales 2000, and related amendments, aim to ensure the health and safety, welfare and convenience of persons in, and about, buildings, and sets minimum building requirements. Part C (2004) relates to ensuring the resistance of buildings to contaminants. This is also the case under the Building Regulations Scotland 2004.

Legislation relating to health and safety for land affected by VOCs contamination includes the Management of Health and Safety at Work Regulations (1999), Construction (Design) Management Regulations (2007) for some sites and the Control of Substances Hazardous to Health Regulations (2002).

It should be recognised that there are some legislative differences between the four different countries in the UK, though land contamination is generally dealt with by the following types of regulation, including:

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- specific Acts of Parliament to investigate and remedy harm caused by land contamination
- conditions placed upon planning permissions for the redevelopment of land
- acts of Parliament and regulations for the control of waste.

New directives emerging from the European Union are leading to the development of extra regulations to help legislate and manage risks from land contamination. Table 1.1 summarises acts/regulations relating to managing risks to human health in the UK from land contamination.

Table 1.1 ***Summary of the main acts/regulations relating to assessing and managing risks to human health from land contamination***

Country	Acts/Regulations
England and Wales	■ Contaminated Land (England) Regulations (2006) and the Contaminated Land (Wales) Regulations (2006) ■ Town and Country Planning Act (1990) ■ Environmental Permitting (England and Wales) Regulations (2007) ■ Pollution Prevention and Control (England and Wales) Regulations (2000) ■ Water Resources Act (1991).
Scotland	■ Contaminated Land (Scotland) Regulations (2005) ■ Town and Country Planning Act (Scotland) (1997) ■ Waste Management Licensing (Scotland) Regulations (1994/2003) ■ Pollution Prevention and Control (Scotland) Regulations (2003) ■ The Water Environment and Services (Scotland) Act (2003).
Northern Ireland	Land contamination in Northern Ireland will be regulated through Part III of the Waste and Contaminated Land (Northern Ireland) Order (1997). Regulations have been published but as of October 2009 statutory guidance has yet to be developed and published. As such the regulations have yet to be enacted. The Waste Management and Contaminated Land Unit (WMCL) of the Northern Ireland Environment Agency will be responsible for enforcing this order.

Investigation, assessment and remediation of land contamination can also be undertaken voluntarily, and is referred to as voluntary remediation action. Voluntary remediation of contamination resulting from historical activities, where the site is not being assessed under Part 2A, enables the proactive assessment and remediation of land contamination. In some cases the remediation anticipates future remediation requirements (for example, if the land-use is likely to change through the planning process) and is encouraged (Defra, 2006). It generally offers stakeholders greater control over timing, costs and safeguarding of reputation.

1.2.1 Non-statutory technical guidance documents

There are several regulatory guidance documents that have been produced for use in the UK that provide a framework for assessing land contamination. These include, but are not limited to:

- a range of guidance documents associated with the Contaminated Land Exposure Assessment (CLEA) methodology, including:
  - *Model procedures for the management of land contamination* (Defra and EA, 2004a)

- *Human health toxicological assessment of contaminants in soil* (EA, 2009a)
- *Updated technical background to the CLEA model* (EA, 2009b)
- *Compilation of chemical data for the derivation of Soil Guideline Values* (EA, 2008)

- *Remedial targets methodology: hydrogeological risk assessment for land contamination* (EA of England and Wales, 2006) developed in consultation with the Scottish Environment Protection Agency (SEPA) and the Northern Ireland Heritage and Environment Service.

1.3 SCOPE AND OBJECTIVES

The overall objective of the VOC handbook is to provide guidance for professionals/stakeholders working on land affected (or potentially affected) by contamination to assess and manage the risks to human health from inhalation of VOCs. Also it provides guidance on how to plan for, collect and systematically assess site investigation data for this purpose.

Specifically, this publication aims to:

- define what is meant by VOCs such that users can ascertain whether this publication is an appropriate tool
- identify an appropriate assessment approach that complements existing guidance and provides a practical, clear but flexible framework that can be applied
- develop a tiered process for investigating and assessing VOCs, which can be exited at various stages
- identify investigation and sampling strategies and methodologies and discuss advantages and disadvantages
- provide guidance on remediation considerations such that users understand the wide variety of factors that need to be allowed for in developing remediation strategies.

The flexibility within this guidance document reflects the huge diversity of sites that are investigated and assessed in the UK, and the continuing technical debate as to how best to assess VOCs at sites affected by land contamination.

To assist in achieving these aims, the publication includes guidance on:

- how to develop a conceptual site model that specifically considers the inhalation of VOCs originating from the subsurface
- how to design an investigation plan and an overview of different exploratory and sampling techniques that can be used to investigate the presence and concentration of VOCs in a range of media (eg soil gas or groundwater)
- guidance on undertaking risk assessments to quantify the potential risk to human health from inhalation of VOCs
- an overview of remediation considerations to help manage identified risks.

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The publication does not include the following aspects, either because existing UK guidance is present or because further work is needed to develop appropriate guidance:

- how to assess compounds in soil gas other than VOCs, included within existing guidance such as:
  - CIRIA C665 (Wilson *et al*, 2007)
  - BRE Report 211 (2007)
  - BS 8485: 2007
- Soil Guideline Values/generic assessment criteria and toxicity values for specific compounds, existing guidance is provided by (and now being revised and updated) the EA, with the support of the Health Protection Agency (HPA) and the Food Standards Agency (FSA)
- specific protocols for designing and undertaking investigations and remediation, such as set out in:
  - BS EN 1997-2: 2007
  - BS 10175:2001
  - BS 5930: 1999.

1.4 METHODOLOGY

The research undertaken to produce this publication comprised six tasks:

1 An initial scoping study.

2 The determination of current practice.

3 Development of good practice in the measurement of VOCs in the environment.

4 Development of good practice in the risk-based assessment of VOCs for human health exposure.

5 Review of good practice remediation (including mitigation) measures.

6 Drawing this information together into a practical document that is consistent with existing guidance.

Existing guidance and information was examined by a focused and comprehensive literature search. The state of current good practice was determined by a questionnaire survey sent to all members of the steering group and the CIRIA email networks (including the local authority contaminated land list), and was available for download from the CIRIA website <www.ciria.org>. Detailed responses were received from thirty-one practitioners with a wide range of expertise in investigating and assessing VOCs at sites affected by land contamination.

1.5 AUDIENCE

This publication and the guidance it contains has been written to be relevant to all parties/stakeholders involved in the consideration of land and/or development (existing or planned) of land, affected by VOCs potentially hazardous to human health following exposure in air. The target audience includes landowners, developers (commercial, industrial and residential),

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building control, professional advisors/consultants (both engineering and environmental), builders and contractors, regulators (such as the EA, SEPA and local authorities) and other professional and non-specialist stakeholders. The guidance has been written assuming that the reader has some familiarity with managing risks associated with land contamination.

1.6 STRUCTURE OF THE GUIDE

The structure of this publication is as follows:

Chapter 1 This chapter

Chapter 2 Volatile Organic Compounds (VOCs)

Chapter 2 provides an overview of common sources of VOCs in the environment and factors influencing their generation and migration towards, and into, a surface air space. The chapter also provides definitions for some of the terms used throughout the guidance, such as vapour intrusion, vapour emission and vapour release.

Chapter 3 Investigation, assessment and risk management framework

This chapter introduces a flow chart designed to aid the practitioner in undertaking an investigation and assessment of the risks associated with VOCs through inhalation exposure at sites affected by land contamination. Points at which it is possible to exit the assessment process are highlighted.

Chapter 4 Vapour intrusion/emission preliminary risk assessment

Chapter 4 describes the process of undertaking a preliminary risk assessment that specifically focuses on the exposure to VOCs through inhalation exposure. Important considerations when undertaking the desk study, site walkover and developing the initial conceptual site model are discussed.

Chapter 5 Developing a site investigation strategy for the VOC vapour intrusion/emission pathways

In Chapter 5, factors that influence the design of the site investigation plan are highlighted and discussed, providing guidance on minimum levels of investigation for different site scenarios.

Chapter 6 Exploratory and analytical techniques for investigating vapour intrusion/emission of VOCs

A wide range of potential exploratory and sampling techniques are summarised in this chapter, including common problems encountered when investigating a range of source media (such as soil gas or air quality).

Chapter 7 Vapour intrusion/emission generic quantitative risk assessment

Chapter 7 provides guidance to the practitioner on how to undertake a generic quantitative risk assessment for the pathways of concern, including how to assess whether the use of existing UK screening levels is appropriate and how to develop new screening levels for a range of source media.

Chapter 8 Vapour intrusion/emission detailed quantitative risk assessment

The most detailed form of risk assessment is described and discussed in Chapter 8. It provides guidance on the collection of site-specific data for use in a range of modelling tools. This chapter also provides guidance on how to consider the results of site measurements versus modelling results and the development of site-specific assessment criteria.

Chapter 9 Remediation considerations

Chapter 9 provides an overview of remediation considerations associated with the migration of VOCs into an air space, including typical source treatment/removal techniques and mitigation techniques. Advantages and disadvantages of different techniques, alongside points of consideration, are provided.

Chapter 10 Recommendations for research

The final chapter in this publication suggests areas for further research.

References

A **glossary** and **list of abbreviations** are provided at the beginning of the publication.

The text is supported by quick reference and example boxes, which provide summarised advice of main points and brief illustrative examples. Short case studies are also included within the relevant chapters. Detailed advice and information, and longer case studies are presented in a series of supporting appendices outside of the main text at the end of the publication.

Tables and figures are embedded within the publication and should be found on the pages following their first reference.

This publication is intended to complement existing guidance, in particular CIRIA C665 (Wilson *et al*, 2007). Wording has been adopted from CIRIA C665 to ensure consistency between the two documents where appropriate.

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2 Volatile Organic Compounds

2.1 WHAT ARE VOCS?

The primary focus of this publication is the investigation and assessment of VOCs that could present a risk from inhalation at sites affected by land contamination. There is a wide range of definitions of VOCs, but the general consensus is that they are organic compounds that are volatile under normal environmental/atmospheric conditions, although they may be found in the ground in the solid, liquid and the dissolved phase as well as in the gaseous phase. Volatile organic compounds in the environment can be derived from natural sources, but are often present following spillage/leakage of solvents or fuels associated with commercial and industrial activity or historically poor waste disposal practices. Typical VOCs include:

- petroleum (non-halogenated) hydrocarbons (eg benzene, toluene, butylbenzenes)
- halogenated hydrocarbons, for example, chlorinated ethenes and ethanes (eg dry cleaning fluids or degreasers) or chlorofluorocarbons (freons)
- organic compounds containing nitrogen, sulphur and oxygen (eg tetrahydrofuran).

Volatile organic compounds are one type of source for hazardous gases in the soil or hazardous vapours. However, there are many hazardous gases that may be encountered frequently at land affected by contamination that require assessment, control and management, such as:

- methane
- carbon dioxide
- radon.

There are other types of potentially hazardous gases in soil or hazardous vapours, which are less frequently encountered, but can also require assessment, control and management, associated with:

- semi-volatile organic compounds
- volatile metals (eg elemental mercury)
- sulphur and nitrogen-containing compounds.

Guidance has already been developed relating to the assessment of risks posed by methane and carbon dioxide (Wilson *et al*, 2007, BS 8485:2007 and Wilson *et al*, 2008), and radon (BRE, 2007), which should be referred to for those gases. In some cases the behaviour and transport of VOCs in soils is fundamentally different from methane, carbon dioxide and radon. As such, guidance developed to address those three gases is not directly applicable to VOCs.

Terminology used to describe the formation and migration of VOCs in the ground is not specifically defined in the UK, and alternative terminology may be used in different countries.

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For the purpose of this publication, the following terms have been adopted:

- vapour intrusion (VI): migration into a structure (typically an indoor air space)
- vapour emission (VE): migration from the ground surface or from an excavation into atmospheric conditions, often into an outdoor air space
- vapour release: the instantaneous release, typically into atmospheric conditions, due to physical ground disturbance.

Quick reference 2.1 ***Terminology as defined in this publication***

There are several different terms used to describe the migration of VOCs in the subsurface.	
Soil gas	used to refer to gases in the subsurface
Vapour	used to describe the VOCs present in an indoor or ambient air space
Vapour intrusion	the process by which VOCs migrate into a structure from the subsurface
Vapour emission	the process by which VOCs migrate from the ground surface or an excavation into atmospheric conditions (often into an outdoor air space)
Vapour release	an instantaneous release of VOCs, typically into atmospheric conditions, due to physically disturbing the soil structure

2.2 COMMON SOURCES OF VOCS IN THE ENVIRONMENT

There are several sources of VOCs in the environment, briefly described in the following sections. The importance of these sources should be considered in understanding the potential origin of VOCs in the ground, in particular the possible contribution of background sources (for example, information provided by the National Air Quality Information Archive) that could contribute to measurements of VOCs at sites affected by land contamination. Important sources of many pollutants in indoor air, including VOCs, are provided in BS EN ISO 16000-1:2006. Sources of VOCs in the ground may be related to a point source (such as a localised spillage from a tank) or a diffusive source (for example, due to crop spraying).

2.2.1 Industry (including spills, leaks and discharges)

Volatile organic compounds are used widely across many industries. Spills, leaks or discharges associated with their production, storage, distribution and use in industrial processing or historically poor industrial waste disposal practices result in the presence of VOCs in different media in the general environment, including soil, groundwater, surface water and air spaces. Data sources such as *Industry profiles* (DOE, 1995) provide references of VOCs that are typically associated with different industrial and commercial activities.

2.2.2 Landfill sites

Trace components are often detected at landfill sites and can be indicators of more significant sources, which can include (among some 500 others) VOCs. These trace components may derive directly from materials present in the waste but also from degradation processes. At sufficiently high concentrations, these compounds can contribute to odour or health effects. The EA has issued a list of priority compounds that should be measured in gases generated from landfills if a potential toxicity risk exists (see Appendix A1). Further information is contained in the EA's guidance document *Monitoring trace components in landfill gas* (EA, 2004a).

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2.2.3 Building, furnishing and consumer household products

Volatile organic compounds are present at variable concentrations in both indoor and outdoor air spaces due to their use in building, furnishing and consumer household products. Examples include aerosols and propellants, cleaning products, carpets, cigarette smoke, wall and floor tiles, furnishings, flame retardants and gas ovens, all that could affect air quality measurements in an indoor air space (see Figure 2.1).

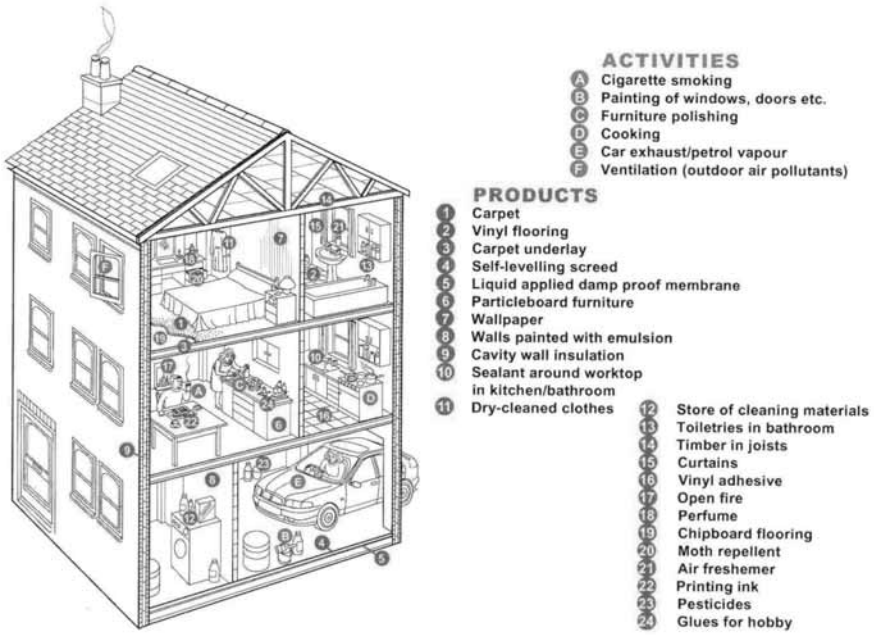

Figure 2.1 ***Typical sources of VOCs in residential properties (courtesy BRE)***

There is a limited database of typical background concentrations for VOCs in indoor air spaces in the UK when compared to some other countries. However, organisations such as the Building Research Establishment (BRE) have undertaken considerable research into the topic of indoor air quality in the last twenty years. Some examples of UK residential properties where the indoor air quality has been studied are included in Table 2.1.

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Table 2.1 ***Mean concentrations of selected indoor pollutants in UK homes (taken from a range of sources)***

Pollutant	Mean concentration in living rooms (µg/m³)				
	Berry *et al* (1996), Avon	Berry *et al* (1996), Herts	Coward *et al* (2001, 2002), 800 homes in England	Venn *et al* (2003), 500 homes in Nottingham	Brown and Crump (1998), 40 homes in Southampton
Total VOCs	396	206	210	448	330
Benzene	8	11	3	6	6
Toluene	50	28	15	–	–
Ethylbenzene	–	–	1.2	–	–
Xylenes	–	–	3.8	–	–
Trimethylbenzenes	–	–	1.9	–	–

Notes:

- Not measured

2.2.4 Vehicle emissions

The use of fossil fuels in vehicles, such as cars, aeroplanes and ships, contributes to the presence of VOCs in the general environment. The emission of VOCs in combustion products from road transport, and other industrial/commercial uses, has decreased steadily in the UK since the late 1980s, as shown in Figure 2.2, although the trend for emissions from air travel is less clear.

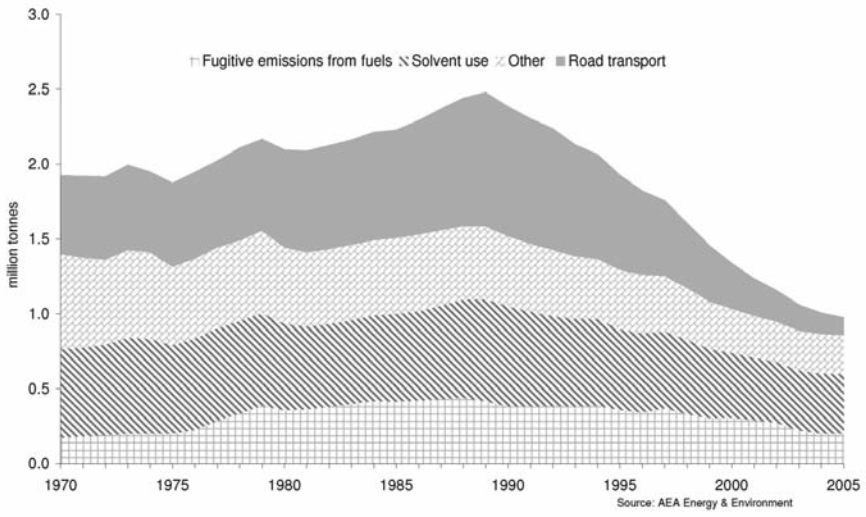

Figure 2.2 ***Emission of non-methane VOCs (1970–2005) from different sources in the UK (AEA Energy and Environment, 2005)***

2.2.5 Naturally occurring VOCs

The natural occurrence of non-methanogenic VOCs is generally low, unlike for other soil gases such as methane or carbon dioxide. However, there are volatile compounds that are known to be naturally occurring, for example:

- carbon disulphide in coastal and marshland areas with high biological activity

- terpenes released from pine trees
- methylated mercury and selenium, observed in global geochemical cycles
- VOCs produced because of metabolic processes (eg Kalin, 2007).

Quick reference 2.2 ***Potential sources***

Potential sources of VOCs in the subsurface include:
- **leaks/spills from industrial land-use**
- **leaks/spills on residential properties, such as heating oil**
- **landfill sites**
- **natural geology, such as marshland**
- **uncontrolled waste disposal.**

2.3 NATURE OF HAZARD

There are several recognised hazards and effects of VOCs, the most common are health effects following inhalation exposure. The human health effects of different VOCs depend on the toxicity of the VOC, the degree, nature, and duration of exposure, as well as the sensitivity and well-being of the receptor.

There are other potential hazards and effects of VOCs in soil gases, such as odour nuisance or flammable/explosive hazards, which may also require assessment at land contamination sites.

2.3.1 Health effects

Health effects are described as "acute" (instantaneous, with the health effect observed in a matter of hours or days) or "chronic" (over a longer period, typically months or years over which the health effects occur).

A similar terminology is also used to describe exposure duration. The following definitions are provided by the Agency for Toxic Substances and Disease Registry (ATSDR):

Acute exposure	Exposure/contact with a substance that occurs once or over a short period (up to 14 days)
Intermediate exposure duration	Exposure/contact with a substance that occurs for more than 14 days but less than one year
Chronic exposure	Exposure/contact with a substance that occurs for longer than a year

Long-term (chronic) exposure is typically assessed by calculating the predicted average daily exposure (ADE) from a measured concentration of a VOC in the environment and comparing it to an appropriate health criteria value (HCV), assessing the risk via the pathway of concern. The HCV is typically derived from toxicological studies into the chronic health effects of the compound under consideration (for example, laboratory-scale, workplace studies and epidemiological studies). Guidance provided by the EA helps practitioners to select appropriate HCVs (EA, 2009a), from sources including the Committee on Carcinogenicity of Chemicals in Food, Consumer Products and the Environment (COC), and the World Health Organisation (WHO). In the UK, toxicological

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effects are split into threshold effects or non-threshold effects (EA, 2009a), with HCVs taking the form of a tolerable daily intake (TDI) or index dose (ID) respectively.

The method for assessing short-term (acute or intermediate) exposure is well defined for certain occupational settings. Workplace exposure limits, or WELs (a single value that replaces the former maximum exposure limits and occupational exposure standards, which formed the basis for occupational exposure levels) are provided by the Health and Safety Executive (HSE, 2005) for this purpose, referenced by the Control of Substances Hazardous to Health Regulations 2002 (COSHH). The WELs are provided for both short-term (15 minute reference period) and long-term (eight hours time weighted average) exposure to many VOCs, last amended in October 2007. These limits are designed for use on sites where workers are exposed to the VOC under consideration during typical working practices (for example, storage of the VOC or use of the VOC), so were not designed to assess risk from land contamination. A similar method for assessing short-term exposure where WELs do not apply is not clearly defined in the UK.

The potential cumulative or synergistic effects of multiple exposures to low level sources of VOCs that can have a similar effect on a receptor may, on occasion, need to be taken into account (EA, 2009a).

2.3.2 Odour

Although there are few direct links between odour and adverse health effects odours can cause symptoms such as nausea, and may increase a perception of adverse health effects. Also, the hazard posed by a particular VOC as a vapour can also be at a lower concentration than the odour detection level. Detection of an odour (for example, a fuel or solvent) can often be a trigger for site investigation. There are several published odour threshold values, for example, the HSE <www.hse.gov.uk>, van Gemert (1999) and Nagy (1999). Potential health and safety, amenity and nuisance effects often have to be considered for VOCs (discussed in more detail in Chapters 5, 7 and 8).

2.3.3 Flammable/explosive risks

A relevant risk could exist when vapour intrusion results in the accumulation of VOCs in an air space. It is unusual for a flammable/explosive risk to simply exist from the accumulation of VOCs. However, there is the potential for either a risk of explosion or fire to exist where there is:

- a source of flammable/explosive gas
- an accumulation of vapours (eg in a confined or enclosed space)
- a source of ignition
- sufficient oxygen to support combustion.

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Case study 2.1 ***Flammable/explosive risks from VOCs***

Bontddu Service Station, Wales

Following a reported leak of petrol (over 60 000L) at the Bontddu Service Station in autumn 1996, exploratory investigations were undertaken to assess the extent and severity of the associated contamination. The petrol vapours present in the subsurface had migrated beneath a neighbouring residential property, accumulated and ignited, resulting in an explosion. Later investigations into the incident suggested that the use of air-flush drilling techniques may have exacerbated the potential for the migration of the vapours and then explosion (HSE, 2000).

Quick reference 2.3 ***Potential nature of risks***

The nature of the risks from VOCs in the vapour phase include:

- acute health effects
- chronic health effects
- odour
- flammable hazards
- explosive hazards.

2.4 FACTORS INFLUENCING THE PRESENCE OF VOCS IN SOIL GAS

2.4.1 Physical and chemical properties

Volatile organic compounds have a wide range in physical and chemical properties, which describe their behaviour in the environment. Many of the physical and chemical parameters are fundamental but there are several chemical-specific parameters that are subject to some variation in quoted values, for example due to temperature fluctuations influencing their chemical/physical properties. Also, variability in quoted literature sources can originate due to the method by which chemical/physical properties have been measured (for example, different laboratory techniques). Chemical/physical properties influence the way in which the substances partition into different states (separate phase, dissolved phase or gaseous) or environmental media (groundwater, soil or soil gas). Some of the chemical/physical properties of a VOC can be influenced by whether the system being observed is in "equilibrium" or whether the system has not yet reached equilibrium. For example the fluctuation of groundwater through soils contaminated by VOCs could disrupt the rate of generation of VOCs in soil gas and the equilibrium of the system.

Some of the main physical and chemical properties that influence the presence of VOCs in the environment in gaseous (or dissolved) phase are shown in Table 2.2, adapted from EA (2009b).

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Table 2.2 ***Important physical and chemical properties influencing the presence and transport of VOCs in soil gas***

Chemical Property	Description	SI Units
Aqueous solubility	Maximum dissolved phase concentration of the VOC in pure water. Temperature dependent.	mg L^{-1}
Henry's law constant	Constant of proportionality measuring the preference of a chemical for the gaseous phase compared to the dissolved aqueous phase. The Henry's law constant can be calculated in different ways and can be reported in a range of units. The air-water partition coefficient (K_{aw}) is the dimensionless form of the Henry's law constant.	Pa.m^3 mol^{-1}
Octanol – water partition coefficient (K_{ow})	An experimental measure of the degree to which a hydrocarbon compound will preferentially dissolve in water compared to an organic solvent.	–
Organic – water partition coefficient (K_{oc})	An experimental measure of the degree to which a hydrocarbon compound will preferentially adsorb to organic carbon in soil compared to water.	cm^3 g^{-1}
Vapour pressure	A measure of the tendency of a hydrocarbon compound to volatilise from solid or liquid state.	Pa
Relative vapour density	A measure of the density of a vapour relative to the density of air.	g cm^{-3}
Relative liquid density	A measure of the density of a liquid relative to the density of water. Non-aqueous phase liquids (NAPLs) are commonly described as light NAPLs (LNAPLs) when *less* dense than water, and dense NAPLs (DNAPLs) when *more* dense than water.	g cm^{-3}
Diffusion coefficient in air	A measure of the diffusion of a molecule in a gas medium because of intermolecular collisions.	m^2 s^{-1}
Diffusion coefficient in water	A measure of the diffusion of a molecule in an aqueous medium.	m^2 s^{-1}

The EA has released guidance (EA, 2008) providing recommended values for the physical and chemical properties for several VOCs that can influence their presence in soil gas. Where reference data for a compound has not been recommended by the EA, and significant variation in literature parameter values is present, the data sources and techniques for estimating chemical/physical properties given by the EA (2008) should be considered to select appropriate physical and chemical data.

2.4.2 Geology

Examples of the physical properties of the subsurface/source media that can influence the partitioning/volatilisation of VOCs into soil gas include:

- soil particle size
- porosity and degree of connectivity
- permeability/fractures
- organic matter content
- presence of water/moisture content (ie degree of saturation).

2.4.3 Timescale

When assessing the soil gas regime, it is important to determine whether the hazardous gas is being replenished, for example due to the presence of a

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continuing source, or whether the gas is a residue that will deplete over time. In general, conditions in the subsurface are unlikely to be at "steady-state" or in full equilibrium so dynamic effects may need to be considered (for example, when designing a site investigation).

2.4.4 Chemical/biological factors

For many VOCs, alongside the soil moisture content (see Section 2.4.2), the temperature can be an important environmental parameter that theoretically influences the rate of partitioning and volatilisation. In practice, however, temperature is likely to be less important than other factors because of the general constancy of ground temperatures in the UK. For other compounds that may be present in soil gas, for example, vinyl chloride, the absence of oxygen is a main factor in their rate of generation in soil gas. This can be because some VOCs undergo reactions that can change their composition and concentration. When assessing risk, potential reaction mechanisms should be considered. The composition and rate of generation of VOCs in soil gas can be altered by several factors such as:

- chemical make-up of the source material, including presence of a range of constituents
- micro-organisms within soils (eg microbial degradation)
- chemical activity within soils
- temperature
- pH value (eg for solids, liquids, primarily for polar organics)
- absence or presence of oxygen
- oxidation-reduction reactions (Redox).

2.4.5 Air pressure gradients

Where the source of the VOCs is present close to the ground surface, or within a system where changing atmospheric pressure influences extend into the unsaturated zone, changing atmospheric (barometric) pressures (and changing air pressure gradients) could potentially influence the rate of generation of VOCs in soil gas transiently. As such, weather changes are capable of causing effects such as the movement of soil gas towards the surface.

2.5 FACTORS INFLUENCING THE MIGRATION OF VOCS IN SOIL GAS

For a VOC in soil gas to migrate away from its source there should be a migration mechanism and an available pathway. For migration to be sustained, a continuing source of VOCs is needed. There are several principle mechanisms that can influence the movement of VOCs in soil gas, and the migration of VOCs in the unsaturated zone:

- diffusive flow (movement of constituent along a concentration gradient)
- advective flow (movement of constituent due to motion of a transporting fluid)
- dispersion (transport resulting from local variations in fluid flow, eg due to friction effects in the matrix).

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For VOCs in soil gas, the main migration mechanism is typically diffusion (EA, 2009b and Evans *et al*, 2002). As such, the deeper the source is within the subsurface, the shallower the diffusive concentration gradient. However, the potential for advective transport of VOCs in soil gases in the subsurface needs to be considered during the conceptualisation of the vapour intrusion/emission pathway (as discussed in Smith *et al*, 1996), and in particular for certain scenarios where advective transport could play a more important role (see Sections 2.5.4 to 2.5.9).

A further transport mechanism for VOCs is in the dissolved phase form within liquids (through both advective and diffusive flow). This can result in the transport of VOCs with groundwater flow, followed by partitioning/volatilisation at a point distant from the original source. Further guidance on investigating and assessing the migration of compounds within groundwater is included within documents such as Carey *et al* (2006). Similarly, if non-aqueous phase liquid (NAPL – see Table 2.2) migrates beneath the subsurface, there is the potential for VOCs to volatilise at a point distant from the original source. The NAPL may migrate with groundwater flow (typical behaviour for an LNAPL), or under the influence of gravity (typical behaviour for a DNAPL, which can also be a factor for transport of gases more dense than the surrounding air). For each of these mechanisms, the presence of preferential pathways can affect the transport of VOCs in the subsurface and above-ground.

The dominant influences controlling the migration and behaviour of VOCs in soil gas through the unsaturated zone are outlined briefly in the following sections. Figure 2.3 is a schematic conceptual site model showing the migration of VOCs in soil gas through the subsurface.

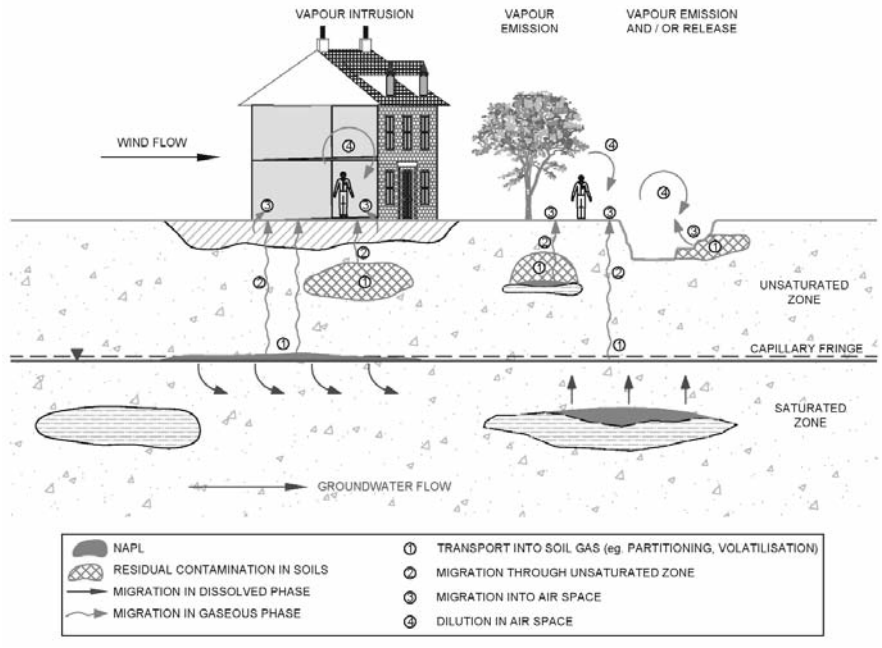

Figure 2.3 ***Schematic conceptual site model illustrating the generation and transport of VOCs in soil gas in the subsurface***

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2.5.1 Physical and chemical properties

The physical and chemical properties of VOCs affect not only the presence of VOCs in soil gas at the source, but also the migration through the unsaturated zone. Some of the important chemical properties that influence the migration of VOCs in soil gas through the unsaturated zone are shown in Table 2.2, adapted from EA (2009b).

2.5.2 Geology/soil properties

The presence of VOCs in soil gas and the movement through the ground is principally affected by the ground conditions. Permeable geology or soil allows migration pathways for soil gas to flow. Conversely, low permeability strata or soils, such as clays, can inhibit and/or provide a barrier to soil gas migration. The tortuosity of the pores (void spaces), namely the shape of the interconnected pore spaces, can also play a part.

Typically, the higher the moisture content of the soil or rock, the lower the potential for soil gases to migrate. The presence of organic matter (or small soil particles) can also influence the transport of those VOCs in soil gas by increasing the potential for VOCs to adsorb ("stick") onto the soil.

Highly heterogeneous geology and soils (for example, significant depositional features, such as bedding, interbedded sand and clay deposits or fractured bedrock/fault zones) or made ground can result in preferential lateral and/or vertical migration pathways through the subsurface.

The presence of voids in the subsurface, for example, because of solution features or even burrowing animals etc, could result in a preferential migration route for VOCs in soil gas.

2.5.3 Chemical/biological factors

As for the presence of VOCs in soil gas at the source, the composition of VOCs can be altered during transport through the unsaturated zone due to attenuation effects, caused by:

- micro-organisms within soils (for example, microbial degradation can be important for some VOCs, see Appendix A2)
- chemical activity within soils
- pH changes
- absence or presence of oxygen
- reduction-oxidation conditions (Redox).

For some compounds, the presence or absence of oxygen is critical to explaining the observed distribution of VOCs in soil gas, notably non-halogenated VOCs such as petroleum hydrocarbons. This is discussed in further detail in Appendix A2.

2.5.4 Atmospheric pressure

A change in barometric pressure could potentially influence the migration of VOCs in soil gases through the subsurface, although it is likely to only affect the migration close to the surface or in particular site settings (see Case study 2.2).

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Under conditions of falling barometric pressure, increased vertical migration rates could occur as the soil gas increases in volume. Conversely rising barometric pressure causes air to flow into the ground diluting soil gas concentrations. The rate of change in barometric pressure may also be an important consideration.

Case study 2.2 ***Long-term remediation using barometric pumping***

Remediation of a site contaminated by chlorinated volatile organic compounds in South Carolina was undertaken over a period of years. The technique harnessed the natural atmospheric fluctuations moving air in and out of the unsaturated zone within a barometric pumping system (passive soil vapour extraction). The system was designed to only allow flow of soil gas out of the unsaturated zone, reportedly reducing the mass of chlorinated volatile organic compounds by over 80 per cent between 1996 and 2001 (see Bosze *et al*, 2001).

The solubility of gaseous VOCs typically increases with pressure, which could result in lower concentrations within the ground as more gas will be dissolved in water. Conversely, a pressure drop could cause the release of dissolved gas from the groundwater into pore spaces and then into an overlying air space or along migration routes. Critical pressure changes are well described by Bolze and De Freitas (1996), Auer *et al* (1996) and Davis *et al* (2004).

2.5.5 Rainfall and hydrogeology/tidal effects

High rainfall may cause groundwater levels to rise, resulting in a reduced available pore space where soil gas can exist. The reduced pore space may lead to an increase in potential release of VOCs in soil gases to the atmosphere, or a decrease as the VOCs dissolve into the infiltrating water (Davis *et al*, 2004).

Heavy rainfall may also increase soil moisture content causing temporary sealing of the ground surface, particularly in fine grained soil, reducing the potential for vertical migration of VOCs in soil gas, but in some cases promoting transient lateral migration. Saturation of the near-surface may also affect microbial activity and Redox conditions.

Infiltrating rainwater has been observed to create pressure gradients within the unsaturated zone (Tillman and Weaver, 2006). However, in urban areas the effect of surface cover and the rainfall "shadow" created by buildings can mitigate all of these effects (along with the reduced potential for evaporation from the ground surface). It is also worth noting that rainfall events frequently occur during a period of falling atmospheric pressure, so differentiating between effects on transport of VOCs in soil gas due to environmental factors can be difficult.

The presence of groundwater can inhibit the migration of gases within the ground. Rising groundwater will reduce the volume of gas within the pore spaces resulting in increased gas pressure and release or lateral migration known as the "piston effect". In some areas close to coastal zones the groundwater resting level can be tidally influenced. Tidal influences on the migration of soil gases depends on the ground conditions and distance to the coast or tidal river. In some cases tidal effects can result in the presence of pressure gradients promoting the migration of VOCs in soil gas. Changes in

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groundwater levels from rainfall or tidal effects can also influence the migration of LNAPLs and dissolved phase through the subsurface.

2.5.6 Temperature fluctuations

The effects of temperature fluctuations, which could result in changes in the volume of soil gas within the subsurface, are likely to only affect the migration of VOCs in soil gas close to the ground surface, due to the relative constancy of soil temperatures at depth in the UK. However, note that air temperature plays an important role in controlling atmospheric pressure. The potential effects of atmospheric pressure are discussed in Section 2.5.4.

2.5.7 Wind

Pressure gradients can be formed by gas in the ground and that in the atmosphere by the effects of wind (the Bernoulli Principle and resultant Venturi effect – velocity). High wind flows across a surface cause a pressure difference, potentially increasing volatilisation rates and resulting in the movement of gas from the soil to atmosphere. Vegetation will have a slight affect on emission or soil gas from the ground by altering the wind patterns close to the ground surface, reducing the potential release of VOCs in soil gas from the ground due to this process. The direction of wind can also be a significant factor (for example, if the ground is domed or undulating).

2.5.8 Anthropogenic influences

Human activities can create preferential migration pathways (for example, mine shafts, service runs, drains, building foundations and piles) and gas accumulation voids (for example, inspection pits and basements). Also, the presence of man-made hardstanding or a building can significantly affect the migration of VOCs through the subsurface, altering the pressure differential between the subsurface and surface. The transport of soil gas into structures is discussed further in Section 2.6.

Case study 2.3 ***Preferential pathways influencing vapour intrusion of VOCs***

Commercial property, southern England

Reports of petroleum hydrocarbons odours in a commercial property close to a petroleum filling station lead to evacuation of the property while investigations were undertaken to determine the source. The odours had entered the property following a period of heavy rainfall. The investigations identified that the drainage associated with the filling station had been laid adjacent to a water supply pipe for the neighbouring commercial property. The water supply pipe entered the commercial property through an unsealed entry point. It was concluded that petroleum hydrocarbon vapours originating from the petroleum filling station drainage system following the rainfall event had migrated through cracks in the pipes/joints below ground, and moved through the unsealed entry point into the commercial building. The water supply pipe entry point was later sealed, with no further reports of odours in the commercial property. Works are ongoing to upgrade the underground pipework associated with the filling station.

2.5.9 Presence of other gases

The transport of VOCs in soil gas through the unsaturated zone may be influenced by the presence of other gases in the subsurface. For example a flux of gases such as methane or carbon dioxide released from a landfill site may act as "carrier gases" aiding the transport of VOC trace components (see Section

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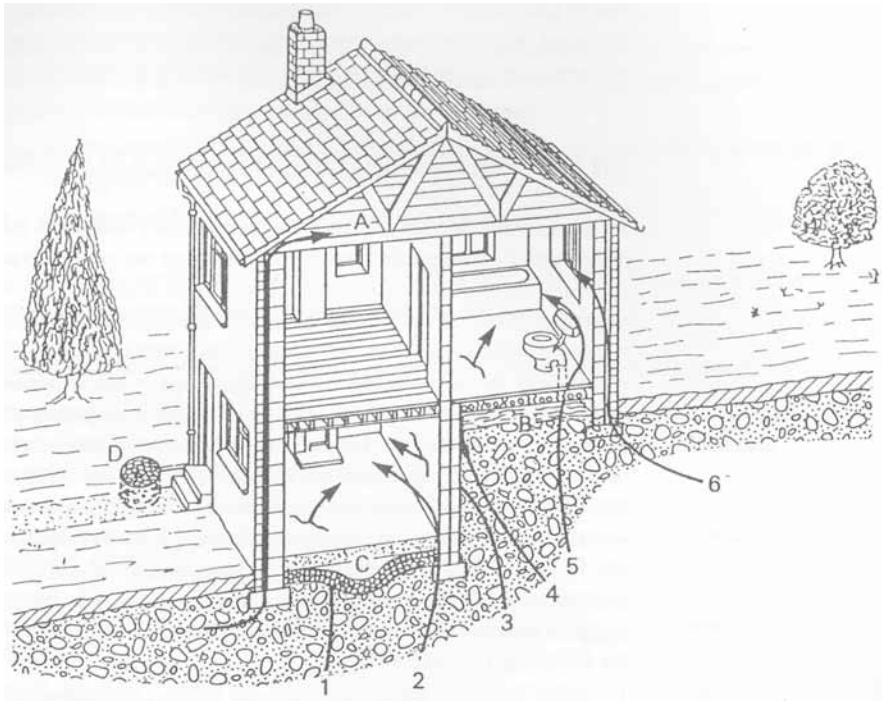
2.2.2) through the unsaturated zone. Limited research has been undertaken to assess the effect of the presence of such carrier gases on the migration of VOCs in the unsaturated zone, but the effects would seem to be limited unless a large flux of carrier gases is present.

2.6 INGRESS INTO BUILDINGS (VAPOUR INTRUSION AND DILUTION)

2.6.1 Vapour intrusion (VI)

Soil gases can enter buildings via the following routes (as depicted in Figure 2.4):

- cracks or gaps in both solid and suspended floors
- joints formed during the construction process
- fractures in subsurface walls
- around/through service pipes and ducts
- presence of piled foundations (eg stone columns)
- wall cavities.



Key to ingress routes:

1. Through cracks and openings in solid concrete ground slabs due to shrinkage/curing cracks.
2. Through construction joints/openings at wall/foundation interface with ground slab.
3. Through cracks in walls below ground level possibly due to shrinkage/curing cracks or movement from soil pressures.
4. Through gaps and openings in suspended concrete or timber floors.
5. Through gaps around service pipes/duct.
6. Through cavity walls.

Locations for gas accumulations:

A	Roof voids.	C	Within settlement voids.
B	Beneath suspended floors.	D	Drains and soakaways.

Figure 2.4 ***Important soil gas ingress routes (taken from Wilson et al, 2007)***

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The presence of a structure can also alter the behaviour of soil gases as they migrate towards and into a building. For example:

- surface pavings or other capping layers may lead to an accumulation of certain VOCs in soil gas beneath a building and/or off-site migration.
- pressure gradients created between the ground and building interior may encourage soil gases to migrate towards buildings. Such negative pressure relative to atmosphere can exist in a building because of:
  - **The Stack Effect:** if the internal temperature in a building is higher than outside, air is drawn into the building due to the pressure differential, either through the external envelope of the building or through entry points in the ground floor construction. In a well-insulated building the air and soil gas is preferentially drawn in through the ground floor. In a heated building, warm air, including soil gas, rises through the stack effect, which is then dissipated throughout the building. Further information can be found in documents including EA (2009b) and Card (1995).
  - **The Bernoulli Principle and Venturi Effect:** positive relative air pressure occurs on the windward site of the building when exposed to wind pressure, whereas on the leeward side, negative relative air pressure ("suction") occurs. So if there are openings on the leeward side, the internal pressure is reduced as air is drawn out. A pressure gradient develops between the inside and the outside. Soil gases may then be drawn into the building through entry points in the ground floor (see Figure 2.4).

The depth and lateral distance from the source to the building can significantly affect the rate and degree of vapour intrusion (for example, Abreu and Johnson, 2005 and 2006).

2.6.2 Building construction in the UK

The intrusion of vapours into a building depends on the construction of the building. In the UK, there is a range of building constructions commonly encountered, including a typical Victorian terraced house with a basement to a new-build with a vented below floor void. Common building constructions are shown in Figure 2.5, comprising:

- suspended slab
  - concrete beam and block construction with vented void (typical of new-builds) – Figure 2.5a
  - concrete foundation slab cast *in situ* (typical of many post-1970 constructions, new-builds) – Figure 2.5b
  - timber with vented void (typical of many pre-1970s housing) – Figure 2.5c
- ground bearing slab (cast *in situ*), raft or semi-raft – Figure 2.5d
- basements present, reinforced solid or cavity walls (typical of many post-1970 constructions new-builds) or permeable basement walls ("wet basement", typical of many Victorian properties, including some public houses) – Figure 2.5e.

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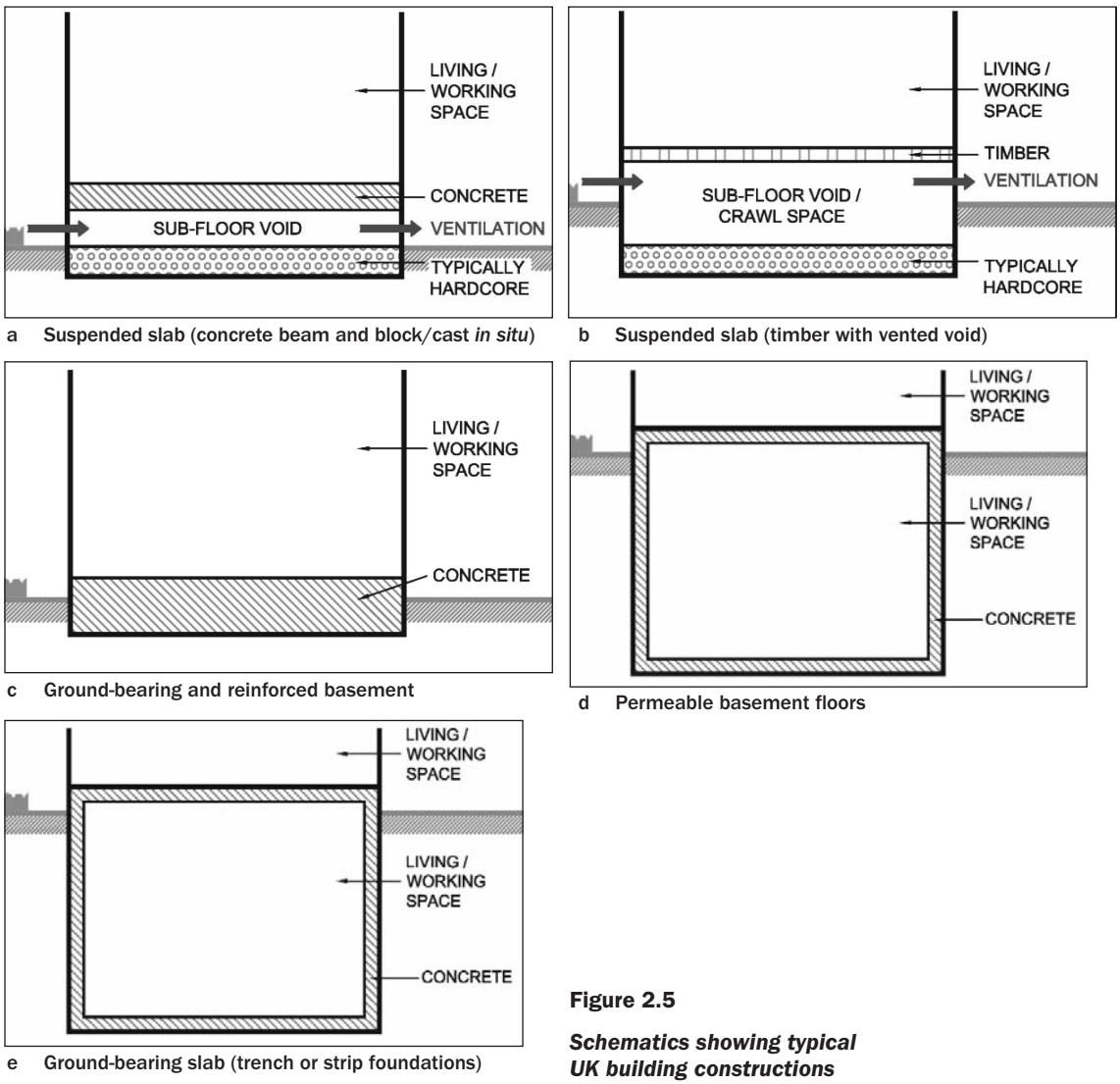

Figure 2.5

Schematics showing typical UK building constructions

Further information relating to typical building construction in the UK can be found in documents such as Johnson (2001) and Crump *et al* (2005).

2.6.3 Dilution in indoor air

Factors that influence the movement and mixing of VOC vapours within a building include:

- vapour composition
- vapour density
- rate of vapour ingress
- rate of ventilation with fresh air (eg HSE, 2008, BS 5925:1991 and Building Regulations 2000, Part F)
- volume of building and room sizes
- nature of the heating/cooling system
- internal geometry of the building, and design (eg the level of insulation and double-glazed windows)
- how the building is used and managed.

The inclusion of potential preferential pathways within a building construction, such as lift shafts that can result in pressure differentials, means that it cannot

always be assumed that the highest concentrations of VOCs in the building are within the basement or ground floor levels. Further information on the intrusion and behaviour of volatile compounds within buildings can be found in existing documents and guidance including Crump *et al* (2005), ITRC (2007), ASTM (2008) and Davis *et al* (2004).

2.7 EGRESS TO OUTDOOR AIR (VAPOUR EMISSION AND DILUTION)

2.7.1 Vapour emission (VE)

Soil gases can enter outdoor (ambient) air through emission from open surfaces or, for example, cracks in hardstanding. As for the vapour intrusion pathway, the depth and lateral distance from the source to the air space should be considered. Factors that influence the emission of vapours into outdoor air include:

- the presence and condition of a cover (buildings, hardstanding)
- the ambient temperature
- the moisture content of the shallow soils
- air flow velocity and direction
- the presence of preferential pathways.

2.7.2 Dilution in outdoor air

Factors that influence the mixing of gases with outdoor air include:

- the rate of vapour egress
- vapour density
- vapour composition
- air flow velocity and direction (wind)
- turbulence effects
- precipitation.

Factors specific to the receptor of concern (in particular the breathing height) can be critical for assessing exposure to vapours in outdoor air spaces.

2.8 VAPOUR RELEASES AND OTHER VAPOUR EMISSION SCENARIOS

The instantaneous release of VOCs as vapours during ground disturbance has the potential to result in acute health effects, and may need consideration where vapour emission could occur (ie both during investigation/remediation, construction and future land-use scenarios). Also, VOCs in vapour form can accumulate within other open spaces present on a developed/development site, such as excavations. Site workers may be particularly at risk during building/drainage works, demolition works or remediation works. Examples of scenarios where vapour releases or emission during occupational exposure could occur, in particular in a confined space include:

- maintenance work/laying piped drains and sewers or other utilities on a brownfield site

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- site investigations/remediation resulting in excavations
- cleaning of underground storage tanks used to store petroleum compounds
- *ex situ* remediation of soils
- installation of foundations.

Case study 2.4 ***Compressed air tunnelling through contaminated soil***

A two metre diameter tunnel was excavated manually through ground contaminated by BTEX. This presented potential risks to the workers through inhalation and direct contact exposure. Measured concentrations of BTEX in the air were variable, ranging from 4 ppm adjacent to the tunnel walls to 202 ppm at a distance of 0.5 m from the wall. The Control of Substances Hazardous to Health (COSHH) assessments were carried out as a first stage in the preparation and delivery of a management control system. Site-specific air quality data were collected as part of the assessment process, and the risks to human health were then minimised using multiple mitigation measures: use of a high standard of personal protective equipment (PPE), decontamination facilities and a forced air extract ventilation system. Biological (personal) monitoring (for example, urinary measurements for benzene) indicated that the use of PPE alone would not have been sufficient to minimise the risk to the workers. This case study also highlights the difficulties both in working and in assessing the risk through inhalation of VOCs under conditions where the air pressure is greater than normal atmospheric conditions. See Slocombe *et al* (2002).

Further information on the emission and behaviour of volatile organic compounds in open air spaces can be found in guidance documents including ITRC (2007), ASTM (2008) and Davis *et al* (2004).

It is important to note that the nature and presence of VOCs in soil gases may be considerably altered due to work carried out during construction and following development. For example the development of a building over previously open land can significantly affect the distribution of VOCs in soil gases in the unsaturated zone (Davis *et al*, 2004). This is discussed further in Chapter 4 (Section 4.7.1 and Figure 4.2).

2.9 SUMMARY

There are numerous sources of VOCs in soil gas and vapours derived primarily from anthropogenic sources. Awareness of these potential sources and options to differentiate between them is necessary to ensure appropriate remediation solutions are applied to protect human receptors associated with existing and future developments.

Knowledge of the physical, chemical and biological properties of VOCs is important when attempting to investigate and assess the potential hazards, and migration potential associated with VOCs in soil gas and vapours.

It is important to identify and understand the site-specific factors that may influence the behaviour and migration of soil gas and vapours, including the source location, magnitude, subsurface conditions and presence of preferential pathways.

The widespread presence and use of VOCs in the surrounding environment, in particular within buildings, needs careful consideration when investigating and assessing VOCs at sites affected by land contamination.

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2.10 FURTHER INFORMATION

BRE (2007)
Radon: protective measures for new dwellings
Report BR211, BRE Press, Building Research Establishment, Bootle (ISBN: 1-86081-328-3)

DAVIS, G B, TREFRY, M G and PATTERSON, B M (2004)
Petroleum and solvent vapours: quantifying their behaviour, assessment and exposure
CSIRO land and water report to the Western Australian Department of the Environment, Perth

ENVIRONMENT AGENCY (2004a)
Guidance for monitoring trace components of landfill gas
Report LFTGN 04, Environment Agency, Bristol

EA (2004a)
Guidance for monitoring trace components of landfill gas
TGN04, Environment Agency, Bristol

EA (2008)
Compilation of data for priority organic pollutants for derivation of Soil Guideline Values
Science Report SC050021/SR7, Environment Agency, Bristol. Available from: <http://publications.environment-agency.gov.uk/pdf/SCHO1008BOVO-e-e.pdf>

EA (2009a)
Human health toxicological assessment of contaminants in soil
Science Report SC050021/SR2, Environment Agency, Bristol. Available from: <http://publications.environment-agency.gov.uk/pdf/SCHO0508BNQY-e-e.pdf>

EA (2009b)
Updated technical background to the CLEA model
Science Report SC050021/SR3, Environment Agency, Bristol. Available from: <http://publications.environment-agency.gov.uk/pdf/SCHO0508BNQW-e-e.pdf>

EVANS, D, HERS, I, WOLTERS, R M, BODDINGTON, R T B and HALL, D H (2002)
Vapour transfer of soil contaminants
R&D Technical Report P5-018/TR, Environment Agency, Bristol

ITRC (2007)
Vapor intrusion pathway: a practical guideline
ITRC vapor intrusion team, Interstate Technology And Regulatory Council, Washington DC, USA. Available from: <http://www.itrcweb.org/Documents/VI-1.pdf>

WILSON, S, OLIVER, S, MALLETT, H, HUTCHINGS, H and CARD, G (2007)
Assessing risks posed by hazardous ground gases to buildings
C665, CIRIA, London (ISBN: 978-0-86017-665-7)

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3 Investigation, assessment and risk management framework

3.1 DEVELOPING AN ASSESSMENT STRATEGY

There are many factors to be considered when developing a risk-based assessment strategy for potential inhalation of VOCs at land affected by contamination, including:

- technical aspects
- legislative context
- regulatory context (eg planning process or Part 2A assessment)
- planned change in land-use
- commercial or operational issues (eg time or financial)
- sustainability (eg environmental or reducing future commercial liability).

The approach for investigating and assessing VOCs at sites affected by land contamination follows a risk-based framework. This is in-line with the overall methodology for assessing potential risks to human health from land contamination presented within the Defra and EA guidance document Contaminated Land Report 11 (CLR11) (2004a). The CLR11 framework allows the assessor to develop a risk-based approach that takes into account a range of different factors including those listed above. During each stage of the assessment process a conceptual site model (CSM) is developed or refined. A CSM is typically a combination of discussion, flow charts and schematic diagrams (for example, as shown in Figure 2.3).

Figure 3.1 illustrates the structured procedure for the assessment of VOCs via the inhalation exposure pathway. The structured procedure presented in this publication follows a tiered approach in-line with Defra and EA (2004a), and has been developed to complement CIRIA C665 (Wilson *et al*, 2007) where appropriate. The framework enables an iterative and flexible approach to the assessment of the vapour intrusion/emission pathways, while still keeping other potentially active pollutant linkages in mind.

One question that should be noted throughout the assessment process is: does my CSM indicate that there could there be a potential for an immediate risk to human health, including from inhalation exposure or risk of explosion?

Where a potential immediate risk to human health is known or suspected, direct action may need to be taken. Such scenarios could include:

- reports of odours in a property
- air quality measurements above acceptable levels
- a large and probably recent spill with significant concentrations of NAPL in shallow soil.

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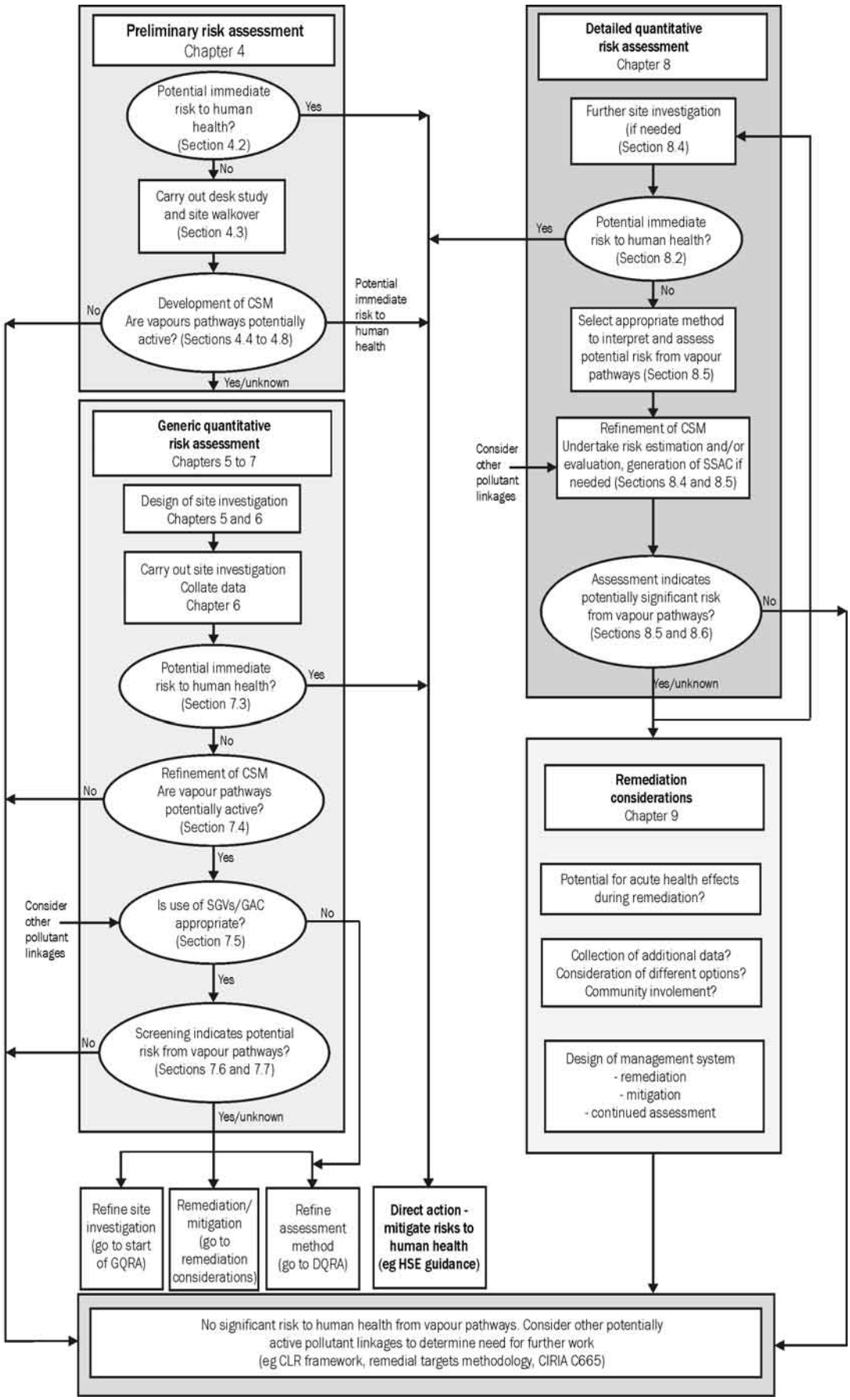

Figure 3.1 ***The assessment framework: structured procedure for the investigation, assessment and risk-management of risks to human health (primarily through inhalation exposure) at sites affected by land contamination***

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3.2 PRELIMINARY RISK ASSESSMENT

The vapour intrusion/emission preliminary risk assessment (v-PRA) forms the first tier of the process. This stage of assessment concludes with the development of an initial CSM for the pollutant linkages of concern through review of desk study information and, where appropriate, a site reconnaissance. The main decision point when undertaking the v-PRA derives directly from the initial conceptual site model is: are the vapour pathways likely to be active? (potential assessment exit point).

This includes consideration as to the potential for immediate risk to human health, which is revisited throughout the assessment process. Methods by which the assessment process can be exited as part of a v-PRA are discussed in more detail in Chapter 4.

3.3 GENERIC QUANTITATIVE RISK ASSESSMENT

The next stage in the process, the vapour intrusion/emission generic quantitative risk assessment (v-GQRA), typically includes the collection of data on different media and samples from different locations for analysis, and refinement of the CSM. Where appropriate, the use of generic assessment criteria is recommended, alongside further forms of screening that help the practitioner screen out lower risk sites from the process. The main decision points when undertaking the v-GQRA are:

- the design of the site investigations and data collection objectives
- whether the vapour pathways are likely to be active or present a significant risk based on semi-quantitative screening/qualitative (potential assessment exit point)
- whether Soil Guideline Values (or related screening levels) are appropriate to assess the site
- whether there are significant exceedances of the screening levels (potential assessment exit point).

Where there is a potentially significant risk from a vapour pathway, the assessor has three options for the next stage of assessment, depending on factors such as regulatory or commercial requirements. Chapter 5 provides guidance on the design of the site investigation, Chapter 6 provides an overview of different exploratory and sampling techniques, and Chapter 7 discusses v-GQRA in detail.

3.4 DETAILED QUANTITATIVE RISK ASSESSMENT

Following the framework given in CLR11 (Defra and EA, 2004a), the next level (or more detailed assessment) in the process is a vapour intrusion/emission detailed quantitative risk assessment (v-DQRA) as outlined in Figure 3.1. Varying levels of v-DQRA can be undertaken depending on the complexity of the site setting and the nature and extent of the contamination. The main decision points when undertaking the v-DQRA are:

- is further site investigation required, and what are the data collection objectives?

- what form of data assessment should be undertaken?
- do the vapour pathways present a significant risk? (potential assessment exit point).

Chapter 8 discusses v-DQRA in detail.

3.5 REMEDIATION CONSIDERATIONS

The final stage of the assessment process is the development of a strategy to enable identified, or potential, risks to human health to be managed. As described within CLR11 (Defra and EA, 2004a), this stage could incorporate development of a remediation options appraisal, including consideration of potential mitigation measures that could be employed to reduce or remove the risk. This is discussed further in Chapter 9.

3.6 FURTHER INFORMATION

DEFRA and EA (2004a)
Model procedures for the management of land contamination
Contaminated Land Report 11 (CLR11), Environment Agency, Bristol (ISBN: 1844322955). Available from: <http://www.environment-agency.gov.uk/static/documents/SCHO0804BIBR-e-e(1).pdf>

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4 Vapour intrusion/emission preliminary risk assessment

4.1 INTRODUCTION

The preliminary risk assessment forms the first stage in the risk assessment process, and is a qualitative assessment typically comprising the following elements (Defra and EA, 2004a):

- desk study
- site reconnaissance (or site walkover)
- development of an initial conceptual site model.

The initial CSM is developed using the information gained from the desk study and site reconnaissance, identifying potential sources, receptors and pathways, which enables potential hazards to be assessed. As outlined in CLR11 (Defra and EA, 2004a), each of these can be present at a site, but can only present a risk if the source has the potential to affect a receptor via a particular pathway. This is the concept of source-pathway-receptor chain, or a pollutant linkage. The development of the conceptual site model is critical when undertaking a risk-based assessment.

Figure 4.1 illustrates a range of scenarios that may be encountered when undertaking a v-PRA. The figure is referred to throughout this chapter as needed, and represents a variety of source media (such as soils, groundwater, NAPL or soil gas), the potential effects of geology on migration pathways for soil gas and groundwater, the potential differences between migration from a source at depth and a shallow source and the importance of different building construction and use.

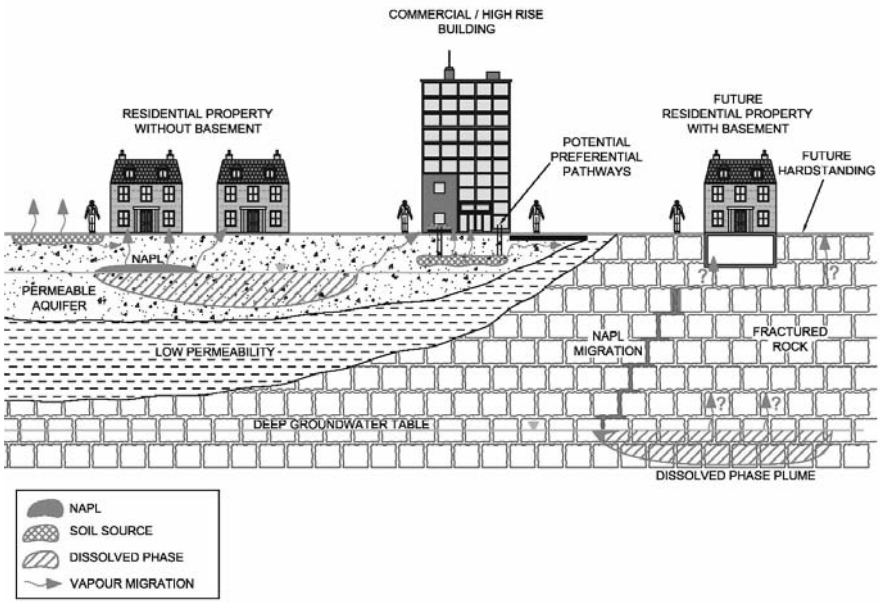

Figure 4.1 ***Example soil gas migration scenarios***

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The following sections provide an overview of stages within a v-PRA, focusing on aspects important to investigating and assessing VOCs for the vapour intrusion/ emission pathways.

Case study A3.1 shows how a v-PRA was undertaken for a site in the UK, including the results of the desk study, site walkover and development of initial conceptual site model. This case study is also referred to in later chapters.

4.2 POTENTIAL IMMEDIATE RISK TO HUMAN HEALTH

For some sites, a potential immediate risk to human health may be identified early in the assessment process. There may be a risk from inhalation of VOCs, typically but not always related to acute health effects, or a risk of explosion through accumulation of VOCs or through exposure to air. Where an immediate risk is present, or suspected, direct action should be taken to mitigate the risk, and appropriate existing guidance should be followed (for example, the Health and Safety Executive/Local Authority (HELA) circulars). Depending on the scenario, the action taken may take the form of:

- removal of people from the area of concern (eg a spill or leak of VOCs would often lead to a temporary evacuation as a precautionary measure)
- temporary cessation of works at a site (eg if unexpected contamination is encountered, see Case study 8.3)
- measurement of air quality (eg reports of an odour in a property. Comparison of measured concentrations to air quality standards may indicate there is no immediate risk to human health, even though the odours may be considered a potential nuisance)
- installation of temporary mitigation measures (eg increasing ventilation in a property where appropriate).

Often, the solution used to mitigate the risk may only be temporary, and further works are likely to be needed to find a permanent solution. In some cases, once the risk has been temporarily mitigated, undertaking investigation and assessment works using the framework in this and related publications, will enable a more permanent risk management plan to be devised.

4.3 DESK STUDY AND SITE RECONNAISSANCE

4.3.1 Introduction and objectives

The first important element of the risk assessment process (Figure 4.2) is the desk study and site reconnaissance. A desk study involves collating information about the site to determine whether there is a potential risk from various sources including VOCs in soil gases. Information gained from the desk study and site reconnaissance will enable the development of an initial conceptual site model, allowing the potential risks from the identified pollutant linkages to be considered at a preliminary, typically qualitative, stage of risk assessment.

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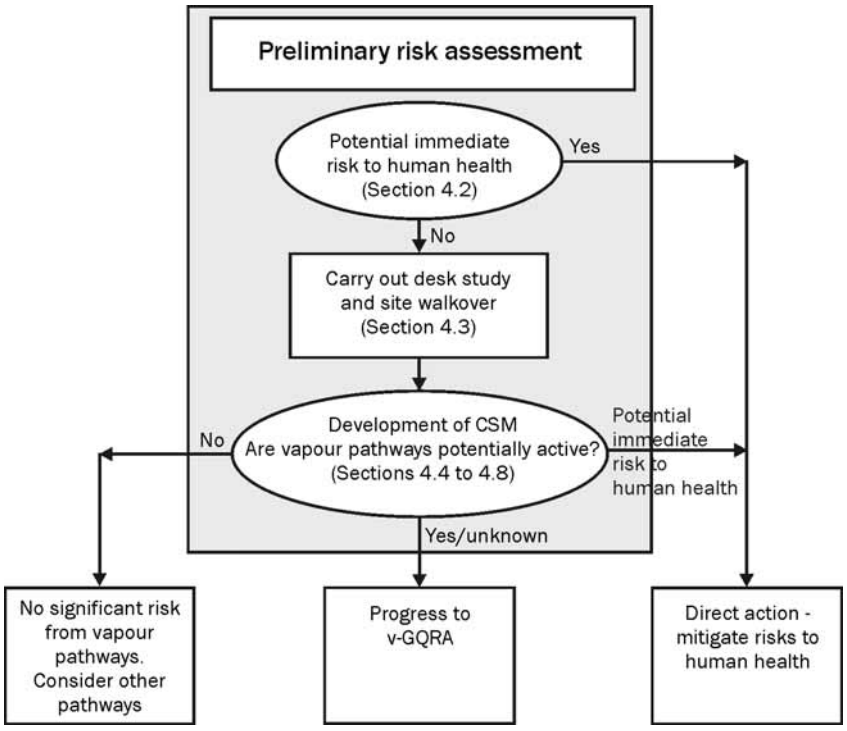

Figure 4.2 ***Preliminary risk assessment – extracted from Figure 3.1***

At the start of a land assessment and remediation project, the context of contamination and the objectives of the assessment/remediation should be identified, taking into account any land development proposals, as appropriate. Typical objectives of a desk study and site reconnaissance related to VOCs in soil gases (based on the risks to human health) are to:

- produce an initial conceptual site model and identify pollutant linkages
- assess the extent and nature of sources of VOCs to soil gas
- assess the implications of identified environmental risks and liabilities associated with the site where possible
- identify the likely ground conditions and identify potential locations for later intrusive investigations, if deemed necessary.

4.3.2 Desk study

The desk study should normally include obtaining, collating and assessing information about a site and its environs from a variety of sources (some publicly available and some that may be private and/or confidential), such as Geological Survey and Ordnance Survey maps. Further information on the scope of a desk study can be obtained from CLR11 (Defra and EA, 2004a), BS 10175 and BS 5930. Information used in undertaking the desk study with a focus on the vapour intrusion and emission pathways includes:

- site records on use of chemical substances including historical chemical inventory if available (ie are VOCs used, or have they been used, at the site?)
- disposal procedures (could VOCs be present in areas of the site where disposal has taken place?)
- drainage surveys (could these form a transport route for VOCs beneath the site?)

- site spill records
- waste records.

If a site is regulated under an environmental permit or control of major accident hazards (COMAH) then more detailed records including procedures, risk assessments and method safety data sheets (MSDS) should be available for review. Since June 2008, any company using substances or preparations as defined under Registration, Evaluation, Authorisation and Restriction of Chemical Substances (REACH) legislation is required to maintain a chemical substances inventory (CSI), which can be useful in undertaking the desk study.

The desk study is used to collate information about the site that can often be confirmed or disproved following a site reconnaissance (see Section 4.3.3). The surface cover of a site and the presence of buildings, for example through review of aerial photographs and historical/current maps, can suggest whether the vapour intrusion and/or emission pathways have the potential to be active. The type of building present can be important (see Figure 4.1), as the likely construction or presence of basements may influence the mechanism by which VOCs in soil gas enter a building. Noting such information, where possible, before visiting the site may help focus the site reconnaissance works. The geology underlying a site, as discussed in Chapter 2, is often critical in determining the likely migration route for VOCs in soil gas, as illustrated on Figure 4.1. Table 4.1 (Section 4.3.4) provides an overview of typical sources of information that may be consulted as part of a desk study.

4.3.3 Site reconnaissance (walkover survey)

Where it is permitted and practical, a typical site reconnaissance with the purpose of collecting information relating to the vapour intrusion/emission pathways should:

- assess visual evidence of contamination or areas of potential contamination (eg unbunded drum storage area or tank farm in poor condition) where VOCs may be present
- assess presence of below ground tanks as these can be potential sources of VOCs in the subsurface (note to lift covers only if safe to do so)
- identify/confirm service plans (such as drainage runs and presence of interceptors) if possible (see Section 2.5.8)
- identify/confirm surrounding land-uses and receptors close to the site that may be at risk of migrating VOCs (see Figure 4.1)
- assess building and ground cover presence, use and construction (eg using a building survey – see Appendix A5), and presence of gas/vapour protection such as vented manholes (see Section 4.7.3 and Figure 4.3). An understanding of the above ground structures is one of the main factors to understanding the migration of VOCs from the subsurface to the surface
- note potential investigation locations, including possible restraints (such as overhead power cables)
- assess hydrogeology/hydrology from local features where possible (see Sections 2.4.2 and 2.5.2), to help understanding of how VOCs might be transported in the subsurface (see Figure 4.1)
- review site operation (for a site in use) to assess the potential for pollution to the subsurface to have occurred such as:
  - interviewing appropriate staff

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- reviewing environmental records held on site
- staining/olfactory evidence (current or based on site records).

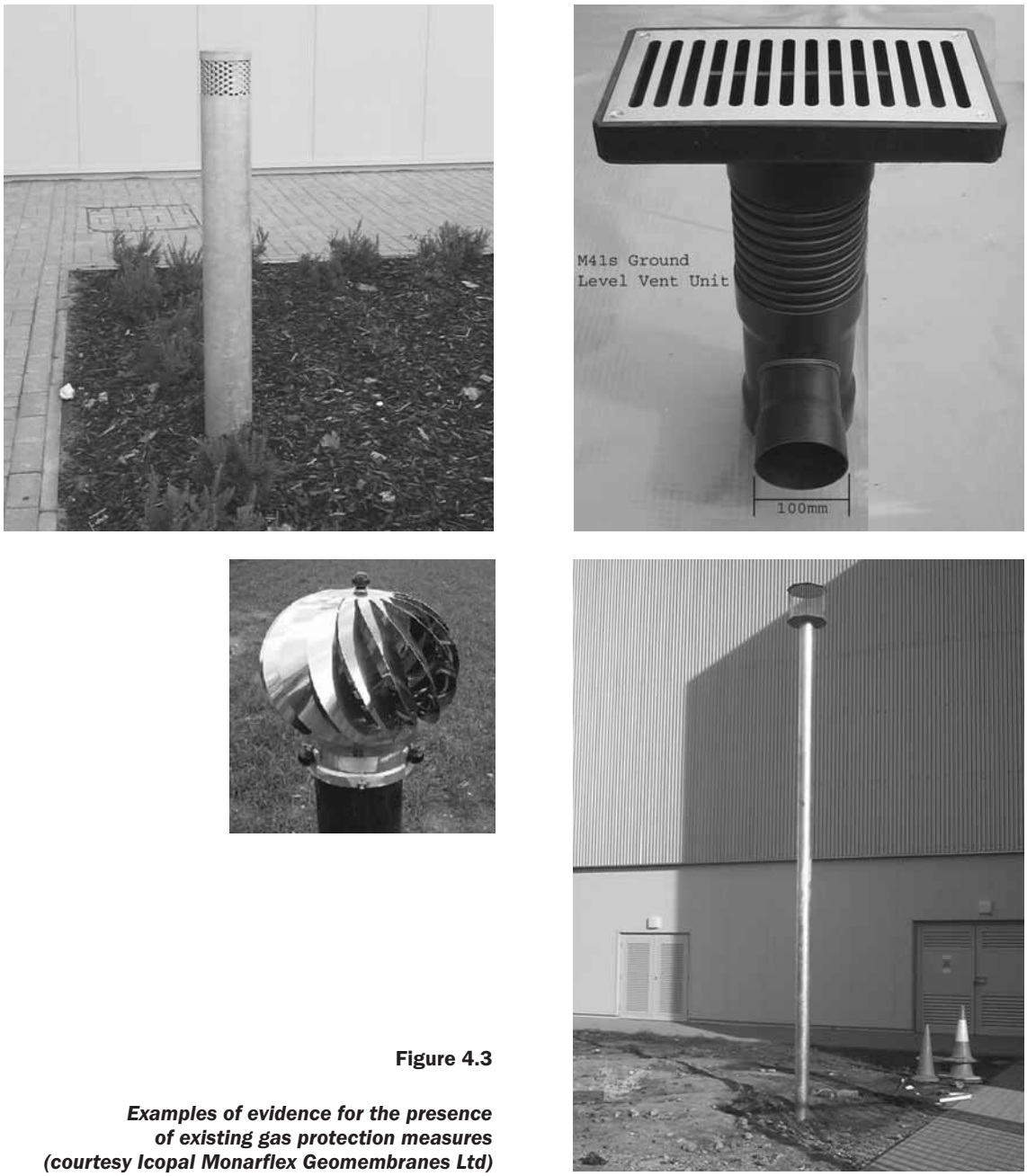

Figure 4.3

Examples of evidence for the presence of existing gas protection measures (courtesy Icopal Monarflex Geomembranes Ltd)

Site visit checklists and/or questionnaires can provide a useful series of prompts during the reconnaissance, as well as providing a permanent record of the observations of the visit. The checklist/questionnaires can be generic for certain types of site, for example, operational industrial estates. However, at times there may be a need to develop site-specific checklists/questionnaires if particular aspects, such as process details, are required. Particular attention should be paid to those areas where compliance of environmental and health and safety (relating to occupational exposure) legislation is required. It is also critical to ensure that all relevant areas of the site are visited, and a plan with the actual site boundary is vital. Assuming permission is not withheld a photographic record is often useful.

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4.3.4 Sources of Information

Table 4.1 summarises the typical sources of information for a desk study/site walkover, considering human health as receptors and focusing on the vapour intrusion and emission pathways.

Table 4.1 ***Summary of typical desk study information***

Information	Importance/relevance	Typical information sources
Site history	Identifies the history of the site and surroundings. In particular identifies areas where VOCs in soil gases may be present (industrial land, infilled quarries, reclaimed marsh areas etc). Presence of existing gas protection measures may indicate potential for vapour intrusion/ emission.	Ordnance Survey, local library, military records, planning records, aerial photos, local residents, Department of Environment industrial profiles, Defra and EA guidance, review of company spill records/permit records, chemical inventory records, previous reports, MSDS.
Geology and hydrogeology setting	Identifies the geology and hydrogeology of the site and surroundings. Identifies potential for migration (permeable strata, joints, fissures and former areas of mining).	Geology and hydrogeology maps, Environment Agency/ SEPA records, borehole records, Natural England, Ordnance survey topographic maps, BGS memoirs, engineering geology records, previous site investigations.
Current land-use	Identifies potential for spills/ leaks, chemical storage/process areas, site receptors, presence of buildings/land cover material and condition, surrounding land-use/receptors, existing control/ mitigation for gases. Helps identify potential contaminants.	Walkover survey, interviews with site staff, site records, Department of Environment industrial profiles (for contaminants related to current use).
Pollution incidents	Location and nature of spills.	Local authority, Environment Agency, SEPA, site records.
Waste disposal/ management licences and records	Types and location of wastes deposited on the site, material used to infill ponds etc.	Local authority (planning records), Environment Agency/ SEPA (licences), site records.
Regulator consultation	Pollution events. Effectiveness of remediation works. Waste/ gas management issues.	Local authority, Environment Agency, SEPA, Natural England, local petroleum officer.
Underground services	Potential pathways and points of accumulation. Design of site investigation.	Utility companies, site records, National Pipeline database.
Public rights of way	Identifies potential receptors that may be affected by the migration of VOCs.	Ordnance Survey, local authority, site records.
Previous investigations/ monitoring/remediation works	Information to establish the ground conditions, soil gas regime and existing remediation measures. Collate ambient air quality data if available.	Local authority, Environment Agency, SEPA, site records.
Redevelopment plans	Identifies future receptors and implications to on-site and off-site receptors (building construction, use, foundation type, level changes and presence of basement).	Developer/owner, local authority.

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4.4 INITIAL CONCEPTUAL SITE MODEL

The development of a CSM is a critical first step to achieve a good understanding of current site conditions with respect to VOCs in soil gas and in planning and scoping later tasks within the risk assessment process. A well-defined site-specific conceptual model will help identify data gaps and uncertainties, and will be an important tool in setting data quality objectives for any ground investigation. It also helps to predict potential future risks, for example, following development. The initial CSM developed as part of the preliminary risk assessment (PRA) should then be revisited and refined/updated following later site investigations, monitoring, sampling and qualitative/quantitative risk assessment. An example of a CSM is shown on Figure 2.3, and a range of potential scenarios that may be encountered when investigating and assessing the vapour pathways is shown on Figure 4.1. The CSM typically considers a range of receptors and pathways, in addition to the vapour intrusion/emission pathways. The following sections focus primarily on the development of a CSM based on the risks to human health receptors via inhalation of VOCs. However, other potentially active pollutant linkages should also always be acknowledged for the purposes of the site assessment.

Through development of the initial CSM, the result of the v-PRA should enable the assessor to conclude whether the vapour intrusion/emission pathways are likely, or have the potential, to be active.

4.4.1 Initial conceptual site model checklist

There are many existing guidance documents that aid the assessor in the development of a CSM, including the vapour intrusion/emission pathways. These include the CLEA documents (Defra and the EA), McMahon *et al* (2001) and Rudland *et al* (CIRIA C552, 2001). A range of checklists have also been developed to help as a prompt for assessors in collating desk study and site reconnaissance information, and developing a CSM. The checklist provided within the ITRC guidance *Vapor intrusion pathway: a practical guideline* (ITRC, 2007) has been adapted for the UK, and is presented in Appendix A4. The checklist is not comprehensive but it should be a useful tool for assessors when undertaking a preliminary risk assessment that includes consideration of the vapour intrusion/emission pathways.

Quick reference 4.1 ***Conceptual site model development***

The development of a robust CSM is vital to the assessment of potential risks from the vapour intrusion/emission pathways. A poorly developed CSM can lead to an inappropriately designed assessment and can have a significant affect on the conclusions of the assessment, especially for the vapour intrusion/emission pathway. In some cases this leads to a large over-prediction, or in other cases an under-prediction, of the risk.

4.5 SOURCES

Typical sources of VOCs in soil gases and the general environment have been discussed in Chapter 2, but this section highlights points that may need to be considered relating to the source when developing the initial CSM.

4.5.1 Could VOCs be present?

When developing the initial CSM, the assessor may not have site-specific data on the ground conditions, including the presence, nature and extent of VOCs in the subsurface.

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Review of desktop information based on the historical/current and surrounding land-uses and site records can indicate whether VOCs are likely to be present. For some sites, intrusive investigation data will already have been collected, and can be incorporated into the CSM. Reference documents such as guidance provided by Defra and EA and the Department of the Environment Industry profiles can be used to help the assessor, in terms of which VOCs could be present, based on the identified land-uses. The type of VOCs present (for example, halogenated or non-halogenated hydrocarbons, see Appendix A2) is important in understanding the likely source distribution and behaviour in the environment.

For some sites, it will not be possible to determine whether VOCs could be present, due to limited desk study information. Where significant uncertainty is present, it would be reasonable to assume that VOCs could be present, until proven otherwise.

Where ground gases (for example, carbon dioxide or methane) could be generated, and potentially act as a carrier gas for the transport of what are referred to as trace components (for example, in a quarry infilled by putrescible waste materials) this potential influence (including the potential for lateral migration of soil gas due to pressure gradients) should be taken into consideration in the development of the CSM. Guidance on typical trace components, encountered at landfilled sites, is provided by the EA (2004a). It is noted that the presence/flow rate of methane at landfilled sites can not always be relied on to determine whether trace components are present (Bradley *et al*, 2002). There is an absence of significant work regarding the interaction between ground gases and VOCs reported in literature now. It is noted that several more common trace components have relatively low volatility (for example, butyric acid), and are not included in typical VOC analysis suites, as the transport mechanism is via the carrier gas, and not volatilisation.

When assessing whether VOCs are present the likelihood of encountering complex mixtures of compounds, and their interaction, should be considered. For example, the effective solubility of a compound can differ when present as part of a mixture. The presence of mixtures may influence the complexity of the design for intrusive investigations, and the behaviour (such as their biodegradation) of certain VOCs in the environment. For example, the level of oxygen present (a requisite for rapid biodegradation of certain VOCs in the unsaturated zone) may be considerably more limited in the direct presence of petrol fuels (which comprise a mixture of more reactive VOCs) than fuel oils (which typically comprise a mixture of less reactive VOCs).

4.5.2 The presence and composition of non-aqueous phase liquid (NAPL)

If NAPL is suspected, or known to be present, volatile compounds in the subsurface should be considered a possibility. Consideration of the NAPL composition, its mobility in the environment and the location of potential receptors could lead the assessor to conclude that the NAPL presents a low risk via the vapour intrusion/emission pathways at a later stage of assessment (based on site-specific information).

The composition of NAPL and its likely distribution should be considered when designing an intrusive investigation (see Figure 4.1 for examples of scenarios where NAPL may be present). Points to consider include:

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- composition/age of NAPL
- whether the NAPL is above or below the groundwater level, as this may affect the design and location of the monitoring wells
- water level variations (particularly for light NAPLs)
- the likely mobility and migration routes for NAPL and whether close to underground services (such as a potable water supply)
- whether residual NAPL is present in soil pore space
- whether the NAPL is close to a building or open air space.

If NAPL is present, the assessor may choose to undertake a v-DQRA (including design of a relatively complex vapour intrusion/emission site investigation), without undertaking a v-GQRA.

4.5.3 Source area, source composition and source distribution

If the presence of VOCs is suspected or known, the environmental source media, location beneath the site, composition and distribution should be considered before designing an intrusive investigation (see Section 4.5.4 for further details on source media and Figure 4.1 for illustrative purposes). The known or suspected location of a spill/leaks should be considered, alongside the likely migration route the spill or leak may take in the subsurface. For example, if VOCs are likely or known to be present in groundwater, then investigation locations may need to target the hydraulically down-gradient part of the site (where possible) as well as the source area. Groundwater is a common transport mechanism for some types of VOCs to migrate off-site, and then volatilise and enter a neighbouring building air space.

Case study 4.1 ***Delineation of VOCs in soil gas using groundwater***

Groundwater with dissolved phase concentrations of chlorinated hydrocarbons including tetrachloroethene, trichloroethene and 1,2-dichloroethene (DCE) migrated beneath several residential homes in Denver, Colorado. Groundwater monitoring wells (32 in total) were installed in several locations, providing a reasonable delineation of the dissolved phase contamination. Groundwater was found to be flowing through a mixture of silts, sands and gravel deposits in alluvial channels that overlay the Denver Formation bedrock. Concentrations of one compound, DCE, were detected at levels above the state action level (0.49µg/m³) in 380 homes overlying the dissolved phase plume, with further monitoring undertaken in 225 homes close to the edge of the plume. The edge of the plume was defined as the state maximum concentration level (MCL) of 1µg/L. The majority of the houses just beyond the plume boundary had measured concentrations of DCE below the action level, although there were some exceptions. The data indicated that vapour intrusion was not occurring, for this particular site, at concentrations of cause for concern at a distance beyond 30 m (100 feet) of the plume boundary (Folkes *et al*, 2007). The case study also highlights the benefits of using dissolved phase concentrations of chlorinated hydrocarbons to aid assessment for potential vapour intrusion (see Section 5.6.2).

The potential co-solvency effects may also need consideration. Many sources containing VOCs are in fact mixtures (for example, petroleum fuels). The behaviour of individual VOCs is affected by the mixture, and its chemical/physical parameters (such as the vapour solubility) may be more dependent on the overall mixture composition than on other factors such as temperature. For instance it has been shown that the additive ethanol in petrol has the effect of increasing the solubility of the certain polycyclic aromatic hydrocarbon (PAH) compounds in groundwater.

The location and extent of a source area in relation to current, or planned, buildings should be considered where possible as part of the initial CSM,

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focusing the design of an intrusive investigation for the vapour intrusion/emission pathways. Also, the likely location of the source with respect to potential natural or anthropogenic preferential pathways should be considered. This is illustrated on Figure 4.1 for several hypothetical scenarios considered.

Before undertaking a site investigation, the presence of a source, and its composition and distribution are typical areas of uncertainty associated with the CSM. As such, where VOCs (or other compounds capable of migrating into an indoor or outdoor air space) are suspected or likely to be present, the initial CSM will commonly include the vapour intrusion/emission pathways as active. One exception to this might be if no receptors are identified (see Section 4.6).

4.5.4 Environmental source media

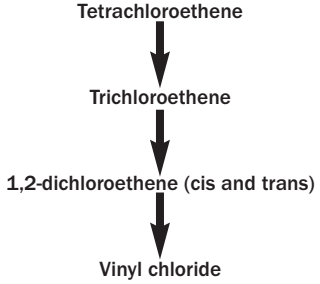
The likely environmental source media need consideration, especially in the design of the intrusive investigation. The initial investigation should aim to target the main (or known) source media, such as soil, soil gas and/or groundwater, although further investigations might be needed to assess different media/different points in the pathway in more detail (see Figure 4.1). Typically, the source of VOCs in the subsurface is via a spill/leak of a liquid. However, for some sites, a release of a gas into the subsurface may have occurred (Hartman, 2002). This should be considered when designing the intrusive investigation, as it could influence which environmental source media are sampled.

Where groundwater is the likely, or known, source medium, the hydrogeological regime needs careful consideration. This should ideally include establishing the depth to groundwater and flow direction/flow rate, whether the groundwater represents a continuous groundwater body, or the potential for vertical leakage to a different aquifer unit and its later transport off-site.

4.5.5 Chemical characteristics/behaviour of VOCs

Different VOCs exhibit varying behaviour as they migrate through the environment, which should be noted when developing the CSM. Detailed discussion on this is provided in Appendix A2. However, the two most commonly encountered types of VOCs – petroleum hydrocarbons (non-halogenated hydrocarbons) and chlorinated solvents (halogenated hydrocarbons) – are known to exhibit different behavioural characteristics in the environment (ITRC, 2007, Davis *et al*, 2004 and McHugh *et al*, 2004) due to factors such as relative density and degradation in the unsaturated zone.

Where degradation of the VOCs is or could be occurring (in dissolved phase or in gaseous phase) the daughter products also require careful consideration as they can be more mobile (and have a higher associated toxicity level to humans) than the parent compound. An example of a commonly encountered degradation chain (reductive de-chlorination, under anaerobic conditions) of tetrachloroethene is shown as:



For the last daughter product, vinyl chloride, the inhalation health criteria value in UK literature is at least one order of magnitude lower than for the other compounds (see Defra and EA, 2004b, 2004c and 2004d).

4.6 RECEPTORS AND EXPOSURE PATHWAYS

The varying effects of a source on a particular receptor depend largely on the amount and duration of exposure and on the receptor sensitivity. Receptors include any people, including construction workers, connected to the source by the pathway.

Quick reference 4.2 ***Potential human health receptors***

Potential receptors at risk from VOCs in soil gases include:

- construction workers involved in redevelopment and future maintenance workers (eg workers in a partially or fully enclosed outdoor air space such as a trench)
- current/future site residents and users
- off-site occupiers
- trespassers.

The initial CSM should consider whether any receptors are present, and the sensitivity of the identified receptors.

Exposure pathways describe the way in which a human health receptor can receive a dose of a VOC, once it is present at the point of exposure. The pathway of focus considered in this guidance is the inhalation of air, typically either in an indoor or ambient air space, including under occupational and residential settings. It is important to identify the likely length, nature and frequency of exposure and carefully consider the characteristics of the receptor (EA, 2009b, Jeffries, 2009).

Quick reference 4.3 ***Potential exposure scenarios***

- inhalation of vapours in an indoor air space by a site commercial worker
- inhalation of vapours in an indoor air space by a site resident
- inhalation of vapours in an outdoor air space by a resident living near to a land contamination site
- inhalation of vapours through occupational exposure to soils/groundwater, for example during remediation works, site redevelopment works or maintenance works on a site.

The type of receptor, the sensitivity of the receptor, and the nature of the exposure scenario could affect the design of a site investigation and assessment.

The potential for short and long-term exposure, and potential future acute health effects (for example, due to vapour release events) should be taken into consideration when developing the initial CSM. The assessor needs to be aware of the potential acute toxicity of the volatile compounds and the exposure scenario, even at the investigation stage, as appropriate measures may need to be put into place before the investigation is undertaken.

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4.7 ENVIRONMENTAL FATE AND TRANSPORT PATHWAYS

Environmental fate and transport pathways describe the migration routes, and attenuation mechanisms, that result in VOCs present in soil gases reaching a point of exposure, such as an indoor air space. Migration routes include conveyance through soil, water or air (see Figure 4.1). Attenuation mechanisms include degradation during transport in the unsaturated zone and dilution in the overlying air space. The potential for preferential routes of transport to the point of exposure also needs consideration.

Factors influencing the transport and fate of VOCs in the environment have been discussed in Chapter 2. The transport of a VOC from the source zone to point of exposure typically includes the following four processes, as illustrated in Figure 2.3:

1 Partitioning or volatilisation of VOCs into soil gas.

2 Migration through the unsaturated zone (laterally and vertically).

3 Emission into an ambient air space, or intrusion into an indoor air space.

4 Dilution in the air space.

When developing the initial CSM the assessor should be aware of these processes, considering vertical and lateral migration routes where appropriate, alongside the potential for preferential migration pathways.

Quick reference 4.4 ***Potential environmental fate and transport pathways***

Potential environmental fate and transport pathways include:

- **migration via permeable soil strata (vertically and laterally)**
- **ingress into an indoor air space**
- **preferential migration routes**
- **migration in dissolved phase through groundwater flow**
- **direct release to air following ground disturbance.**

4.7.1 Site use and condition

The presence of hardstanding or a building over, or close to, the source can have a considerable effect on VOCs in soil gas as they migrate through the unsaturated zone. Research carried out to assess the extent of the effect demonstrates that placing a slab/building onto an open space alters the concentration gradient of VOCs in soil gas within the unsaturated zone, as shown in the Figure 4.4 adapted from Davis *et al* (2004).

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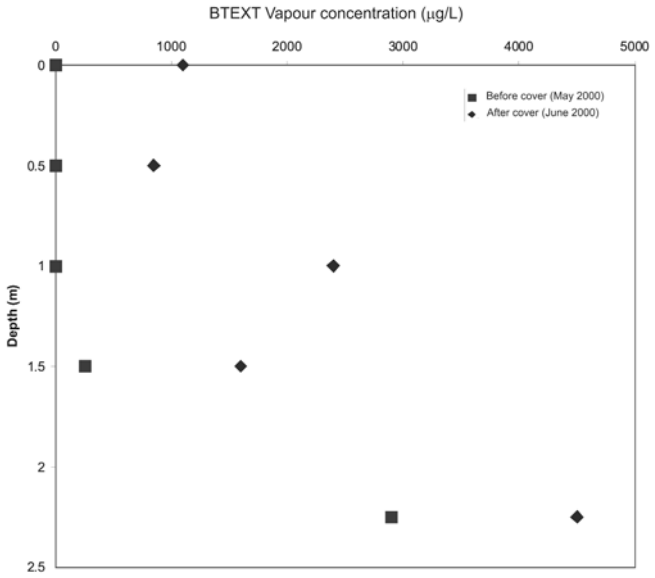

Key

BTEXT: Benzene, toluene, ethylbenzene, xylenes and trimethylbenzenes

Figure 4.4 ***The effect of introducing hardstanding on concentrations of BTEXT in soil gas (adapted from Davis et al, 2004)***

Similar results have been observed by different authors (for example, van Geert *et al*, 2003 and 2004), although data to the contrary has been recorded under a house in Australia (Davis *et al*, 2004), where coarse fill materials were present between the house and clay-rich natural soils. The authors hypothesized that the net flux of gasoline-related VOCs from the clay soils was low compared to the net flux of oxygen from the atmosphere through the made ground promoting degradation of the VOCs. The hardstanding effect observed in Figure 4.4 can be attributed to several factors, including change in the concentration gradient (diffusion-driven), the stack effect (where a ventilated building is present) and, for petroleum hydrocarbons, a decrease in oxygen content due to reduced replenishment from the atmosphere and then reduced degradation. As such, the initial CSM should consider whether a change in end use of the site is planned, which will then affect the design of an intrusive investigation (see Section 4.4.7). For example, if the assessor plans to measure VOCs in soil gas on a site where new development is planned, the samples would need to be taken from the depth of the source or outside the influence of advective effects rather than the overlying shallow unsaturated zone so the significance of the pathway can be assessed. Also, if hardstanding is introduced on a site, a change in moisture content as a result could affect the soil gas regime in the unsaturated zone.

4.7.2 Vertical and lateral migration in the unsaturated zone

The potential for both vertical and lateral migration should be acknowledged when developing the initial CSM, including the likely variability in the soil permeability. For example, the presence of a low permeability soil type overlying the source area could promote the lateral, rather than vertical, migration of soil gases. Typically, the lateral permeability of soils is higher than the vertical permeability, although this is dependent on the soil type and the homogeneity of the deposits. Also, the CSM should include an evaluation of whether vertical or lateral migration could be improved by the presence of potentially preferential pathways. For example, a service route surrounded by permeable backfill material that runs through a clay-rich soil could act as a conduit for the preferential migration of soil gases.

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4.7.3 Vapour intrusion, vapour emission or vapour release

The ingress of vapours into a structure, excavation or open air space was discussed in Chapter 2, but factors the assessor should note when developing the initial CSM include:

- the location of current (or planned) buildings and ground cover
- the nature and condition of ground cover
- the construction of buildings present, or planned
- the potential for preferential pathways (in particular for vapour intrusion into a building)
- the potential for build-up of vapours in enclosed spaces (in particular where ventilation rates are low)
- the presence and construction of neighbouring properties
- the potential for future ground disturbance causing a vapour release (see Section 7.3.1).

Undertaking a building survey during the site reconnaissance may help the assessor to develop an initial CSM: an example is included as Appendix A5. It will not be possible to undertake a detailed building survey on all developed sites due to access restrictions and/or difficulties with risk communication and, possibly, causing undue concern within the community (for example, on a residential site). In some cases, contacting the local authority may help in data collection where no access to the building is possible.

4.7.4 Future site construction

Construction of a new building or hardstanding at a site has already been shown to have a potential effect on the migration of VOCs in soil gas (Section 4.7.1). However, there are other factors that need consideration when developing the initial CSM, including the possibility that new soil will be introduced to the site, the site levels may change and that conditions that approximated equilibrium may be disturbed (potentially resulting in a release of vapours, see Section 7.3.1). Further discussion and practical advice on this topic is provided by Mallet and Beale (2008) and USEPA (2008).

4.8 MULTIPLE LINES OF EVIDENCE

For the assessor to conclude that the vapour intrusion/emission pathways are unlikely to be active or to present a significant risk during a v-PRA, multiple lines of evidence are warranted. This is particularly the case where a source is presented, or suspected. This is a concept commonly applied in risk assessment, requiring the assessor to provide more than one reasoned line of evidence as to why the pathway is considered inactive/unlikely to present a significant risk.

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Case study 4.2 ***Multiple lines of evidence in vapour intrusion/emission assessment***

Site in central England

A desk study was undertaken for agricultural land adjacent to a road. The site was intended to be redeveloped for use as a hotel and car parking. Multiple lines of evidence were used to demonstrate that the potential for a vapour intrusion or emission pathway was unlikely to be active, including the nature of the historical and current site use (agricultural land). This meant that VOCs were unlikely to be present, and the nature of the proposed development (including hardstanding across a large portion of the site and the building constructed without the potential for significant preferential pathways via service entry points) and the low permeability of the underlying clay-rich deposits meaning that the potential for vertical or lateral migration of soil gas was limited.

4.9 RESULT OF THE PRELIMINARY RISK ASSESSMENT

The information collated during a v-PRA regarding potential sources, receptors and pathways is used to identify pollutant linkages needing further assessment. Based on this information, the need to undertake a generic quantitative risk assessment (including intrusive site investigation works), a higher stage of quantitative risk assessment or to put a risk management/mitigation plan into action (for example, where an immediate risk to human health is suspected) can be determined. Selecting the next stage of assessment often depends on commercial or community factors rather than technical factors. The design of any site investigations needed should be based on the plausible pollutant linkages identified in the CSM.

Case study 1 (Appendix A3) for a site in southern England illustrates a site where the v-PRA indicated the potential for vapour intrusion was identified, leading to the design and a site investigation being carried out.

4.10 SUMMARY

The v-PRA is the first stage of the site assessment process, compiling available data and developing an initial CSM relevant to the project objectives. The results of the v-PRA should demonstrate:

- if the vapour intrusion/emission (or release) pathways could potentially represent active pollutant linkages
- the estimated probability/degree of the risk (through qualitative risk assessment)
- the need to progress to a higher level (more detailed form) of assessment.

Where an immediate risk to human health is known, or suspected, risk management and/or mitigation measures should be applied directly, before undertaking further investigative or risk assessment, to safeguard human health.

For many sites where VOCs are present or suspected in the subsurface, the vapour pathways are considered active at a v-PRA stage (ie no data to suggest that they are not active). Further site data will be required to refine the CSM, and confirm whether this pathway is (or is likely to be) active and to quantify the risk to the identified human health receptors.

Where a source is present, or suspected, at a site, multiple lines of evidence should be used before exiting the process at a preliminary stage of assessment.

The assessor can progress to the next stage in the assessment process – a v-GQRA – or may choose to progress straight to a v-DQRA (including intrusive site investigation works if none have been undertaken). For example, this may be the case for sites with a complex geological or hydrogeological setting, an unusual exposure scenario/site us or where significant preferential pathways are suspected (or known).

It would be unlikely for the assessor to exit the risk-based process and consider remediation methods at this stage, without quantification as to the likely level of risk.

For the majority of sites, the CSM needs to take extra pollutant linkages into consideration (such as risks to controlled waters). Detailed guidance on the assessment of different pollutant linkages is given in existing documents, for example, the CLEA documents (Defra and EA) and the EA's Remedial targets methodology: hydrogeological risk assessment (Carey *et al*, 2006). These further pathways should be considered before a decision of no further action can be taken for a site.

4.11 FURTHER INFORMATION

FOLKES, D J, JEFFREY, P K and SANPAWANITCHAKIT, C (2007)
"Vapor intrusion as a function of lateral distance from a groundwater plume boundary"
Proc Air and Waste Management Association Vapor Intrusion conf, Providence, RI, September 2007

MALLET, H and BEALE, L (2008)
Guidance for the safe development of housing on land affected by contamination
R&D Publication 66, National House-Building Council (NHBC) <www.nhbcbuilder.co.uk>, Environment Agency (EA) <www.environment-agency.gov.uk> and the Chartered Institute of Environmental Health (CIEH) <www.cieh.org> (ISBN: 978-1-904306-82-5)

USEPA (2008)
Brownfields technology primer: vapor intrusion considerations for redevelopment
EPA 542-R-08-001, Office of Solid Waste and Emergency Response, United States Environmental Protection Agency, Washington DC, USA

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5 Developing a site investigation strategy for the VOC vapour intrusion/emission pathways

5.1 OVERVIEW

This chapter provides guidance on the design of site investigations targeting VOCs, which could present a risk to human health from the vapour intrusion or vapour emission pathways. An overall objective for site investigations of potentially contaminated sites, including sites where VOCs may be present, is:

> *"To provide information on actual and potential contamination…to permit an assessment of environmental and physical risks and allow decisions to be made on the needs for and nature of any remedial work necessary…."*
>
> (Barry *et al*, 2001)

The objectives should be kept under regular review and modified as appropriate to reflect the findings of investigations in the context of the overall assessment. Based on the objectives for the investigation, the assessor should be able to develop an investigation strategy, designing a scope of works as part of the investigation plan that will enable appropriate site-specific data to be collected.

There are several existing guidance documents that should also be referred to when designing a ground investigation for VOCs, whether focused on the vapour intrusion/emission pathways or considering extra pathways, such as:

- health and safety guidance (eg Site Investigation Steering Group, 1993, EA, 2004a and Steeds *et al*, 1996)
- CLEA methodology documentation (Defra and EA)
- BS 5930:1999 *Code of practice for site investigations*
- BS EN 1997-2:2007 Eurocode 7. *Geotechnical design. Ground investigation and testing*
- BS 10175:2001 *Investigation of potential contaminated sites. Code of practice*
- CIRIA guidance (R132, Steeds *et al*, 1996)
- EA (2000a, 2000c, 2000d and 2004b)

This chapter supplements these documents by providing more detailed guidance specifically focused on aspects important to the investigation and assessment of VOCs.

5.2 SETTING THE SITE INVESTIGATION OBJECTIVES

The objective for the site investigation, which influences the design and scope of works, is determined on the basis of the CSM. A well-defined CSM states that pollutant linkages could be active, requiring site-specific knowledge before specific pollutant linkages can be proved or disproved as active. The objective of

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the site investigation is to collect site-specific data to aid this process. The data collected during site investigations is used to refine the CSM (as part of a v-GQRA or v-DQRA) and determine whether one or more pollutant linkages are:

- likely to be active
- potentially active
- unlikely to be active.

Where the vapour intrusion or emission pathways are considered likely or potentially active, the site investigation data can also be used to characterise the source and pathway in more detail. For example, for the scenarios provided on Figure 4.1, the questions that could be posed, allowing objectives to be set for the investigation, could include the following:

1 For the residential property with a basement located on fractured bedrock, what data could be collected to improve the conceptual understanding of the migration pathway? What effect could the future construction of a building and hardstanding have on the potential for the vapour pathways to be active and present a risk, and how could the investigation be designed to take this into account? Is there a likely risk of migration of VOCs in soil gas from dissolved phase concentrations at depth?

2 For the commercial/high rise building, how could the potential preferential pathways be investigated? How could the potential for lateral migration of soil gas beneath the surface slab be considered further through the collection of site data?

3 For the residential properties without basements, what data would be needed to assess the risk from the LNAPL present on shallow groundwater, alongside the risk of emission from VOCs in shallow soils?

The CSM may have been developed within a v-PRA (see Chapter 4), or as part of a more detailed form of assessment (see Chapters 7 and 8 for discussion on refining the CSM). The investigation and assessment process is often iterative, and the objectives of undertaking investigative works may change throughout the process.

Where an immediate risk to human health is known or suspected, the design of the site investigation will need to give extra consideration to health and safety concerns (for example, can a safe working environment be created for those investigating the site?) and may take a different form to an investigation where an immediate risk to human health is not suspected.

Underlining the design of every site investigation should be the multiple questions:

- What are the data collection objectives needed for the investigation, how can the investigation be designed to meet those objectives, and how can the investigation be carried out safely?

5.3 DEVELOPING THE SITE INVESTIGATION STRATEGY FOR VOCS

The scope of the site investigation, which is likely to include exploratory techniques, is designed to meet the overall objectives of the works. As such,

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there are many questions the assessor may need to consider while developing the investigation strategy, such as:

1 What is the primary aim of this stage of the vapour pathway investigation?
2 What are the potential health and safety concerns associated with the investigation?
3 At what stage of the overall assessment process (see Figure 3.1) is the investigation being undertaken?
4 What are the regulatory requirements?
5 What are the practical constraints on the site (such as access or services)?
6 What exploratory techniques are technically feasible and practical given site constraints?
7 Are the types of VOCs likely to be encountered known and/or understood?
8 Does the investigation need to consider more than VOCs?
9 What environmental media (such as groundwater or soil gas) need investigation?
10 Are potential bulk ground gases such as methane or carbon dioxide likely to be present?
11 What are the data quality objectives?
12 If carrying out laboratory analyses, are the method detection limits fit for purpose, and will the analysis allow decisions to be made at the critical level of interest?
13 How many samples are required to provide a representative data population?
14 Are the potential areas of concern accessible?
15 Are the likely ground conditions known and understood?
16 Do preferential pathways need to be considered?
17 Are there commercial constraints?

The three main factors to the design of every investigation are listed here. By considering each factor during development of the investigation plan it should be possible to answer these questions, and others, on each site:

- health and safety
- selection of exploratory and analytical technique(s)
- number and location of investigation points.

Each of these factors is discussed in the following sections.

5.4 HEALTH AND SAFETY

Any investigation involving the disturbance of ground in which VOCs or other hazardous soil gases are suspected should be carried out with appropriate safety precautions. Whatever the scenario under investigation, until the presence and extent and degree of contamination is determined those undertaking the site investigation may be at risk, for example, from inhalation exposure or an explosion. These risks should be managed appropriately under the Management of Health and Safety at Work Regulations (1999). For some sites the Construction (Design) Management Regulations (2007) may also apply.

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Further guidance on how to minimise the risk to health during site investigations (or remediation/construction/demolition works) can be found on the HSE website <www.hse.gov.uk>.

There are specific guidelines for the safe investigation by drilling of contaminated land and landfills (Site Investigation Steering Group, 1993) and coal seams (HSE, 2007), which cover potential hazards associated with areas where hydrocarbons are present and on actively gassing sites. British Standards (BS 10175:2001, BS 5930:1999 and BS 10381-3:2002) should also be referred to during the design and execution of the investigation. Further health and safety guidance is also provided for specific circumstances by the British Drilling Association, CIRIA (Steeds *et al*, 1996) and the EA (EA, 2004a). CIRIA has also developing guidance on the assessment of risks associated with unexploded ordnance (Stone *et al*, 2009).

The minimum level of risk assessment usually required before undertaking an investigation for VOCs would comprise a control of substances hazardous to health (COSHH) assessment and a site-specific health and safety plan (HASP). As part of the COSSH assessment a determination should be made as to whether employee health monitoring will be required for the works. The types of health monitoring vary and are discussed within HSE guidance documents on COSHH and employers' responsibilities.

Examples of some of the potential risks that may need consideration when designing an investigation plan are highlighted in Table 5.1.

Table 5.1 ***Potential hazards to consider when designing an investigation plan***

Risks	Possible problems
Toxicological risks to human health	Could the investigation result in an instantaneous release of VOCs into the working atmosphere? See Section 7.3.1 for further discussion.
	Could an accumulation of VOCs lead to acute health effects for the investigation workers?
	Is there a potential risk to users of the site, or surrounding land-users during or after the investigation?
Risks of explosion	Could VOCs accumulate within a confined/semi-confined space close to a source of ignition?
	Are the investigation and monitoring tools fit for purpose (eg can they protect against risk of explosion)?
	Could the investigation technique result in migration of soil gases beneath the subsurface? (eg use of air flush drilling techniques)

There may also be procedures in place to help protect site workers, which will need to be followed on each site. For example, many active commercial or industrial sites operate a permit to work system.

5.5 SELECTION OF EXPLORATORY AND ANALYTICAL TECHNIQUES

There is a wide range of exploratory and analytical techniques that can be used to investigate whether VOCs are present at a site and the extent of contamination. Chapter 6 provides an overview of a wide range of exploratory and analytical techniques. The selection of exploratory and analytical techniques

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depends on several factors, alongside those listed in Section 5.1, and is typically site-specific. Factors to consider that have been referred back to Figure 4.1 for illustrative purposes, include the following:

1 Which VOCs are likely to be present, and in which source media? For example, could NAPL be present (as beneath the residential properties without basements on Figure 4.1), or is the contamination likely to be present in dissolved phase only?

2 Is the technique appropriate given site-specific health and safety concerns?

3 What are the practical constraints? (eg access and structures). On Figure 4.1, for the commercial/high rise building, how practical would it be to investigate beneath the building?

4 Which are the pathways of concern? For example, are both vapour intrusion and vapour emission pathways likely to be active, as for the residential property on Figure 4.1?

5 How far could contamination extend, both laterally and vertically?

6 How will the investigation data be assessed?

7 How many source areas require investigation? On Figure 4.1, multiple sources are shown to be affecting the commercial/high rise building

8 Is there a requirement to keep ground disturbance to a minimum?

9 Does the investigation need to target preferential pathways? For example, the lateral migration of soil gas beneath hardstanding (Figure 4.1, commercial/high rise scenario)

10 Which other pollutant linkages need investigation?

11 What are the data quality objectives?

12 Are multiple investigation techniques needed?

5.5.1 Which VOCs are likely to be present?

Different VOCs have already been shown to exhibit varying behaviour in the environment (Chapters 2 and 4). The type of VOCs present will influence the selection of both the exploratory and analytical techniques. This is illustrated in Case study 2 (Appendix A6), where the suspected presence of both halogenated hydrocarbons (in this case chlorinated solvents) and non-halogenated hydrocarbons resulted in the use of more than one *in situ* probing technique. However, the variability in how different VOCs behave also influences which environmental media need to be investigated. This is discussed in more detail in Section 5.6.

5.5.2 Combining exploratory and analytical techniques

A combination of exploratory techniques may be employed, in particular where VOCs are present in more than one source media (such as soil and groundwater) or as part of a wider ground investigation. Case study 2 (Appendix A6) again provides a good example of how different exploratory techniques can be combined as part of a ground investigation.

5.5.3 Target depth required and investigation location

To target the source of VOCs in subsurface intrusive investigations, exploratory techniques should be suitable to attain the depth and location at which the source is considered to be present. This factor influences the type of exploratory

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technique chosen. Also, the behaviour of the source in the environment may influence the depth that the investigation progresses to. For example, the potential for a zone of smearing above the water table associated with the presence of an LNAPL or the uncertainty associated with how a DNAPL may have migrated through superficial deposits with clay lenses, can influence the depth of the investigation required. Where a source is present beneath a structure, there is a range of exploratory techniques that can be used to investigate beneath the slab (for example, horizontal drilling or sub-slab soil gas sampling) and often associated technical and operational constraints. Whatever technique is employed, the investigation should be designed to prevent the installation acting as a preferential pathway for vapour intrusion/emission.

5.5.4 Data quality objectives

Data quality objectives (DQO) need to be set for the investigation. The DQOs are quantitative and qualitative criteria that:

- clarify investigation and assessment objectives
- define appropriate types of data to collect
- specify the tolerable levels of potential decision errors.

The quality assurance/quality control (QA/QC) requirements are rigorous for investigations involving VOCs. Volatile organic compound samples are more easily influenced by collection, storage and transport methods than most other parameters measured during a land contamination site investigation. The need for a robust QA/QC system is discussed further in Chapter 6.

5.5.5 Flexibility

The exact source and location of the VOCs is not always known before a site investigation is designed. In this situation, the flexibility of the investigation technique and the capability of the planned investigation to react to site-specific circumstances can be critical. The need for a phased, or iterative, approach to designing and undertaking investigations should be noted. Flexibility can be improved by using real time measurement instruments that can guide the detail of the investigation in the field.

5.5.6 Timescales

The time it takes to complete an investigation for the presence of VOCs will also reflect the investigation technique chosen. Although the timescale is an important consideration and can sometimes be a vital restriction of the project, it should be noted that the quicker and simpler exploratory techniques are not always suitably accurate and reliable. When investigating for the presence of VOCs, given the iterative nature of investigations and assessment, several sampling events may be necessary before firm conclusions can be drawn regarding the data collected. The DQOs can affect the investigation timescales.

When investigating VOCs, the timescale involved in near-equilibrium conditions being reached needs consideration. For example, when investigating soil gas quality within the source area, there is a higher probability that equilibrium conditions will have been reached than for soil gas samples at a distance from the source area. This is discussed further in Chapter 6.

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5.5.7 Costs

There is a range in costs associated with the various exploratory techniques. Lower cost techniques may not provide the most reliable or accurate means of investigation, while higher cost techniques may be above and beyond requirements on some sites. On large sites it may be possible to reduce the overall costs of an investigation and increase understanding by the appropriate use of a non-intrusive or temporary technique (such as ground penetrating radar or *in situ* probing) before an intrusive permanent technique.

5.6 INVESTIGATION OF DIFFERENT ENVIRONMENTAL MEDIA

5.6.1 Hierarchy of investigating different environmental media

The exploratory and analytical techniques adopted for a first phase of investigation are likely to differ from those adopted for a later phase of investigation. Typically, the hierarchy of data collection on Figure 5.1 would be undertaken, targeting different environmental media, although this depends on the overall investigation objectives and exposure scenario of concern.

The hierarchy was developed based on the literature review conducted as part of the handbook, and relates to several factors, such as:

- the need to collect the data to enable extra pollutant linkages to be assessed
- the familiarity and ease with which the media can be investigated
- how the data will be assessed (eg whether as part of a v-GQRA or v-DQRA)
- stakeholder considerations.

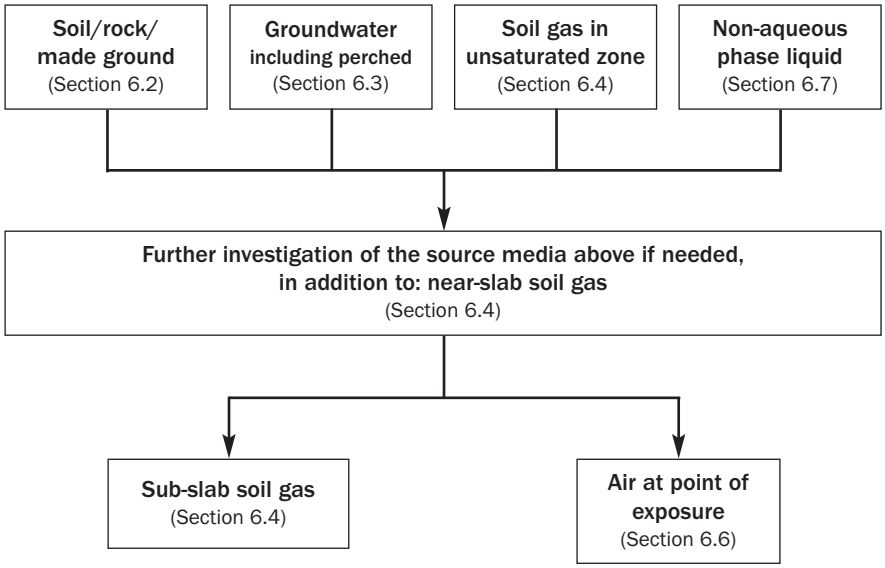

Figure 5.1 ***Hierarchy for investigation of different environmental media***

Two case studies (Case studies 5.1 and 5.2) are presented to illustrate different investigation hierarchies.

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Case study 5.1 ***Following the hierarchy for investigating different media***

Active petrol filling station site, southern England

The site was an active petrol filling station with some redundant underground storage tanks located away from the main forecourt area, close to the shop building. An investigation was planned to assess whether contamination was present in the soils due to the presence of the historical tanks, and whether there was a potential risk to the shop users from inhalation of petroleum-based VOCs originating from the underlying soils. Collection and later laboratory analysis of soil samples from close to the shop building, near to the former storage tanks, demonstrated the presence of VOCs, including benzene, at concentrations that exceeded soil screening levels based on the protection of human health (v-GQRA). A later sub-slab soil gas investigation illustrated that the attenuation of the VOCs between the source and foundation slab was significantly greater than modelled. The CSM was refined as part of a v-DQRA to show no significant risk to the shop workers from the vapour intrusion pathway.

Examples of scenarios where this hierarchy would not, or might not, be followed include:

- potential immediate risk to human health
- complaints of odours, such as inside a building
- source located immediately beneath a building foundation
- monitoring of instantaneous releases of VOCs, such as during remediation works (see Case studies 8.3 and 9.1)
- sites due for development, where sub-slab/near-slab and point of exposure sampling (for future site occupiers) are unlikely to apply
- investigation undertaken to verify that remediation works (including mitigation measures) have been undertaken appropriately.

Case study 5.2 ***Undertaking an investigation outside the hierarchy for investigating different media***

Former gravel works, Maidenhead

This site comprises gravel pit backfilled with a variety of contaminated materials including drums of solvents. Concerns were raised about the potential influence on adjoining properties, so boundary soil vapour monitoring was carried out just beyond the boundary of the gravel pit, demonstrating that cross-boundary migration could be occurring. Because of this work the local authority carried out a programme of indoor vapour monitoring in the closest houses. This method of investigation was undertaken in preference to further soil gas sampling/sub-slab sampling due to the likely disruption to the residents. This work did not identify any elevated VOCs in the indoor air, but it should be noted that the indoor air monitoring was cut short due to objections from the residents. This highlights the potential difficulties associated with undertaking such work on an occupied site.

5.6.2 Environmental media investigation requirements for different VOCs

The behavioural differences between types of VOCs have been discussed in some detail in Chapters 2 and 4 and in Appendix A2. Based on this discussion, three categories of VOCs have emerged:

1 **Petroleum (non-halogenated) hydrocarbons**

This category includes compounds such as the volatile aromatic hydrocarbons benzene, toluene, ethylbenzene and xylenes. Site

investigations that focus on collecting soil and groundwater samples for these compounds, and then adopt commonly used modelling tools (such as the Johnson and Ettinger vapour intrusion model, known as the J&E model) to predict the concentration at the point of exposure, tend to over-predict the concentration. In some cases, the predicted concentration at the point of exposure is well over an order of magnitude greater than the measured values. There are exceptions to this rule (such as when NAPL is present, where this rule of thumb cannot necessarily be applied), but for the majority of sites where these compounds are detected in soil and/or groundwater further investigation into the pathway (such as collecting soil gas samples) is likely to demonstrate that the risk is lower than originally predicted. This behaviour has primarily been attributed to the attenuation processes (in particular biodegradation) that occur for these compounds, alongside their behaviour when they are part of a mixture of non-halogenated hydrocarbons.

2 Halogenated hydrocarbons

This category includes the chlorinated hydrocarbons, such as tetrachloroethene and trichloroethene, and degradation products such as 1,2-dichloroethene and vinyl chloride. Site investigations that rely on the collection of soil data to assess these compounds may under predict the concentration at the point of exposure, as no clear correlation between concentrations of these compounds in soil and soil gas has been found to date. A better correlation is observed for these compounds between groundwater and soil gas. However, the level of attenuation between the source and point of exposure can be considerably lower than for the non-halogenated volatile hydrocarbons. This has been attributed to the reduced potential for biodegradation of these compounds during transport towards the point of exposure, or in some cases, the increase in concentration of certain compounds during migration in the unsaturated zone (for example, the production of vinyl chloride through reductive de-chlorination). The potential for lateral transport of these compounds in gaseous form has been recognised as being higher than for non-halogenated hydrocarbons.

3 Nitrogen, sulphur and oxygen-containing organic compounds

This category includes a range of compounds that can be considered VOCs, such as tetrahydrofuran (C_4H_8O) and carbon disulphide (CS_2). There have been fewer peer-reviewed studies looking at the behaviour of such compounds when compared to other types of VOCs, and some are ionisable and/or polar, which can affect their fate and transport in the environment. Where these compounds are present, or their presence suspected, their behaviour in the environment should be carefully considered (for example, potential for vigorous reaction upon exposure to the atmosphere and other chemical/toxicological properties that affect worker health and safety) when designing an investigation plan.

Other volatile compounds, notably inorganic volatiles including elemental mercury, may also need consideration for the same pathways. When designing an investigation plan for these compounds, a similar approach should be adopted as for the nitrogen, sulphur and oxygen-containing organic compounds, often requiring consideration of their potential behaviour in the environment on each site.

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Table 5.2 ***Initial investigation of environmental media for different VOCs and inorganic volatile compounds***

Type of VOC	Type of scenario (see Figure 5.2)	Initial investigation[3]		
		Groundwater quality (if present)	Soil quality	Soil gas
Petroleum (non-halogenated) hydrocarbons	1 Receptor air space overlying or close to[1] known or suspected contamination (in soils and dissolved phase contamination)	Y	Y	O
	2 Receptor air space overlying or close to[1] known or suspected dissolved gas contamination	Y	N/A	O
	3 Receptor air space overlying o r close to known or suspected NAPL/residual NAPL (source) from which volatilisation into the unsaturated zone could occur	Y	Y	Y*
Halogenated hydrocarbons	4 Receptor air space overlying known or suspected contamination (in soils), which has leached out groundwater, or overlying known or suspected dissolved phase contamination	Y	Y	O
	5 Receptor air space overlying or adjacent to known or suspected contamination, but a) contamination not present/representative in groundwater[2] and/or b) NAPL/ residual NAPL (source) present from which volatilisation to the unsaturated zone could occur	Y	Y	Y
	6 Receptor air space close to[1] but not overlying, known or suspected contamination (in soils, dissolved phase or NAPL/residual NAPL) contamination with the potential for volatilisation into the unsaturated zone in the subsurface	O	N/A	Y
Nitrogen, sulphur and oxygen-containing Volatile Organic Compounds	For Volatile Organic Compounds that do not fall into the above two categories, a site specific assessment needs to be considered, based on the conceptual site model and likely behaviour of the compounds to aid design of the investigation.	Contaminant-specific assessment of requirements[4]		
Inorganic Volatile Compounds	For inorganic volatile compounds (such as elemental mercury), a site specific assessment needs to be considered, based on the conceptual site model and likely behaviour of the compounds, to aid design of the investigation	Contaminant-specific assessment of requirements[4]		

Notes

1 The definition of how "close" the air space needs to be to the source to warrant investigation is related to the conceptual site model. However, one example is the method adopted in the US where an exclusion criteria of 5 m to 30 m between the source (including dissolved phase plume) and receptor is adopted depending on the type of compound present (for example, petroleum hydrocarbons versus halogenated hydrocarbons), the conceptual site model (for example, the presence of preferential pathways) and the state guidance. See Section 7.3.5 and Appendix A2 for further details of the US approach.

2 Contamination may not have reached groundwater (for example, due to depth to groundwater, age of spill) or presence of potential preferential pathways (such as fractures/ fissures within the unsaturated or saturated zone) mean that measurements of groundwater quality may not represent the overall level/extent of contamination beneath the site.

3 Further investigation of the vapour intrusion/emission pathways may be required as part of a more detailed assessment of the site (such as indoor air monitoring). The need for the collection of such data should be considered on a site by site basis, depending on the conceptual site model and data collection objectives.

4 To include consideration of the physical/chemical properties of the contaminant alongside the conceptual site model.

* Assuming NAPL could remain *in situ* at the site.

Y Recommended for inclusion in investigation as a minimum level of assessment.

O Optional investigation technique, which can be included as part of an initial investigation.

The behavioural differences between the types of VOCs mean that there will be variable minimum data collection requirements for the three groups of compounds. This is summarised in Table 5.2 and Figure 5.2, which can be used to help the assessor develop a site investigation plan. Where the framework is not considered suitable for a site condition, the site investigation plan should be developed, and exploratory techniques selected, to meet the DQOs.

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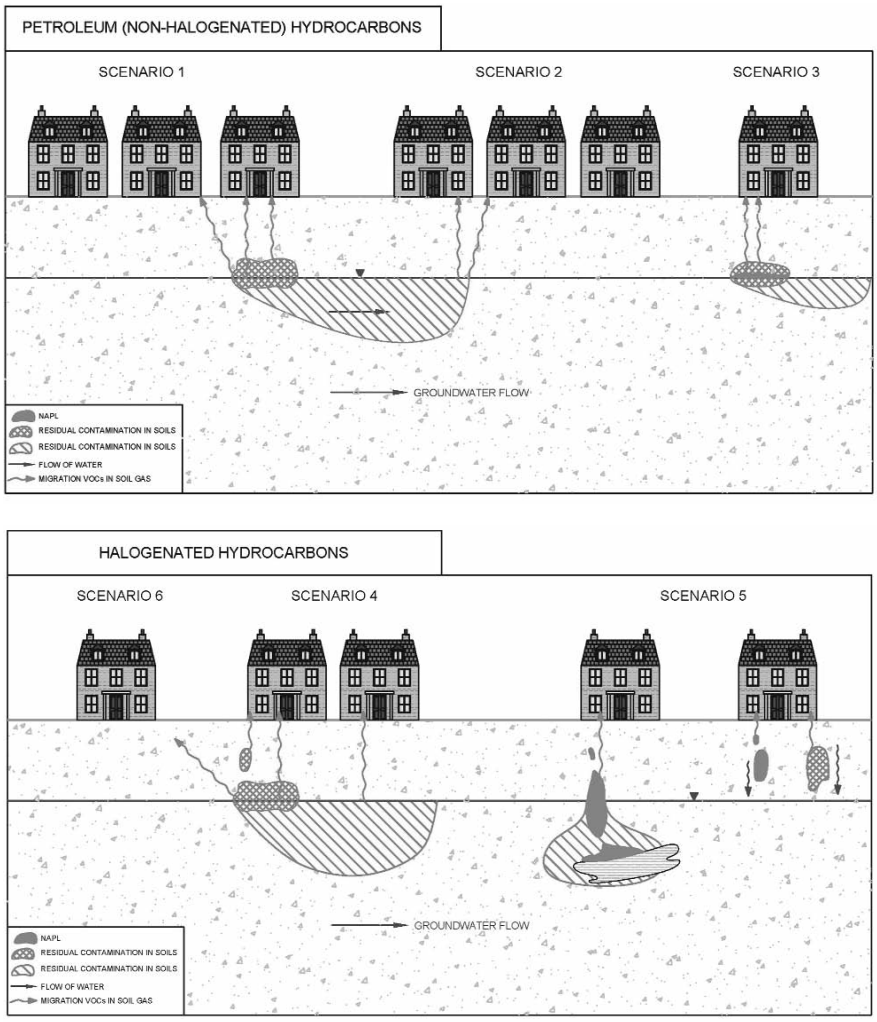

Figure 5.2 ***Initial investigation of environmental media for different VOCs***

5.7 NUMBER AND LOCATION OF INVESTIGATION POINTS

The number and location of exploratory locations required for any site should be based on the CSM and the need to provide appropriately robust data for assessment and design. The location and number of investigation points will depend on several site-specific factors. In principle, two basic approaches to sampling design are available (EA, 2000a):

1 Targeted or judgemental sampling.

2 Non-targeted or systematic sampling.

In practice, most VOCs investigation strategies will involve a combination of targeted and non-targeted sampling. Guidance on aspects of sampling strategies is provided in the Contaminated Land Report 4 (CLR4) (DoE, 1994), EA (2000a), Steeds *et al* (2000), BS ISO 10381-1:2002 and API (2005). The following areas of a site will normally be targeted for investigation:

- critical areas of the site where the desk study has identified a higher risk of VOCs being present (eg location of former industrial processes, a location between the VOCs source and a receptor, or within zones of permeable geology that could provide migration pathways), ie focus on understanding the source area

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- areas of developments (or proposed developments) that are sensitive to VOC migration in gaseous phase (eg below building footprints and location of service pathways), ie concentrate on understanding the potential points of exposure
- areas of lower risk (or areas off-site where feasible and practicable), to enable background concentrations to be collected to confirm the absence of VOCs.

The number and selection of location of investigation points influences how the data are interpreted, such as the use of zoning and statistical testing. Further discussion on the use of statistical testing, in particular the limitations when applied to the vapour intrusion pathway, is provided in Chapters 7 and 8.

For some sites, where preferential pathways could be present, the exploratory locations may be chosen to target one or more preferential pathway to assess the likely significance of the pathway. Where a risk of cross-boundary migration of VOCs has been identified, the boundaries between areas of land with different legal ownership often require site-specific attention. This includes where the assessment relates to the risks of migration onto the site from a source on a nearby site and migration off-site beneath or onto neighbouring land.

The spacing of exploratory locations depends not only on the location and number of sources of VOCs, but also the sensitivity of the site use (or proposed end use) to the vapour intrusion or vapour emission pathways. For example, spacing of exploratory locations may be different within the source area compared to a location distant from the source area. Areas where investigation is not possible or comprehensive because of site constraints should be clearly identified.

Where the preliminary risk assessment has not identified particular areas of the site as priority or target areas then the most suitable method of setting out exploratory locations to give a representative indication of the distribution of VOCs is often a uniform grid pattern (Raybould *et al*, 1995). The spacing of exploratory locations should vary according to the specific site conditions and the degree of risk associated with the VOCs source.

5.8 SUMMARY

The design of a site investigation is based on the CSM, and the DQOs defined for the site. The design and objectives of the investigation should be kept in regular review, to ensure that appropriate data are collected, and the investigation may be iterative in nature.

There are a range of factors that influence the design of the investigation strategy, including health and safety concerns, technical factors, commercial concerns and operational issues.

A combination of exploratory and analytical techniques may be appropriate to investigate a site, depending on the data collection objectives.

Different investigation techniques, including assessment of different environmental media, may be required depending on the types of VOCs known, or suspected, to be present.

5.9 FURTHER INFORMATION

API (2005)
Collecting and interpreting soil gas samples from the unsaturated zone. A practical strategy for assessing the subsurface vapor-to-indoor-air migration pathway at petroleum hydrocarbon sites
API Publication 4741, American Petroleum Institute, Washington, USA.
Available from: <www.api.org/>

EA (2000a)
Secondary model procedure for the development of appropriate soil sampling strategies for land contamination
R&D Technical Report P5-066/TR, Monitor Environmental Consultants Ltd under contract to Environment Agency, Bristol (ISBN: 1-85705-577-2)

STEEDS, J E, SHEPHERD, E and BARRY, D L (1996)
A guide for safe working on contaminated sites
Report 132, CIRIA, London (ISBN: 978-0-86017-451-6)

STEEDS, J E, SLADE, N J and REED, M W (2000)
Technical aspects of site investigation in relation to land contamination
R&D Technical Report P5-065/TR, Environment Agency, Bristol (ISBN: 1-85705-545-4)

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6 Exploratory and analytical techniques for investigating vapour intrusion/emission of VOCs

6.1 INTRODUCTION

This chapter provides an overview of different exploratory and analytical techniques that can be used to identify whether VOCs are present at a site, and at what concentrations. The exploratory technique is defined as the methodology used to collect or investigate a sampling location, whereas the analytical techniques are the methods by which the presence and degree of contamination are quantified. Soil and water quality exploratory and analytical methods will be briefly discussed in this chapter, although the focus is on soil gas investigation and sampling, and air monitoring. Note that there are existing guidance documents on undertaking investigations for the presence of VOCs in the soil mass and groundwater, and some are listed in Sections 6.2 and 6.3.

The selection of exploratory and analytical method is inherently linked with the aims of the assessment, as described in Chapter 5. The assessor should be aware of the main advantages and disadvantages of different techniques that could be used when designing the investigation works.

A comparison of the relative advantages and disadvantages of investigating different environmental media is provided in Table 6.1, adapted in part from ITRC (2007).

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Table 6.1 ***Relative advantages and disadvantages of investigating different environmental media***

Type of measurement	Relative advantage	Relative disadvantage
Soil	■ often collected as part of overall ground investigation ■ easy to combine range of sampling techniques to assess level of impact ■ familiar to most investigators/assessors.	■ heterogeneity in soils can lead to uncertainties in level of impact and poor repeatability in results ■ discrete samples collected ■ assumptions needed to model the migration from soil to the point of exposure.
Groundwater	■ often collected as part of overall ground investigation ■ easy to collect multiple samples from monitoring wells ■ good repeatability.	■ well screening can be critical to level of certainty with data ■ assumptions needed to model the migration from groundwater to the point of exposure.
Soil gas (away from building influence)	■ can target the source higher within the vadose zone ■ can reduce uncertainty in modelling the vapour emission/intrusion pathways ■ "nested" wells allow assessment of attenuation effects.	■ requires a higher level of experience to install sampling points and interpret than for some other techniques (such as soil, groundwater) ■ can produce high level of variability in results ■ need an understanding of the distribution of impacts to design the soil gas investigation ■ investigation design needs care on sites due for redevelopment.
Sub-foundation slab soil gas	■ gives concentrations directly beneath building/receptors, often reducing uncertainty in modelling the vapour intrusion pathway ■ useful if preferential pathways in the natural geology are known/suspected.	■ may contain compounds from interior sources ■ requires building access and drilling through foundation slab, can be disruptive to building occupants (requires risk communication) ■ not applicable unless building is present on site ■ need for high level reinstatement/risk of breaking existing gas protection measures.
Near-foundation slab soil gas	■ less intrusive than sub-foundation slab soil gas, as does not require access into building ■ useful if preferential pathways in the natural geology are known/suspected	■ may underestimate concentrations of certain compounds in soil gas compared to sub-foundation slab sampling ■ not applicable unless building is present on site.
Emission flux	■ can provide information on the flux of gas being emitted from the ground surface.	■ limited use for many sites, and difficult to incorporate the data into an assessment.
Point of exposure (air) sampling	■ sampling at the point of exposure reduces uncertainty in modelling ■ relatively simple to undertake sampling ■ may be more convincing to site users.	■ background sources can be significant, need for pre-sampling surveys ■ data interpretation often requires higher level of experience than some other techniques (such as soil, groundwater) ■ requires access to buildings (indoor air sampling) and can be disruptive to site users (requirement for risk communication) ■ risk of sabotage for sample/sampling location ■ low reporting limits often required due to toxicity of compound in air.
Non-aqueous phase liquid	■ understanding the composition, properties and distribution of NAPL typically needed to understand risks associated with a potential continuing source.	■ can be difficult to collect data, especially where residual NAPL is present in soils or DNAPL present within an aquifer.

6.2 INVESTIGATING VOCS IN SOIL

The investigation of soil for the presence of VOCs can be undertaken using numerous exploratory techniques, and the most common are outlined in Table 6.2. Specific guidance on the investigation of soil quality, including the number of sampling locations, is provided in existing documents such as:

- BS 10175:2001 *Investigation of potentially contaminated sites. Code of practice*
- BS ISO 15175:2004 *Soil quality. Characterization of soil related to groundwater protection*
- BS ISO 10381-1:2002 *Soil quality. Sampling. Guidance on the design of sampling programmes*
- BS ISO 10381-2:2002 *Soil quality. Sampling. Guidance on the design of sampling techniques*
- ASTM D5730-04 *Standard guide for site characterization for environmental purposes with emphasis on soil, rock, the unsaturated zone and ground water*
- ASTM D4547-06 *Standard guide for sampling waste and soils for volatile organic compounds*

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Table 6.2 ***Different exploratory and on-site analytical techniques for investigating VOCs in soils***

Technique	Nature of installation	Brief description	Method of sampling	Methods of analysis	Advantages	Disadvantages	When to use
Hand auger	Temporary	A hand-held auger with extendable sections is manually driven into the ground and small diameter cores are withdrawn	Collection of soil samples into a container	■ qualitative (odours, visual inspection) ■ semi-quantitative (eg PID, see Section 6.2.1) ■ quantitative (laboratory analysis of soils)	■ simple operation ■ allows visual inspection of soil.	■ can be physically difficult ■ can be time consuming ■ cannot penetrate difficult ground ■ limited depth and sample size.	Useful for delineating relatively shallow impact by VOCs in soils. Sole reliance on hand augers is not recommended
Trial pits	Temporary	Mechanical excavator used to create a trench/pit	Collection of soil samples into a container	As for hand auger	■ quick and easy technique with up to 10 or more trial pits excavated per day ■ generally deeper than hand driven tools ■ alows visual inspection of soil and strata ■ can be used as part of overall ground investigation.	■ maximum depth limited by ground stability and reach of excavator ■ causes ground disturbance that could cause difficulties on operating sites ■ potential access difficulties for tracked excavator ■ may cause hazard to public health and danger to persons on site as may bring contaminated material to surface ■ disturbances of ground and backfilling can affect results of future investigation in the vicinity.	Useful for delineating impact by VOCs to soils to a depth of around 3 m – 4 m below grade, where site coverage and visual inspection of soil strata and contamination distribution is desired
Boreholes	Temporary	Use of a variety of techniques to form a hole. For example, rotary (flushed with water), percussive, track mounted window samples	Collection of soil samples into a container	As for hand auger	■ greater depths achievable ■ minimises ground disturbance ■ can be used as part of overall ground investigation ■ allows visual of soil strata.	■ may have access problems (certain rigs) ■ brings contamination to the surface ■ use of flush techniques can result in migration/change in contamination distribution ■ more costly and often slower than other soil investigation techniques.	Useful where investigation of multiple source media (for example soil and groundwater) is required, and where impact by VOCs extends to depth. Minimal ground disturbance, so can be more useful for operating sites than trial pits
In situ probing	Temporary	Probe is advanced into the ground and real time data is fed through cables to an electronic receiver	*In situ* testing of soils	Generally semi-quantitative (eg LIF, see Section 6.2.1)	■ real time data collection, with up to 10 or more locations investigated per day ■ can collect data on a millimeter scale if needed ■ minimises ground disturbance ■ can be used as part of overall ground investigation ■ greater depths achievable than trial pits.	■ typically needs validating with additional techniques (for example, boreholes) ■ requires expertise to interpret the data ■ probes can be sensitive so need careful handling ■ careful selection of probe.	Useful where detailed delineation required, data can be interpreted easily within a GIS allowing lateral and vertical contamination distribution to be visualised

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The type of investigation technique used at a site will depend on several factors as discussed in Chapter 5.

There has been considerable debate within existing guidance as to the value of collecting and analysing soil samples for VOCs to assess the vapour intrusion/emission pathways. This stems in part from the absence of clear data showing a link between predicted and measured concentrations of certain VOCs in soil gas originating from a soil source. Before collecting soil samples for quantitative analysis, the assessor should refer to Chapter 5 and Appendix A2, and note which VOCs are likely to be present.

Ideally, to reduce uncertainty associated with the use of soil quality data in the vapour intrusion/emission pathway assessment, a multiple lines of evidence approach (including the sampling and analysis of different media such as groundwater or soil gas) would be applied.

A comparison of the relative advantages and disadvantages of collecting soil quality data over other investigation techniques is also provided in Table 6.1.

6.2.1 Site-based analytical techniques

One of the benefits of sampling soils is that there are several analytical techniques that can be adopted to assess the distribution and level of contamination. In many cases, laboratory analysis of the soils for VOCs is desired, but this can be costly and add significant timescales to a project. Site-based qualitative and semi-quantitative analytical techniques as shown in Table 6.2, and discussed in more detail here, can be useful for field screening which soil samples (within either the unsaturated or saturated zone) are likely to have VOC contamination. This will give a guide to selection of samples for further analysis. Guidance for the use of on-site testing methods is given by the American Society for Testing of Materials (ASTM, 2003).

Note that it is not always the samples with the highest measured concentrations of VOCs that have the greatest potential to represent a risk. This is because the soil type and sample depth/location also need consideration, as these are important in the partitioning and forms of attenuation affecting VOCs as they migrate through the unsaturated zone.

Types of on-site testing and probing commonly used include:

- site observations (eg evidence of staining or olfactory evidence)
- hand-held instruments (eg a photo-ionization device (PID) or flame ionization detector (FID))
  - often used to screen soil samples to assess the need to undertake further quantitative analysis. A relatively quick, easy and cheap method for screening soils
- driven *in situ* probing tool (eg a laser-induced fluorescence (LIF) probe)
  - real time data are collected while the probe is advanced through the ground from several locations, often used to inform the design and location of more targeted investigation and sampling points, such as drilling of a borehole
- portable gas chromatograph (with a range of different possible detectors)

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- semi-quantitative analysis of soil samples for the presence of VOCs, often used during remediation or construction works, to aid site-based decision making.

Soil screening techniques helps to support laboratory analyses, but should not replace them. The hand-held instruments are commonly used tools for identifying the presence and relative level of contamination in the subsurface, in particular in soils. Example 6.1 highlights how a hand-held instrument may be used.

Example 6.1 ***Use of a hand-held instrument (PID)***

Several discrete samples are taken from a borehole core, each of which is screened using a PID for the presence of volatile aromatic hydrocarbons (10.6 eV UV bulb) to create a profile of volatile aromatic hydrocarbons throughout the borehole core.

1 The core is removed from the borehole and logged based on soil type.
2 A small section of the core is removed, and the depth from which it originated noted.
3 The sample is split into two, and each half of the sample is placed into a separate sample container.
4 The first sample container (often a bag) is partly filled and sealed to include a small headspace (air pocket) overlying the sample, and broken up gently within the container (for example, by shaking).
5 The second sample container is sealed with minimal headspace present, and placed into a coolbox.
6 An appropriate bulb is fitted to the PID (depending on the VOCs likely to be present), and the PID is calibrated.
7 After around 15 minutes, a small hole is made in the top of the first sample container, and a reading of the headspace taken by inserting the PID tube through the hole.
8 The method is repeated for several samples at different depths from the soil core.
9 Several of the second sample containers are sent for laboratory analysis, depending on the results of the PID screening, site observations (where appropriate) and the data collection objectives.

Note: the steps provided in this example are only an illustration.

Before using a site-based analytical technique, the assessor should note whether the technique is appropriate, or has a low enough level of detection, to identify the presence of the VOCs of concern.

6.2.2 Common problems with soil sampling

Table 6.3 presents some of the common problems and difficulties with sampling and analysing soils for VOCs.

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Table 6.3 ***Common problems and difficulties with sampling soils for VOCs***

Common problem	Description	Possible solutions
No correlation between field screen and laboratory result	Results returned from the laboratory do not agree with those obtained during field screening	■ soils should be split with sample for possible analysis placed in a zero headspace jar before PID/FID or GC screening in the field on the first source ■ use of appropriate eV bulb in hand-held detector ■ soil sent to the laboratory and the soil screened with the PID/FID or GC need to come from the same stratigraphic horizon, this may require a larger diameter borehole to provide adequate sample ■ field screening method should be standardised ■ gently shaking/breaking soil sample used for on-site screening to aid release of volatiles ■ minimising the effect of ambient temperature variations by undertaking soil screening within a building if practicable ■ ensuring moisture does not enter on-site screening tool (especially sensitive for PID screening) ■ consider whether contaminants encountered in laboratory analysis would be detected using the adopted field screening methodology.
Loss before analysis	Loss/decay of VOCs in the soil sample before analysis. The degree to which this occurs depends on the type of compound(s) being tested for and the soil type	■ storage of soil samples with minimal headspace in a glass container ■ sealing of soil in sample container as quickly as possible ■ use of different sample for on-site headspace screening than that sent for laboratory analysis ■ cool storage temperature after sampling (typically less than 4°C) ■ transport to point of analysis as quickly as possible.
Cross-contamination	Factors such as poor decontamination procedures during the investigation, volatilisation and breakage in transport can result in cross-contamination occurring	■ trip blanks ■ sample equipment decontamination ■ samples packed and stored, typically at 4°C.
High variability/ unexpected results	Because of the nature of VOCs the degree of variability in sample concentrations may be greater than that expected in a soil of heterogeneous composition. VOCs tend to partition into organic rich horizons in soils or may collect on top of and in the upper horizons of less permeable strata or may be present in a smear zone at the top of the groundwater table. Variability can also be caused by inconsistent sampling and analysis.	■ ensure consistency where possible during, and between, sampling events. Use of well-documented appropriate QA/QC techniques, duplicate sampling is recommended at 10–15 per cent of total ■ collection of sufficient soil samples to demonstrate the level of variability present due to natural heterogeneity within soils ■ confirmation that the data are being interpreted correctly (eg ppm does not equate to ppmV). For an online conversion of mg/m³ to ppmV, see: <www.epa.gov/athens/learn2model/part-two/onsite/ia_unit_conversion_detail.htm>.

6.3 INVESTIGATING VOCS IN GROUNDWATER

As with soils, data regarding contamination by VOCs in groundwater can be collected using several exploratory techniques, the most common are outlined in Table 6.4. Alternatively, quantitative data (groundwater samples analysed within a laboratory setting) can be obtained from monitoring wells, typically installed in boreholes. Throughout this section, reference should be made to the following for further guidance and advice on undertaking groundwater investigations:

- BS EN ISO 5667-1:2006, BS 6068-6.1: 2006 (and related series) *Water quality. Sampling. Guidance on the design of sampling programmes and sampling techniques*
- BS 10175:2001 *Investigation of potentially contaminated sites. Code of practice*
- BS 5930:1999 *Code of practice for site investigations.*

Table 6.4 ***Different exploratory techniques for investigating VOCs in groundwater***

Technique	Nature of installation	Brief description	Method of sampling	Methods of analysis	Advantages	Disadvantages	When to use
Monitoring wells (typically within boreholes)	Semi-permanent or permanent	Use of a variety of techniques to form a hole, monitoring well is then installed within the hole	■ bailers or other manual device ■ low-flow tubing (pumped) ■ passive diffusion bags	■ qualitative (odours, visual inspection) ■ semi-quantitative (PID) ■ quantitative laboratory analysis of groundwater.	■ similar to those for boreholes (soils) ■ allows multiple samples to be collected if needed ■ allows groundwater elevations to be determined ■ can be used as part of overall ground investigation.	■ similar to those for boreholes (soils) ■ limited by screening of monitoring well.	■ useful where investigation of multiple source media is required, where VOCs are present in groundwater.
In situ probing	Temporary	Probe is advanced into the ground and real time data is fed through cables to an electronic receiver	*In situ* testing of groundwater	Generally semi-quantitative (MIP, LIF, mobile laboratory	■ real time data collection, with up to 10 or more locations investigated per day ■ can collect data on a millimeter scale if needed ■ minimises ground disturbance ■ can be used as part of overall ground investigation.	■ typically needs validating with further techniques (for example, boreholes) ■ requires expertise to interpret the data ■ probes can be sensitive so need careful handling ■ careful selection of probe for compounds present.	Useful where detailed delineation required, data can be interpreted easily within a GIS allowing lateral and vertical contaminant distribution to be visualised

Groundwater samples collected external to a groundwater monitoring well (for example, from a trial pit excavation) may provide an indication as to the presence of contamination by VOCs, but should not be relied upon for assessing the potential risk to human health.

6.3.1 Design of groundwater monitoring well

The design of the groundwater monitoring well is particularly important when investigating the presence of VOCs in groundwater (BS EN ISO 5667-1:2006/BS 6068-6.1:2006 and related series, and Lapham *et al*, 1997). Factors that affect the design of the monitoring wells include the following:

- lateral and vertical extent of impact
- the type of VOC present, and whether NAPLs are expected (see Section 6.7)
- hydrogeological regime (such as the groundwater level and groundwater flow direction)
- changes to geology (such as consolidated or unconsolidated sands, chalk, or hard rock).

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Monitoring wells are commonly constructed of uPVC or HDPE. HDPE is the preferred material as it is more resistant to attack by aggressive chemicals commonly encountered on contaminated sites. Other highly resistant materials such as stainless steel may also be used if severe contamination by aggressive organic chemicals is known to be a potential issue on site. Threaded joins between pipe sections should be used in place of glue joins. When undertaking an investigation into the possibility of vapour intrusion or emission the perforated section of the monitoring well should be screened so that it intersects the water table. This allows the concentration of the VOCs close to the surface of the water table to be measured, representing the surface from which volatilisation is conceptualised as occurring. The design of the monitoring well should also account for the possibility of fluctuations in the groundwater level with time (Lapham *et al*, 1997).

6.3.2 Groundwater sampling methods

Once the groundwater monitoring well has been prepared for sampling (for example, monitoring well development) there are several different methods for collecting groundwater samples from a groundwater monitoring well, each of which have advantages and disadvantages. The methods include:

- sampling with bailers
- pumped sampling (low flow rate)
- passive diffusion sampling.

A description of each sampling technique is provided in existing guidance, such as in British Standards series and ITRC (2007). A single dataset for groundwater quality provides an indication as to the level of contamination, and distribution of contamination, but extra monitoring visits are usually warranted to assess any trends in the observed concentrations and distribution of VOCs with time (for example, variation in groundwater flow direction, recharge events, or tidal influences).

Some of the advantages and disadvantages for using each sampling technique for dissolved phase VOCs are provided in Table 6.5.

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Table 6.5 *Advantages and disadvantages of different groundwater sampling techniques*

Technique	Advantages	Disadvantages
Bailers or other manual equipment (eg tubing and foot valve)	■ relatively cheap ■ easy to use	■ difficult to determine point in water column being sampled ■ need to use dedicated equipment to avoid cross-contamination ■ can result in aeration/ degassing and turbulence during sampling.
Pumped sampling (low flow rate)	■ can target a set horizon ■ minimal disturbance to water column ■ relatively easy to monitor hydrogeochemical data for water in aquifer	■ experience needed to operate equipment ■ longer time to undertake monitoring than bailers.
Passive diffusion sampling (use of a semi-permeable membrane left in the groundwater column to allow equilibrium between VOCs in the groundwater and sampler container to be reached)	■ limited disturbance to water column ■ limited generation of waste water	■ timescales (typically up to one to two weeks) ■ sampling limited to close to well screening, as does not draw new water into well ■ a less familiar tool.

6.3.3 Common problems with groundwater sampling

Table 6.6 presents some of the common problems and difficulties with sampling and analysing groundwater for VOCs.

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Table 6.6 ***Common problems and difficulties with sampling groundwater for VOCs***

Common problem	Description	Possible solutions
Poor monitoring well design	There are several potential problems with installing an appropriately designed monitoring well (see BS 10175:2001 and BS 5930:1999). Problems include installation of the perforated section of the well so the contamination cannot be sampled, installation across more than one water body, and not using an appropriate filter pack	■ use of *in situ* probing techniques to identify location of contamination and water bodies ■ development of robust CSM before investigation ■ allowing room for filter pack to be installed between the borehole side and monitoring well.
Monitoring well dries out	A monitoring well may dry out for several reasons, such as a drop in groundwater elevation, silting up within the well or due to over-purging in a low permeability aquifer. The effect can be temporary, semi-temporary or permanent	■ good quality well installation, to avoid silting up ■ install well to take into account potential for groundwater level changes ■ use of appropriate purging technique.
Cross-contamination	Cross-contamination between sampling locations can occur, giving erroneous results	■ good house-keeping, including use of dedicated sampling equipment where appropriate (eg dedicated bailers)
Sediment within the groundwater sample	Groundwater samples taken from a monitoring well contain fine sediments, which can affect the laboratory analysis, misrepresenting the true dissolved phase concentration of VOCs	■ development of the monitoring well at least one day before samples are taken from the monitoring well ■ use of a sampling technique which minimises sediment entrainment (such as low flow sampling or passive diffusion sampler) ■ use of low disturbance purging technique before sampling ■ use of a monitoring well sock during installation.
Large volume of waste water	The well purging and sampling technique can result in a large quantity of waste water generated which requires disposal	■ use of purging technique which minimises waste water production (monitoring hydrochemical parameters instead of removing a fixed volume of water) ■ use of passive diffusion samplers.
Loss before analysis	Loss/decay of VOCs in the groundwater sample before analysis. The degree to which this occurs depends on the type of compound(s) being tested for	■ storage of groundwater in appropriate container without headspace ■ sealing of groundwater in sample container as quickly as possible ■ cool storage temperature after sampling (typically less than 4 °C) ■ transport to point of analysis as quickly as possible.

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6.4 INVESTIGATING VOCS IN SOIL GAS

The investigation of soil gas quality is an acknowledged and tested methodology for providing the assessor with further data to conceptualise the vapour intrusion and emission pathways (for example, ITRC, 2007, ASTM, 2008, Davis *et al*, 2004, API, 2005, EPRI, 2005 and Geoprobe Systems, 2006). Benefits to collecting soil gas quality data include:

- measuring concentrations of VOCs in soil gas can help reduce uncertainty in modelling the vapour intrusion/emission pathways, by removing the need to consider partitioning or volatilisation
- specific horizons can be targeted
- the data can be used as part of a multiple lines of evidence approach
- the potential to assess cross-boundary migration of VOCs in soil gas
- investigating the potential for reduction in VOCs by biodegradation and for biodegradation products of VOCs in soil gas.

General guidance on designing an investigation that includes soil gas measurement is presented in BS 10175:2001. A comparison of the relative advantages and disadvantages of collecting soil gas quality data over other investigation techniques is given in Table 6.1.

There are several different investigation, sampling and analysis techniques for collection of soil gas quality data. A range of commonly used techniques are summarised in Table 6.7. The table is split into two parts, highlighting the investigation and sampling techniques that are active and those that are passive. Several advantages and disadvantages of each technique are included in the table. Further details on each technique are provided in Appendix A7. It is noted that some of the techniques do not allow the local geology to be determined, and this should be acknowledged during the design of the investigation.

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Table 6.7

Technique	Nature of installation	Brief description	Methods of sampling and analysis*	Advantages	Disadvantages	When to use
Active sampling techniques						
Shallow/driven probe (hollow rod)	Temporary or semi-permanent	Use of a hollow metal spike to drive into the ground. A seal is formed between the surface and the spike. A soil gas sample is collected from the rod while still in the ground	■ semi-quantitative screening tool (such as a PID meter) used to collect and analyse sample from rod ■ pump used to retrieve sample collected within soil gas container or on sorbent material, followed by laboratory analysis.	■ relatively quick ■ does not leave material in the ground (rod is removed on completion of sampling)	■ difficult to drive into consolidated/ coarse grained soils, can result in smearing in clay-rich soils ■ not as easy to target specific horizon as for other methods ■ potential for false-negatives ■ potential for atmospheric/cross-flow influences.	Useful where single point measurements are required. Usually in conjunction with or followed by further investigation techniques, but not a technique recommended where other techniques could be used in its place
Driven buried soil gas monitoring tube/pipe	Semi-permanent or permanent	Narrow diameter tube/pipe driven into ground (hand-driven, drills, drilling rig), with specialist implant probe or targeted screening installed	■ semi-quantitative screening tool (such as a PID meter) used to collect and analyse sample from rod ■ pump used to retrieve sample collected within soil gas container or on sorbent material, followed by laboratory analysis.	■ allows multiple sampling events if needed ■ targeted sampling of a particular horizon relatively easy.	■ equipment tends to be more costly than for other sampling techniques ■ usually requires knowledge of distribution of impacts to install at appropriate depth, possible smearing in clays.	Used where multiple visits are likely to be required, where a specific horizon needs to be targeted (using implant probe) and/or where “nested” sampling points are needed
Buried soil gas monitoring tube/pipe (sub-slab)	Semi-permanent or permanent	Drill used to create narrow void through slab, narrow diameter tube/pipe with specialist implant probe or targeted screening inserted into void	■ pump used to retrieve sample collected within soil gas container or on sorbent material, followed by laboratory analysis.	■ targeted sampling directly beneath a slab ■ allows multiple sampling events if needed.	■ can only be used where slab is present ■ can be disruptive, requiring drilling through a slab (for example, inside a building).	Typically used for sub-slab sampling
In situ probing	Temporary	Probe is advanced into the ground and real time analytical data is fed through cables to sensor	*In situ* testing of soil gas	■ relatively quick with minimal ground disturbance.	■ still an emerging technology, not in common use.	Delineation of presence and level of contamination at several locations, potentially where preferential pathways are present
Soil gas monitoring well	Semi-permanent or permanent	Use of a variety of techniques to form a hole (see soil investigation techniques). Standpipe installed into hole with gas tap fitted to allow sample collection	■ pump used to retrieve sample collected within soil gas container or on sorbent material, followed by laboratory analysis.	■ can be used as part of overall ground investigation ■ allows multiple sampling events if needed.	■ design of monitoring wells can mean limited benefit for other uses (such as landfill gas measurement) ■ purging of gas from the well before sampling often required.	Most useful as part of overall ground investigation (for example, designed to sample groundwater and soil gas just above groundwater
Passive sampling techniques						
Driven rod/ borehole	Temporary or permanent	Typically a rod is driven into the ground or a narrow diameter borehole is drilled leaving a void	■ burial of sorbent material into ground, removal and analysis by laboratory (typically semi-quantitative).	■ time-integrated so reduces uncertainty with temporal effects.	■ limited documentation assessing its suitability and validation, so typically only semi-quantitative output.	Most useful where active sampling techniques are not appropriate, potentially useful for delineation purposes

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6.4.1 Active and passive sampling of soil gas

Active sampling techniques withdraw soil gas from the horizon under assessment, typically using some form of pump. A known volume of soil gas is drawn through sample tubing (where possible not through the pump) and via gas-tight valves and fittings into the sample container. The sample can be sent for laboratory analytical testing, providing measured concentrations of a compound, or compounds, within the soil gas (typically presented in the form of parts per million or converted to $mg_{compound}m^{-3}_{air}$).

Passive sampling for soil gas quality data usually takes the form of burial of a sorbent within the subsurface for a period of time – a soil gas sample is not actively removed from the unsaturated zone. This helps to reduce variability introduced by temporal factors (time-integrated). However, the concentration of a compound within soil gas cannot be easily quantified, as the volume of air associated with the sample is estimated from uptake rates (compound, sorbent and time specific).

Active sampling techniques are often the preferred approach for collecting soil gas data for laboratory analysis for use in a risk assessment, as it is easier to quantify the concentration of VOCs in the sample. However, where active sampling is undertaken, in conjunction with a sorbent media, a well-calibrated pump is critical to ensuring appropriate fully quantitative analysis of the data. Example 6.2 highlights how an active sample may be collected in the unsaturated zone.

Example 6.2 ***Collection of a soil gas sample using a sorbent tube and pump***

1. A narrow diameter (buried) soil gas monitoring well is installed to the desired sampling depth (see Case study 6.1 for an example of well installation). This is achieved through the drilling of a narrow diameter borehole (125 mm to 25 mm in relatively cohesive soils), lowering the monitoring installation into the borehole, insertion of a sand pack around the monitoring point and backfilling using an appropriate sealant.
2. The monitoring well is sealed appropriately at the surface to minimise the potential for leakage, and tested (see Section 6.4.7).
3. The monitoring well is left for a minimum period of 24 to 48 hours.
4. Before, and while undertaking samples, the ambient conditions (such as temperature, rainfall, wind and pressure) are recorded.
5. The monitoring well is purged by removal of three line volumes. The sampling equipment is also tested for leakage before collecting the sample.
6. The pump is calibrated before sample collection. The sampling period is defined (see Section 6.4.4).
7. The seals are removed from the laboratory-prepared sorbent tubes immediately before use. The sorbent tubes are connected to the sampling pump using inert tubing. When duplicate samples are required two sorbent tubes are connected in parallel to the pump using a y-connector (see Figure A7.3).
8. The calibrated pump is turned on and the soil gas is passed through the sorbent tubes for the sampling period.
9. The sorbent tubes are removed, the seals replaced and the samples are prepared appropriately for storage (target temperature below 4°C for certain sorbent tubes) and transport off site.
10. On completion of sampling, the pump rate is re-measured, using a flow meter, to confirm the total volume of air pumped through the sorbent tubes during the sampling period.
11. The sorbent tubes are sent to the laboratory for analysis. Records are kept relating to the sample period and pump rate to allow the analysis results to be quantified and interpreted.

Note: the steps provided in this example are only an illustration.

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6.4.2 Variability in the presence and extent of contamination in soil gas

Consideration should be given to whether VOCs in soil gas are likely to be in, or close to, steady-state conditions when selecting the sampling technique and location. Does the assessor have a reasonable degree of confidence that measured concentrations will not increase significantly in the future? Factors affecting the presence and migration of VOCs in soil gas were discussed in detail in Chapter 2 and can be significant, in particular when considering potential future risk following remediation/construction or after development where the ground conditions are altered. The degree of variability will depend on several factors, such as:

1 How close the sample was to the source zone?

2 How long the source has been present in the ground?

3 What type of VOC is present in soil gas?

4 Is degradation likely to be occurring?

5 Could the composition of the VOC change along the migration route?

6 What are the physical/chemical influences on the behaviour of the VOCs?

7 What is the soil type?

8 Are there preferential pathways present?

Specific techniques to assess whether near-steady conditions are likely to be present are discussed in API (2005) based on work undertaken by Johnson *et al* (1999) and API (1998). The API (2005) provided a guide to estimating the time for different contaminants in soil gas to reach near-steady state conditions. The following discussion and equation was provided by the API.

$$T_{ss} \approx > \frac{R_v \theta_v L^2}{D_v^{eff}}$$

where T_{ss} is the time in (seconds), R_v (dimensionless) is the vapour-phase retardation factor, θ_v is the air-filled porosity (dimensionless), L is the distance from the source to ground surface (cm) and D_v^{eff} is the effective diffusion coefficient (typically between 0.01 to 0.001 cm^2s^{-1}). While gases such as oxygen are reported to have an Rv of close to unity, typical VOCs have an Rv in the order of 10 to 100. The API reported that use of this equation suggests that the time for a shallow source (<1 m depth) to reach near-steady state conditions is typically of the order of hours to days, while for deeper sources the time can be significantly longer. It was noted that if significant biodegradation were occurring, the time taken would likely be considerably shorter due to the effectively reduced path length. These factors can all help the assessor in designing the investigation and deciding how to interpret the data collected.

6.4.3 Purging before sampling

Existing guidance (for example, ITRC, 2007) recommends that before sampling for VOCs from a semi-permanent or permanent soil gas monitoring installation, potentially stagnant air within the monitoring tube should be purged. ITRC recommends three to four system purge volumes, provided the purge volume is not large. However, this depends on site-specific factors, such as the soil permeability (see Case study 6.1). For large purge volumes, it is recommended that the assessor monitors the changing concentration in soil gas with volume

purged (for example, using a mobile laboratory or hand-held monitoring detector). The potential disturbance on equilibrium conditions (if present) by purging, and where purging is or is not appropriate is still a subject requiring further research.

Case study 6.1 ***Difficulties with purging soil gas in low permeability soils***

Active light commercial use site, England

Soil gas sampling wells had been installed to a depth of 5 m below ground surface, with a perforated section of tubing about 0.5 m in length. The borehole diameter was 0.1 m. The soil had reasonably high clay content (see Figure 6.1).

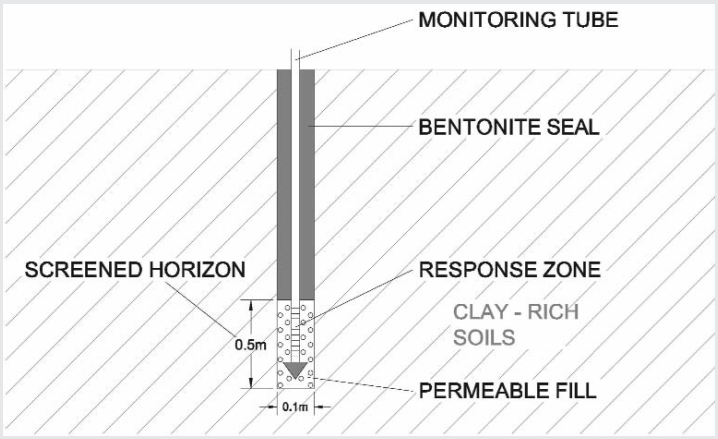

Figure 6.1 *Soil gas monitoring point installation details*

A mechanical pump was used to purge the monitoring well at an initial rate of 50 mLs^{-1}. The pump switched off after around one minute. The rate was reduced to 20 mLs^{-1}, and the pump had sufficient air to continue running for longer, but still for less than five minutes. A back-of-the-envelope calculation indicated that the pump had effectively pumped all the air from the base of the sampling tube, due to the low permeability of the surrounding soils, in under five minutes.

Volume of tube allowing soil gas to permeate:	π . (0.05 m)². 0.5 m = 0.004 m³ air
Volume of gas in L:	0.004 m³ . 1000 = 4 L (4000 mL)
Time to pump 4L from the base of the well:	4000 mL/50 mL/sec = 80 seconds
Time in minutes:	80 seconds/60 = ~1 minute

The results of purging the system indicated that it was not possible to achieve a low enough flow rate with the pump to allow continuous recharge of soil gas into the monitoring tube.

6.4.4 Sample volume, flow rate and timescales

The sample volume, flow rate (active sampling) and time for sample collection depend on several factors, such as:

- the concentration of VOCs likely to be present in the soil gas
- the preferred laboratory detection limit to allow assessment of the data
- the permeability of the soils in the unsaturated zone
- volatility of compounds
- how the data will be interpreted (eg to represent a typical working day)
- the sampling method used (active or passive sampling)
- the nature and volume of the sample container.

Further guidance is provided in existing documents such as ITRC (2007) on how to select appropriate sample volumes, flow rates and sampling timescales.

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6.4.5 Sampling for other gases

When sampling soil gas for VOCs, it is sometimes advisable to analyse for other gases concurrently. This is especially the case for gases that represent potential degradation products of VOCs, such as carbon dioxide. For example, the presence of elevated concentrations of carbon dioxide but lower concentrations of oxygen within the soil profile can indicate that aerobic microbial degradation of non-halogenated hydrocarbons is occurring. Building up a profile of these extra gases with depth can demonstrate how effective certain attenuation mechanisms are in reducing the concentration of VOCs between the source and ground surface. Sampling for such gases can in many cases be undertaken using a hand-held detector, such as a landfill gas analyser.

6.4.6 Common problems with soil gas sampling

Table 6.8 presents some of the common problems and difficulties with soil gas sampling, adapted in part from API (2005).

Table 6.8 ***Common problems and difficulties with sampling soil gas for VOCs***

Common problem	Description	Possible solutions
Dilution of soil gas samples through entrainment of atmospheric (ambient) air (short-circuiting)	Entrainment of ambient air into the sample typically occurs because of poor installation of soil gas sampling points, difficulties with installing a sampling point due to site conditions or cracks in surface cover (or absence of cover). This is often because the tube/pipe or rod is not sealed properly in the ground	See Section 6.4.7 – leak tests, locations (1) and (2) on Figure 6.2
Leakage between above-ground sampling equipment and atmospheric (ambient) air	Leakage of soil gas out of the sampling equipment into the atmosphere (or vice versa). This typically occurs due to faulty or poorly fitted connections	See Section 6.4.7 – leak tests, location (3) on Figure 6.2
Short-circuiting due to utility lines or other conduits	Soil gas can be drawn from the utility line or other conduit if care is not given to the location of the soil gas sampling point	Consider the presence of underground features which could influence the sampling of soil gas
Cross-contamination	Concentrations of compounds are present in the sample that are unexpected, or at concentrations that appear higher (or lower) than expected. If leakage effects have been discounted, other sources may be contributing. These are numerous but can include inappropriate storage of sample containers where background sources are present, sample containers reuse of equipment without decontamination, cross-contamination from pump	■ use of QA/QC techniques (such as trip blanks and duplicates) during sampling ■ when using sorbent material within a tube, connecting the tube in front of the pump to avoid cross-contamination from the pump ■ sample equipment decontamination
High laboratory detection limits	The method used to collect the sample, especially when using an active (pumped) system relies on a good degree of user experience in the system set-up before sampling and an understanding of how the data will be interpreted by the laboratory	■ select appropriate sampling volumes and flow rates when using a sorbent tube ■ use of well-calibrated pumps to ensure sample volumes are known ■ liaison with the laboratory before sampling
Loss during transport	Loss/decay of contaminants in the soil gas sample container before analysis. This depends on the type of compound(s) being tested for	■ appropriate storage of the container and quick transport to the laboratory. ■ on-site testing if feasible and appropriate
High variability in results	As for any investigation and sampling technique, a degree of variability in the results is expected. However, high variability may be due to variable field techniques during different visits to a site, such as changing the purge volume, use of a different laboratory to undertake the analysis or incorrect equipment set up	■ ensure consistency where possible between sampling events, including the purge volume (Lahvis, 2002) and use of well-documented appropriate QA/QC techniques

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6.4.7 Leak tests

Tests can be undertaken, before collecting samples to assess the presence of VOCs, to investigate whether leakage is occurring within the sampling system. Figure 6.2 illustrates the most common locations where leakage can occur, introducing errors into the analysis. The highest potential for leakage to occur is for soil gas samples collected close to the ground surface, where entrainment of atmospheric (ambient) air can occur.

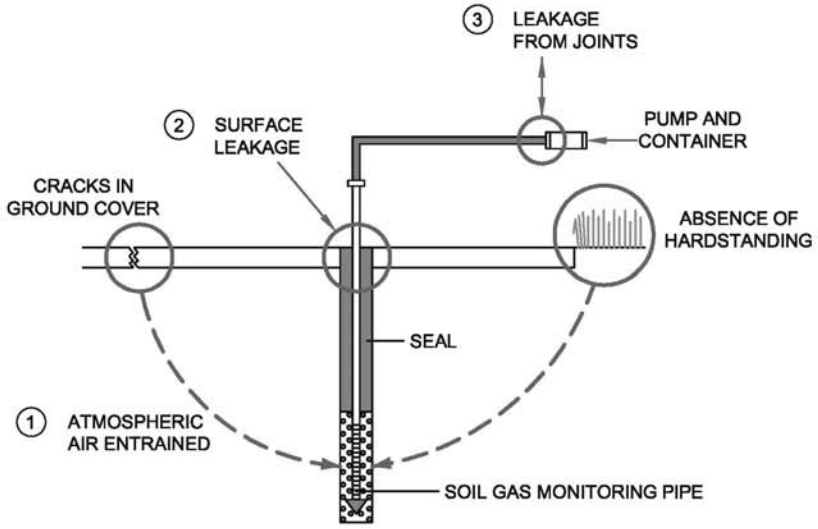

Figure 6.2 ***Potential sources of leakage when assessing soil gas quality***

1 Atmospheric (ambient) air entrainment

Ambient air can be introduced into the sample during active sampling, as shown on Figure 6.2. This is sometimes referred to as "atmospheric short-circuiting". A relatively simple method that can be used to investigate whether ambient air is entrained is the measurement of the oxygen (and carbon dioxide) content within the soil gas sample. If concentrations approach those expected in ambient air, dilution of the soil gas sample is likely to be occurring.

2 Surface leakage

Entrainment of ambient air into the soil gas sample through a poorly sealed surface-pipe connection (or leakage of soil gas through the seal) can again lead to dilution effects. Several methods have been proposed within existing guidance (such as ITRC, 2007 and API, 2005) to investigate this including:

- use of a tracer gas introduced at the surface beneath a "shroud"
- use of a liquid compound introduced at the surface.

Gaseous compounds include propane and helium, liquid compounds include isopropyl alcohol, pentane or freons (ITRC, 2007). Specific guidance on application of a tracer gas or liquid is provided within API (2005). It is noted that tracer concentrations up to 10 per cent within the sample are usually deemed acceptable within existing guidance.

3 Leakage from above-ground sampling equipment

Leakage of the soil gas sample, for example, through poorly fitted joints/ connections can affect the quality of the sample. One method for testing for

leakage is described by the API (2005) where a tracer gas (such as diluted helium at a known concentration within a Tedlar bag) is sampled, and the recovery recorded. A reduced recovery indicates that leakage is occurring. Alternatively, *in situ* pressure testing of the above ground sampling train can be undertaken

6.4.8 Number of sampling locations

The number of soil gas sampling locations is dependent on site-specific factors, such as the end use of the site and the presence of existing structures. Ideally, where structures are present at the site, soil gas investigation data relating to each structure would be collected. For large sites, or where the source is present beneath multiple structures, enough data should be collected to provide adequate spatial coverage, taking into account the potential for variability in contaminant distribution and ground conditions beneath the different structures.

6.4.9 Sampling frequency

The sampling frequency should be defined to sufficiently characterise the potential temporal variability between the source and the receptor. This could be related to natural seasonal cycles (for example, winter versus summer conditions) or anthropogenic cycles (for example, differing use of a building during the day or the night). For some sites, a single monitoring visit may be adequate, provided that the data are used as part of a multiple lines of evidence approach and are well below the assessment criteria. For example, if the data obtained through soil gas monitoring in the unsaturated zone match the expected concentrations based on the measured concentrations in the source medium (such as within groundwater), then further sampling events may not be warranted. However, for some scenarios (for example, where measured concentrations of VOCs in soil gas are close to the adopted target levels) multiple sampling events may be needed.

6.4.10 Sampling location

Soil gas samples can be collected from different parts of the unsaturated zone, and are commonly split into different investigation methods:

- sampling soil gas within the unsaturated zone
  - at depth, adjacent to or within the source zone
  - at a range of depths (or lateral offset from source) with and without cover (such as a building) present
- sampling soil gas directly under surface cover, typically under a building foundation (sub-slab)
- sampling soil gas close to, but not under, the foundation of a building (near-slab).

The different investigation methods are discussed in further detail in the following sections of this chapter, including summary tables adapted from API (2005), illustrating how the data might be used and points to note when using the investigation technique.

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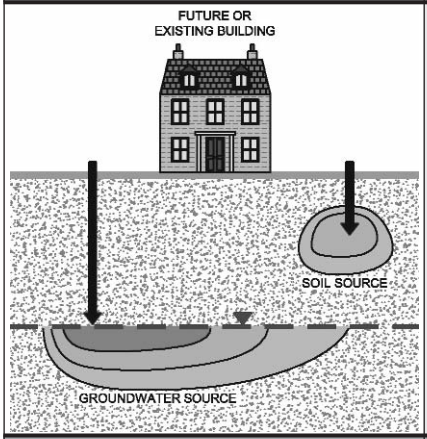
6.4.11 Sampling soil gas in the unsaturated zone

Tables 6.9 and 6.10 illustrate different sampling locations and methods (such as "nested wells") that can be used to investigate and sample soil gas from the unsaturated zone. Where nested monitoring points are installed within a single borehole, care should be taken to install a good quality seal between screened sections of each monitoring point, to avoid flow of soil gas between the targeted soil/geological horizons. Soil gas monitoring installations for VOCs are typically narrow in diameter, minimising the potential for sample integrity concerns (ITRC, 2007).

Table 6.9 ***Sampling soil gas adjacent/within the source***

Soil gas quality adjacent to/within source	Sampling location
	Soil gas samples are collected directly above the groundwater table or within soil source zone
Use of data	**Points to consider**
■ the concentrations measured should represent the highest within soil gas, as directly adjacent to source ■ the data can be used within software models in place of, or alongside, a soil or groundwater source term to provide further lines of evidence as to the level of risk from the vapour intrusion or emission pathways	■ concentrations recorded in soil gas adjacent, or within the source, should be greater than concentrations closer to the surface or within a structure if other contributory sources are not present ■ the location of sampling points, and offset between an existing structure and the source, needs careful consideration when interpreting the data ■ concentrations of VOCs adjacent to the source, unless close to the site surface, should be relatively unaffected by changing temporal or surface conditions. However, the moisture content, which can be heavily linked to rainfall, has been recorded to affect the concentration of VOCs in soil gas (eg Van Geert *et al*, 2003)

Note

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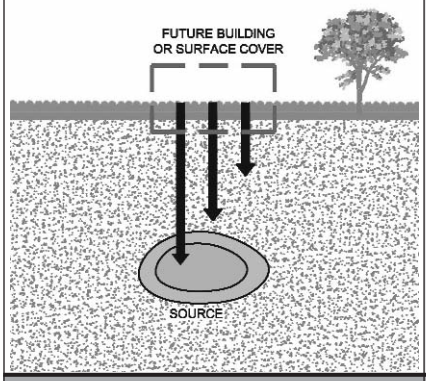
Table 6.10 *Sampling soil gas throughout the unsaturated zone*

Soil gas quality within vadose zone (ground surface uncovered) or away from structure	Sampling location
	Soil gas samples are collected from different depths within vadose zone, above and around the source, commonly referred to as a "nested" installation, either within separate holes close to, or within a single borehole. Source may be groundwater or within the unsaturated zone
Use of data	**Points to consider**
■ changes in concentrations with depth can illustrate whether attenuation is occurring as VOCs in soil gas migrate through the vadose zone.	■ future construction of a paved surface or structure has been shown to affect the migration of VOCs in soil gas through the vadose zone ■ the contaminant distribution in soil gas will vary for some sites depending on factors influencing the transport (such as climatic changes or variable groundwater levels) ■ unlikely to be a useful technique where the source is near the surface ■ the location of sampling points, and offset between a distant existing structure and the source, needs careful consideration when interpreting the data ■ the way in which different VOCs degrade in the subsurface.

Note

Arrows on the figure represent a soil gas monitoring point/probe

6.4.12 Sampling near-slab soil gas

Table 6.11 illustrates an investigation and sampling method referred to as near-slab sampling, similar to sub-slab sampling (see Section 6.4.13) and typically used where a structure is present at a site.

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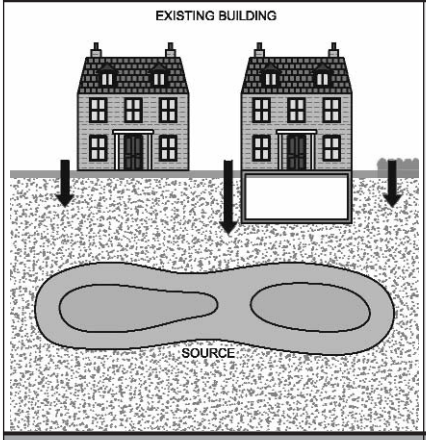
Table 6.11 *Sampling near-slab soil gas*

Soil gas quality near-foundation slab	Sampling location
	Soil gas samples are collected from adjacent to a structure foundation/basement or paved surface
Use of data	**Points to consider**
■ usually combined with air sampling in the space overlying the slab/paving to quantify the level of attenuation during transport into the air space ■ can be particularly useful where preferential pathways are present within the soils/geology between the source and structure/surface covering.	■ less disruptive than sub-foundation slab sampling ■ as for sub-foundation slab, potential for contributory sources to affect the results of the analysis as closer to the site surface ■ there is the potential for concentrations of certain VOCs (primarily the halogenated hydrocarbons) in soil gas to be higher directly beneath the structure, especially for sites where there is limited refreshment of substructure soil gas by atmosphere ■ give consideration as to whether the measured concentrations represent near-steady state conditions (see Section 6.4.2).

Note

Arrows on the figure represent a soil gas monitoring point/probe

6.4.13 Sampling sub-slab soil gas

Table 6.12 illustrates an investigation and sampling method referred to as sub-slab sampling, typically used where an above-ground structure or paved surface is present at a site. Before undertaking sub-slab soil gas sampling one important consideration is whether a risk communication plan is needed, in particular before entering occupied properties.

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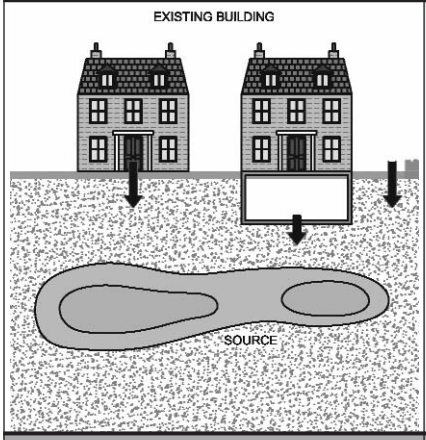
Table 6.12 ***Sampling sub-slab soil gas***

Soil gas quality sub-slab	Sampling location
	Soil gas samples are collected from directly beneath a structure foundation/basement or paved surface
Use of data	**Points to consider**
■ usually combined with air sampling in the space overlying the slab/paving to quantify the level of attenuation during transport into the air space ■ can be particularly useful where preferential pathways are present within the soils/geology between the source and structure/surface covering.	■ can be disruptive if undertaken within occupied/operational structures (such as through the need to drill through the foundation) ■ higher potential for contributory sources to affect the results of the analysis as closer to the site surface ■ potential for spatial variability beneath the building, as such a single sample location is unlikely to be sufficient ■ the contaminant distribution in sub-slab soil gas will vary for some sites depending on factors including the climatic changes and use of heating/cooling systems within a building ■ the source composition and degree of contamination (eg whether NAPL or dissolved phase is present beneath the building). For lower levels of impact, differences between near-slab and sub-slab soil gas sampling are often minimal (Abreu *et al*, 2007), although this can depend on the type of VOCs present ■ consideration needs to be given as to whether the measured concentrations represent near-steady state conditions (see Section 6.4.2) ■ the potential for migration of VOCs from background indoor air sources into the subsurface (McHugh *et al*, 2006).

Note

Arrows on the figure represent a soil gas monitoring point/probe

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6.4.14 Sampling installation

The design of the soil gas sampling installation, including the zone the soil gas is sampled across and the construction material, depends on the investigation technique, sampling location (such as sub-slab versus near-slab) and the aims of the sampling. The "response zone" (see Figure 6.1) of a sampling point refers to the length of the filter pack adjacent to the perforated length of well or pipe, which allows the soil gas in the horizon under assessment to enter the pipe. The depth of the perforated well or pipe, alongside the dimensions of the filter pack, is used to dictate the horizon from which the soil gas is collected, with a low permeability medium (typically bentonite) used to seal between the horizon being investigated and other horizons alongside the use of un-perforated well material. However, each sampling installation should be designed specifically for each site or location, paying particular attention to the local stratigraphy.

6.5 INVESTIGATING SURFACE EMISSIONS OF VOCS

The emission of VOCs in vapour form can be measured directly from a surface using a flux chamber. Flux chambers (also known as flux boxes) comprise a box that is open at the base, and is placed on the surface of the site, allowing gas that is being emitted to be collected. The rate of gas accumulation is measured by monitoring the increase in concentration of the soil gas of interest within the box at set intervals. Because the volume and the "footprint" area of the box are known, the emission rate can be calculated in mass of gas/unit area/unit time. The reporting units used are typically $mg_{gas}m^{-2}s^{-1}$.

Comprehensive guidance is provided by the EA (2004a) on measuring surface emissions using flux chambers. However, this guidance was specifically written for compliance monitoring of landfill caps with respect to methane (from a global atmosphere perspective) and so there is no explicit guidance on the use of flux chambers for investigating the emission of VOCs from alternative sites affected by land contamination. While flux boxes have been used in agricultural studies and for landfill sites for many years, and the method is well established, it is not used frequently to assess other types of land contamination sites. It is not normally considered to be a primary method of investigation for emission of VOCs, but it can provide valuable information relating to site-specific conditions that is difficult to obtain by other methods.

A comparison of the relative advantages and disadvantages of collecting surface emission data over other investigation techniques is provided in Table 6.1, adapted in part from ITRC (2007).

Table 6.13 provides several advantages and disadvantages to undertaking surface emission measurements using flux chambers, alongside typical scenarios where they might be undertaken. They are not appropriate for use on every site, in particular where future development is likely to change the vapour emission characteristics. However, flux chambers can be used to assess vapour emissions to a range of different air spaces provided they meet the data collection objectives and can be interpreted within the assessment process (see also Appendix A7).

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Table 6.13 ***Role of flux chambers***

Technique	Nature of installation	Brief description	Methods of sampling and analysis	Advantages	Disadvantages	When to use
Flux chamber	Temporary	An inverted chamber is placed on the prepared site surface and any gas collected is sampled through a valve over a recorded timescale	■ semi-quantitative (hand-held detector	■ provides an indication of soil gas emission rates	■ box can be disturbed and is difficult to seal	Typically only used in the UK to estimate emissions to an outdoor air space. Not commonly used to assess VOC emissions, except at landfill sites, as value of data is uncertain
			■ collection of sample in container and quantitative (laboratory analysis)	■ can assess many locations per day	■ variability in the soil surface, including moisture cotent causes variability in results	

6.5.1 Static and dynamic flux chambers

There are two types of flux chambers:

1 Static, or closed systems – where the gas is simply allowed to accumulate in a closed chamber.

2 Dynamic, or open systems – where controlled positive flow of clean air is passed through the chamber (eg via a portable pump or similar).

Many methodologies using static chambers end up being semi-dynamic, as the instruments used to sample and measure the gas of interest within the chamber remove air each time a measurement is taken. Sampling methodologies are similar to those employed for soil gas sampling, ranging from semi-quantitative (such as a PID or FID) or quantitative (collection within a sample container for laboratory analysis).

Some of the advantages and disadvantages of using a static chamber or a dynamic chamber are presented in Table 6.14 (adapted from Wilson *et al*, 2007 and Hartman, 2004).

Table 6.14 ***Advantages and disadvantages of static and dynamic chambers***

	Static chamber	Dynamic chamber
Advantages	■ can be left in place to monitor over a long period ■ simple to set up and use ■ can be easier to interpret results ■ very low detection limits possible ■ no use of gas swept through chamber so lower possibility of cross-contamination.	■ it is reported that dynamic chambers have less effect on the soil gas regime because there is no induced draw (as long as induced flow rate is kept very low) or restricting effect on gas emissions ■ faster equilibrium state means more readings can be obtained in one day.
Disadvantages	■ can restrict movement of gas into the chamber (probably only significant with very high flux rates) or induce increased flux rate due to withdrawal of gas from the chamber (although installing balancing valves, and avoiding small chamber sizes will minimise these effects) ■ flux variations due to temporal effects may not be observed unless sampling regularly.	■ more complex equipment, can be harder to set up and use ■ detection limits tend to be higher due to dilution effect of "clean air" ■ impractical to leave on most sites for a long period ■ measured emission rates depend on induced flow rate, and can be difficult to "balance".

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6.5.2 Duration of monitoring for measurement of surface emissions

When sampling soil gas: in deciding on the length of time to undertake measurements of surface emissions of VOCs the assessor should consider the exposure scenario in question, and the potential for temporal variability between the source and the receptor. If undertaking measurements of emissions within a building, the typical use of the building (such as an eight hour working day for a commercial building) dictates the length of time over which the monitoring of surface emissions would usually take place (Hartman, 2004 and ITRC, 2007). Similar considerations apply when sampling air quality (see Section 6.6). The Environment Agency provides further guidance on the duration of monitoring for measurement of surface emissions, which should be referred to (such as EA, 2004a).

6.5.3 Measurement frequency during monitoring

A single sample collected over a period of time provides an average value for that time period, and may be useful for semi-quantitative screening purposes. Measurements taken throughout the monitoring duration are a preferred option (Hartman, 2004), as this provides an indication of variability in emissions that would otherwise be missed.

6.5.4 Number of sampling locations

Factors to note when collecting surface emission data and also the number of sampling locations include:

- whether ground/surface cover is variable across a site
- whether the aim of the investigation is to understand points of highest gas emission or to quantify emission rates at a specific location
- the size of the site and the site use.

6.5.5 Extra exploratory techniques

For many sites where remediation or construction works are planned, it may be appropriate to undertake a semi-quantitative assessment of the potential for emission of VOCs, to indicate whether a significant risk to human health could occur. Case study 6.2 is an example of a semi-quantitative assessment of the potential for the emission of VOCs from soils (demolition rubble), used to aid the development of a site (reuse of materials on site during redevelopment, where appropriate, is being actively encouraged in the UK).

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Case study 6.2 ***Investigating the potential for vapour emission of VOCs from demolition rubble***

Former mill, north west England

A former mill in the north west of England was demolished, with around 16 000 m³ of the partially crushed material left on site, overlying made ground. The intention was to reuse the demolition material during the site development, using it to form two level development platforms on what was a sloping site. Laboratory analysis of the demolition material indicated the presence of VOCs, including benzene (maximum concentration 0.084 mg/kg) and naphthalene (maximum concentration 24.7 mg/kg). The presence and concentration of benzene and naphthalene throughout the demolition material was believed to be variable. As such the potential for emission of VOCs could not be readily assessed using predictive modelling tools, and measurements could not be undertaken *in situ* due to the potential for contribution from the underlying made ground. A semi-quantitative screening system was set up, where demolition material was placed in skips filled close to the top. The material was covered with a layer of sand then covered with plastic sheeting to act as a cap, and a second layer of sand to cover the cap and hold it in place. Active sampling of vapours emitted into the first sand layer was undertaken from a 1 m slotted pipe using sorbent tubes following a period of two weeks to allow gas concentrations to approach equilibrium.



Figure 6.3 *Testing of the demolition material in skips*

The demolition material with the highest detected concentrations of total VOCs also demonstrated the highest concentrations of VOCs in emitted vapours. The results of the testing generally indicated that concentrations of emitted VOCs were lower than in ambient air. The reuse of the material for the site development was deemed acceptable on the basis of this investigation.

6.5.6 Common problems with surface emissions measurements

Many of the common problems associated with measuring emissions of VOCs from a surface are similar to those encountered during monitoring of VOCs in soil gas, namely difficulties with use of sampling equipment (see Section 6.10). Several problems associated with measurement of surface emissions are provided in Table 6.15.

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Table 6.15 ***Common problems and difficulties with surface emission sampling for VOCs***

Common problem	Description	Possible solutions
Dilution of vapours through entrainment of atmospheric (ambient) air	Entrainment of ambient air into the sample typically occurs because of poor installation of flux chamber on the surface. This is often because the chamber is not sealed properly in the ground	Similar testing as for soil gas sampling.
Emission rate is unexpected	The rate of emission of VOCs from the surface is higher or lower than expected. This could be due to the presence of gases such as carbon dioxide or methane acting as a "carrier" gas for VOCs or, for a lower rate, because of temporary ground sealing (such as rainfall)	■ consider the potential for other gases to be present, affecting the migration of VOCs ■ consider the affect of climatic changes (such as rainfall) on the results of the monitoring.
Leakage between above-ground sampling equipment and atmospheric (ambient) air	Leakage of vapours out of the sampling equipment into atmosphere (or vice versa). This typically occurs due to faulty or poorly fitted connections	■ see solutions for testing sampling equipment in Section 6.4.7.
Cross-contamination	For dynamic chamber, a flux of "clean" air is swept into the chamber during the sampling period. The presence of VOCs in the "clean" air, for example, from background sources means the true flux of VOCs from the surface is not ascertained	■ use of a static chamber to undertake the measurements ■ use of dynamic chamber only where background sources are likely to be negligible.
High variation in results	A degree of variation in the result is expected to a degree, due to factors such as climatic change. However, high variation may be due to changing field techniques during different visits to a site, incorrect equipment set up or placing the chamber in a different location	Ensure consistency where possible between sampling events, monitor factors that could vary between events (such as climatic conditions or groundwater elevations).
Loss during transport	Loss/decay of contaminants in the vapour sample container before analysis. This depends on the type of compound(s) being tested for	Appropriate storage of the container and quick transport to the laboratory. On-site testing if feasible and appropriate.

Further information on the advantages and disadvantages of the use of flux chambers to measure emission rates, including common problems, is provided by Hartman (2004).

6.6 INVESTIGATING VOCS IN AIR

For some sites, collection of air samples and analysis for VOCs will be appropriate, whether inside a building, in an outdoor air space or within a semi-confined space, such as an open excavation. Collection of air quality data typically provides the assessor with concentrations of VOCs at the point of exposure, rather than relying on modelling to predict the concentration in the air space of concern. It is noted that one important problem with sampling VOCs in air relates to data interpretation, and whether the VOC identified is present due to ambient (background) conditions or due to migration from the subsurface. Throughout this section, reference should be made to BS EN ISO

16000 series (2006–2008) and BS EN ISO 16017 parts 1 and 2 (2001) for further guidance and advice on undertaking air sampling and monitoring investigations.

Table 6.1 gives a comparison of the relative advantages and disadvantages of collecting air quality data over other investigation techniques (adapted in part from ITRC, 2007).

As for sub-slab soil gas monitoring, one of the main considerations before undertaking air quality sampling is whether a risk communication plan is needed, in particular before monitoring air quality in occupied properties. Also, the assessor should consider whether undertaking the sampling has an associated level of risk (for example, due to the level of contamination present), and if so, what measures need to be in place before completing the work. The decision to undertake air quality monitoring, in particular in an indoor air space, should not be taken lightly, due to the potential for immediate adverse effect on the property (eg property value) and undue stress for the occupant/property owner. In some circumstances, sampling air quality off-site will also be required, adding further to the difficulties of risk communication and causing undue stress.

BS EN ISO 16000-5 provides the following exposure scenarios where sampling of air for the presence of VOCs might be undertaken:

- complaints about poor air quality
- the need to determine exposure of occupants to certain substances
- the need to measure whether specified limits are being maintained
- testing the effectiveness of remediation
- observed or suspected effects on the occupants' health.

Case study 8.3 highlights a scenario where sampling air for the presence of VOCs was undertaken during remediation works, allowing the potential risks to remediation workers and neighbouring residents to be managed appropriately.

There are several different investigation, sampling and analysis techniques for collecting air samples for VOCs assessment. The exposure scenario under consideration will influence the choice of investigation technique used at a site. It is advisable to consider how the data will be interpreted (for example, using an indoor air quality standard) before collecting the data, as this can have a significant effect on the required detection levels. A range of commonly used sampling and monitoring techniques are summarised in Table 6.16. Several advantages and disadvantages of each technique are included in the table.

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Table 6.16 ***Different exploratory techniques for investigating VOCs in air***

Technique	Nature of installation	Brief description	Methods of sampling and analysis	Advantages	Disadvantages	When to use
Active sampling (use of pump)	A pump is used to draw vapours out of the air from a set height/ location	■ air drawn into analysis device (such as a PID meter)	■ qualitative or semi-quantitative (PID, FID)	■ quick and easy	■ only semi-quantitative.	Most useful as a form of screening, combined with a quantitative investigation technique
		■ air drawn into sample container (such as a Tedlar bag or Kevlar bags) at a set rate and time frame	■ quantitative (laboratory analysis)	■ adjustable flow rate, linked to desired method detection limit ■ samples collected over a relatively short period.	■ needs relatively continuous monitoring by operator ■ higher degree of disturbance to building occupiers than passive sampling.	Can be used to sample a range of difference air spaces
		■ air is passed through a tube containing sorbent material at a set rate and time frame.	■ quantitative (laboratory analysis).			
Active sampling (use of a pressurised sampling vessel)	Air is drawn into a container, which is sent into the field under vacuum, from a set height/location	■ the container (such as a summa canister) is certified "clean" and leak-free and sent to the field under vacuum. During use, the container fills with air at a fixed flow rate	■ quantitative (laboratory analysis)	■ allows analysis of multiple compounds from same container (ITRC, 2007) ■ ease of deployment and retrieval (ITRC, 2007).	■ some containers (such as Summa canisters) typically not commonly used in the UK ■ container needs preparation before use.	Not commonly used in UK for analysis of VOCs in air, but same scenarios as for pumped samples
Passive sampling	Sorbent is placed in sample location and left for a period of time. Based on diffusion of compounds onto the sorbent	■ the passive sampler is typically suspended/ hung at the sample height/ location for a specified time period, then collected for analysis.	■ semi-quantitative/ quantitative (laboratory analysis).	■ passive sampler can be left without continuous monitoring so limited disturbance to occupiers of a building ■ can offer lower overall uncertainty than active sampling where significant temporal changes occur.	■ higher potential for background effects as sampler left unattended ■ appropriate exposure times for sampling can be difficult to determine.	Typically used in residential buildings or buildings/air space where use of a pump/ continual monitoring is undesirable

6.6.1 Short- and long-term measurements

BS EN ISO 16000-5 defines two timescales for measuring air quality, as:

- short-term measurements (less than one hour to a few hours)
- long-term measurements (usually a few days to several days or weeks).

Sampling techniques for short-term measurements, as shown in Table 6.16, are typically active (see Section 6.4.1), using a pump to draw the sample across a sorbent material or into a sample container (BS EN ISO 16000 series, 2006–2007). Short-term measurements can be useful for scenarios such as under occupational conditions (working hours) or where the measurements are undertaken to assess the source of an odour. They cannot easily be used to provide information on a long-term, averaged exposure.

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Sampling techniques for long-term measurements, also shown in Table 6.16, are typically passive (see section 6.4.1). "Diffusive samplers", which primarily work based on the principle of diffusion, are left in the air space and provide an integrated value as a mean over the selected exposure period (BS EN ISO 16000 series, 2006-2007). This sort of sampling is often used to record indoor air quality in residential homes, where the measurement period can be many days. Use of diffusive samplers is appropriate for some scenarios, although the variation in VOCs concentrations within the time measured cannot be easily determined, and may need to be understood for certain site settings (for example, if the building use changes throughout the day resulting in considerably higher concentrations during certain times). When using diffusive samplers, an adequate air flow needs to occur across the sampler (BS EN ISO 16000 series, 2006–2007). Note that it can be difficult to compare the results of diffusive flow analysis (for example, from an indoor air space) with a pumped sample (for example, collected from sub-slab).

6.6.2 Sampling duration and frequency of measurement

The sampling duration can depend on several factors such as:

- the use of the air space (ie during working hours or as a residential living space)
- the types of compounds expected and their behaviour (including toxicity)
- the technique adopted to collect the samples
- the limit of quantification of the analytical method
- the averaging time inherent within the air quality standard that the data will be compared against
- breakthrough volume, if using a sorbent tube.

For monitoring indoor air quality, the ITRC suggests that the sampling duration is directly linked to whether the building is used for residential or commercial purposes. Typically, monitoring at a commercial site is over an eight hour period (typical working day) whereas monitoring at a residential property may be over 24 hours or longer (BS EN ISO 16000 parts 5 and 6, 2007).

The frequency of measurements also depends on the use of air space and technique adopted, but is likely to be closely linked to the exposure scenario under consideration. Also, the variables that could affect the migration of soil gas into the air space, as discussed in Chapter 2 (see Crump, 2003) should be considered.

6.6.3 Use of sorbent tubes

For active (or pumped) sampling of air (indoor, ambient and workplace air), BS EN ISO 16017-1 recommends the use of sorbent tubes, rather than other sample containers, for laboratory analysis. Air is pumped through one (or more) sorbent tube, usually set up in series. There is a range of different sorbent materials (such as carbon molecular sieve, graphitized carbon or porous polymer), typically contained within a stainless steel tube. Further details on different types of sorbents and selecting an appropriate sorbent is provided in BS EN ISO 16017-1, although for indoor air sampling for VOCs, the recommended methodology is use of a Tenax™ TA sorbent tube (BS EN ISO 16000 series, 2006-2007). However, achieving a good degree of confidence in the results relies on the use of a pump (calibrated on site and tested before and

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after sampling) or a bubble flow meter (or similar equipment), capable of measuring accurate flow measurements.

Guidance on undertaking passive sampling of air using a "diffusive sampler" (indoor, ambient and workplace air), including selection of an appropriate sorbent is provided in BS EN ISO 16017-2:2000.

Where a different sampling technique is used (such as a pressurised container) existing protocols on their use (such as ASTM standards) may need to be referred to. Appropriate justification should be given as to why an alternative approach to that recommended within the relevant British Standard has been used. Further guidance on the different types of sample container is presented in CIRIA C665 (Wilson *et al*, 2007).

6.6.4 Common problems with air sampling

Table 6.17 presents some of the common difficulties associated with monitoring air for VOCs.

Table 6.17 ***Common problems and difficulties with air monitoring for VOCs***

Common problem	Description	Possible solutions
Anomalous or unexpected concentrations of VOCs in air	Measured concentrations of VOCs in the air space are considerably higher (or lower) than predicted from the existing site data. This may be because of using an inappropriate modelling tool to predict the air concentration, or because the potential for background contribution was not assessed fully	■ the potential fate and transport pathways should be reviewed against the site data, including potential preferential pathways and temporal/spatial variability ■ undertaking a pre-sampling survey and survey while sampling to identify potential background source contribution ■ the modelling tool used to predict the air quality could be revisited.
High laboratory detection limits	High laboratory detection limits can be linked to a range of factors. The most common when undertaking air quality testing may be due to uncertainties in the volumes of air sampled, resulting in difficulties in quantifying the level of contamination	■ select an appropriate sampling methodology given the compound of concern ■ assess the detection level needed before starting the investigation.
Loss during transport	Loss/decay of contaminants in the air sample container/ sorbent tube before analysis. This depends on the type of compound(s) being tested for	■ appropriate storage of the tube/ container and quick transport to the laboratory ■ on-site testing if feasible and appropriate.
High variability in results	As for any investigation and sampling technique, a degree of variability in the results is expected. However, high variability may be due to changing sampling techniques, time, use of a different laboratory to undertake the analysis or incorrect equipment set up	■ ensure consistency where possible between sampling events and use of well-documented appropriate QA/QC techniques.

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6.6.5 Sampling for VOCs in indoor air

Sampling of indoor air quality typically occurs after the subsurface conditions have been characterised, but may also occur where the exposure scenario is such that direct measurement of indoor air quality is appropriate (such as complaints of odours). When sampling for VOCs in indoor air, there is a range of different factors that need consideration, from the potential disturbance for building occupiers and whether an alternative form of measurement/modelling could be used, to technical factors such as the measurement timescales. Table 6.18 outlines several important factors the assessor should note before and during monitoring of indoor air quality for VOCs. Throughout the process reference should be given to the existing British Standards for indoor air sampling and monitoring.

Table 6.18 ***Factors to consider when undertaking indoor air monitoring***

Factor	Points to consider
Choice of sampling equipment	■ is the equipment suitable for the measurement task in terms of size, sampling rate, and noise of operation? ■ does it interfere with normal use of the room? ■ is it appropriate for the types of VOCs present? ■ is more than one VOC being targeted? ■ is using a combination of equipment appropriate? (semi-quantitative and quantitative).
Sampling location	■ has the possible heterogeneous distribution of VOCs in air been considered when choosing the sampling location? ■ how will the data be interpreted – should the sampling equipment be placed at breathing height? ■ has disruption to building occupants been minimised where possible? ■ is the building fitted with a heating, ventilation and air conditioning (HVAC) system?
Sampling timescales and volumes	■ what is the exposure scenario being assessed? ■ how is the building used? ■ will the sampling timescale affect the detection limit? ■ are peak or time averaged readings of interest? ■ the hourly sampling volume in the room should be less than 10 % of the ventilation rate (if not known, the hourly sampling volume should be less than 10 % of the room volume) ■ are the ventilation rates likely to change during the monitoring period?
Background sources	■ has an inventory been taken to identify contributory sources? (see Section 6.6.8) ■ could activities (such as painting, cleaning) take place during sampling which could influence the air quality? ■ do contributory sources need to be removed/assessed, and ventilation of the room carried out before sampling?
Risk communication	■ has a risk communication plan been developed and carried out before undertaking indoor air sampling? ■ for air quality complaints, has a systematic record of complaints been kept?

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The sampling location and number of samples collected should be based on the overall aim of the investigation, the likely (or suspected) source location and the building use and construction. It is not necessary to collect samples from every room in a building or apartment block, as long as it is appropriate to assume similar conditions in other rooms. Further guidance on the choice of sampling location is provided in BS EN ISO 16000-5. The collection of at least one outdoor air sample in parallel to the indoor air sampling is, where possible, also recommended to understand the potential interaction between the building and the outdoor air (for example BS EN ISO 16000 series, 2006–2007 and ITRC, 2007).

Depending on the scenario being assessed, the room (or rooms) may need to be prepared before monitoring takes place. This can include removing background sources (see Section 6.6.8), or sealing the room for a certain time period. Guidance within BS EN ISO 16000-5:2007 suggests a protocol, summarised in Table 6.19.

Table 6.19 ***Preparing a room before air quality monitoring***

Scenario	Considerations
Clarify the reasons for complaints from room occupants, possibly in association with checking compliance of guideline values for indoor air using short-term measurements	**Naturally ventilated rooms** ■ intensive ventilation of room for 15 minutes ■ doors and windows kept closed for around eight hours (optimally overnight), without extra sealing measures ■ sampling is performed with room still closed ■ the room can then be ventilated intensively after sampling for five minutes, the windows and doors are again shut for one hour and the sampling is repeated. This helps to illustrate the effectiveness of hourly intensive ventilation.
	Rooms with mechanical ventilation ■ where an HVAC system is in use, the system should be operated according to building codes or other normative guidelines ■ ventilation using the system for at least three hours before sampling takes place ■ monitor the function of the system during sampling (BS ISO 16000-8) ■ if complaints are related to unusual conditions, measurements should also be undertaken during these conditions ■ the measurements should be carried out under the climatic conditions usually present when the room is used.
Determination of average concentration over a relatively long time period – exposure study (such as for a building where VOCs have been identified in the subsurface)	■ room ventilation preparation does not need to be undertaken if monitoring period exceeds 24 hours (typically less than one month) ■ room occupiers should continue their usual ventilation behaviour and other activities, although these need to be documented before undertaking measurements (including intermittent sources).

The standard also provides guidance on unusual, or special conditions, for short-term use of a solvent within the building (BS EN ISO 16000 series, 2006–2007).

Where there is a vented sub-floor void (for example, beneath timber floors in a Victorian property), it may be appropriate to take measurements of air quality from this space. Similar factors to consider when undertaking indoor air monitoring will apply in this scenario, alongside the factors considered when undertaking sub-slab monitoring. This includes the potential for background sources (such as using consumer products in the house) or ambient air to influence the air quality (for example, see McHugh *et al*, 2006). The methodology adopted is likely to be site-specific, depending on the nature of the foundation construction, the size of the vented air space and the objectives of the data collection. The following methods are likely to be appropriate given the type of suspended-floor construction present (see Figure 2.5):

- **lower permeability foundation construction (eg concrete slab cast *in situ*):** sample the vented void using a similar methodology as for sub-slab sampling
- **higher permeability foundation construction (eg timber with vented void):** sample using a similar methodology as for an indoor/outdoor air space.

Further suggestions of points to consider for more unusual air quality sampling scenarios are provided in Section 6.6.7.

6.6.6 Sampling for VOCs in outdoor air

The sampling of outdoor (ambient) air quality should be undertaken concurrently as part of an indoor air monitoring programme (see Section 6.6.5) but can also be undertaken because VOCs may be present at concentrations that could present a risk to human health due to emissions from VOCs in the subsurface. Table 6.20 outlines several important factors the assessor should consider before and during monitoring of outdoor air quality for VOCs. One factor is the local wind conditions (speed and direction), which can vary considerably and be strongly influenced by local topography. Throughout the process reference should be given to the existing British Standards for outdoor (ambient) air sampling and monitoring.

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Table 6.20 *Factors to consider when undertaking outdoor air monitoring*

Factor	Points to consider
Choice of sampling equipment	■ is the equipment suitable for the measurement task in terms of size, sampling rate, and noise (for some equipment) of operation? ■ will it be affected by climatic conditions, such as rainfall? ■ is it appropriate for the types of VOCs present? ■ is more than one VOC being targeted? ■ is use of a combination of equipment appropriate? (semi-quantitative and quantitative)
Sampling location	■ how will the data be interpreted and what height should the sampling equipment be placed at? ■ has the wind direction and speed been considered appropriately? ■ is there vegetation nearby that may affect the results?
Sampling timescales and volumes	■ what is the exposure scenario being assessed? ■ how is the air space used? ■ will the sampling times affect the detection limit? ■ are peak or time averaged readings of interest? ■ are meterological effects likely to change over the sampling period?
Background sources	■ has an inventory been taken to identify contributory sources? ■ does the sample location need adjusting to minimise the potential contribution from background sources?
Risk communication	■ is a risk communication plan required? ■ for air quality complaints, has a systematic record of complaints been kept?

The CSM should consider whether instantaneous releases of VOCs in vapour form to outdoor air are likely to occur. If so, the method for sampling and sampling location may need further consideration (see Section 6.6.7).

Further guidance on choosing sampling locations, methods and sampling times are provided within existing guidance including BS EN ISO 16017-2 (2003) and ITRC (2007). BS EN ISO 16017-2 makes particular reference to environmental factors that can affect the result of outdoor (ambient) air sampling (with the associated Annex A), including temperature and pressure, humidity, wind speed and transportation of the sample containers before and after sampling.

6.6.7 Sampling for VOCs in other air spaces

There is a range of alternative potential exposure scenarios that may not fall into the categories of indoor air or outdoor air sampling.

Emissions of VOCs into a confined or semi-confined space, such as an excavation or tunnel may require monitoring using similar techniques employed to sample outdoor air spaces. Emissions may occur from the floor, walls or ceiling of a confined or semi-confined space. The points to consider when undertaking sampling in such a space are similar to those for undertaking sampling in an indoor or outdoor air space, including:

- ❑ the safety of the assessor, and whether sampling can be undertaken without the need for entry into the confined space

- the type of data required (such as short or long-term measurements)
- the type of VOCs likely to be present
- how the data will be used and assessed.

An instantaneous release of VOCs due to ground/soil disturbance could result in a relatively short-term presence of VOCs in an air space (see Section 7.3.1, Box 7.1 for further discussion). This could occur under several scenarios, such as excavation of soils during ground works or ex situ remediation treatment of soils contaminated by VOCs. Under such scenarios, a combination of sampling techniques may be appropriate to assess the level of the release to atmosphere, such as surface emission measurements and air quality measurements. Studies have been undertaken to estimate the release of vapours over time (DeVaull, 2001) using mathematical models developed to aid prediction of the release of vapours (see Case study 9.1), but have not always proven successful (see Case study 8.3). Case study 6.3 presents a site in the UK where the potential release of VOCs from soils was specifically investigated and assessed.

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Former landfill site, Berkshire

The site was a former landfill site in Maidenhead, with contamination in the ground arising from the historical disposal of oil and solvent-based wastes, producing VOCs that were mobile in both liquid and vapour phase. There was significant concern for the potential acute and chronic toxic health effects from VOCs known to be present. The site was located within the permeable Thames Gravels overlying Chalk. The proposed remediation options to restore the site to useable land for development were considered both within an Environmental Statement and public inquiry as part of the planning process, with removal of waste from the site one viable option.

An important element of the remediation options appraisal involved the assessment of whether potential vapour emission and releases to air presented a significant risk to health. To characterise the potential releases of VOCs to atmosphere, several investigations were carried out to identify contributions of emission components from each of the principal potential release pathways. The tests included flux box testing, borehole gas analysis, and trial excavations and monitoring to identify the potential release of VOC during waste agitation and drop from the excavator to the truck. This final form of investigation included assessment of the mass transfer of VOCs once waste was removed, with air (wind) passing over or through the excavated waste surfaces. The approach informally became known as the "fluff" test.

The trial pit excavation was carried out using a mechanical digger to excavate waste, depositing it on the ground surface to identify the expected release and emission rate of VOCs during the removal of waste from the site. Two locations were selected for the trial excavation pits that would provide differing emissions characteristics based on the different type of material present. The first trial was carried out in close to a trial pit location where the highest levels of contamination had previously been identified from intrusive investigations. A second trial was also carried out where further peak contaminant levels had been identified.

A polytunnel was constructed to collect air that passed over and around the soil. The tunnel was tapered so that the cross-sectional area decreased and accelerated the airflow. Airflow and VOC concentrations were measured at the end of the tunnel. The tunnel provided a laminar (or straight) flow with greater velocity than would otherwise be achieved. By reducing directional fluctuations, uncertainty in the measured results was reduced.



Figure 6.4 *Construction and use of the polytunnel*

Airborne concentrations of VOCs were measured by two monitoring methods. The first, a time-of-flight portable MS, was calibrated before an assessment of vital components being investigated, sampling every 10 seconds. This achieved detection levels of parts per billion and provided identification of how peak concentrations varied with time during waste excavation. Monitoring over the duration of the trial excavation was also carried out by taking pumped samples of extracted air from the polytunnel and passing the extracted air through sorbent tubes. The tubes were later analysed at an accredited laboratory using GCMS. A pumped sorption tube was located about 20 m upwind of the trial pit to establish background baseline VOC concentrations that occurred during the test. The polytunnel was set up directly downwind of the proposed excavation trial pit and was fitted with the MS and a sorbent tube to measure the concentration of VOC generated. A vane anemometer determined the wind speed within the tunnel, and other considerations were taken into account, such as the slope of the ground surface.

The calculated release rate per unit volume of excavated material was incorporated into a complex dispersion model to predict how releases of VOCs, using worst-case assumptions, would then disperse in the atmosphere. To minimise the risk to public health, the trial excavation was carried out for a short time, and the width of the trial pit minimised. The wind direction during testing was also in the opposite direction to the houses closest to the pit. Air quality monitoring carried out 20 m downwind of the sampling location confirmed that no appropriate air quality standards would have been exceeded during the trial excavation.

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6.6.8 Background contribution to air quality

There are many potential background sources that can affect air quality, and the most significant should be taken into account on each site. This will determine whether VOCs detected in air (or soil gas) are derived from land contamination or an alternative source. In some cases, in particular where background contribution is likely to be high, it may be necessary to measure air quality in a comparable air space (as a "control") away from the influence of vapour intrusion or emission from a subsurface source. A good example of this is shown in Case study A8.3 where indoor air sampling was undertaken in over 100 properties. The majority of these properties were located in north west England next to a potential source of VOCs (an in-filled quarry) but 21 houses were located elsewhere in England for comparison purposes.

In indoor air spaces, typical background sources include:

- VOCs generated through human behaviour, such as cigarette smoke, including that sorbed to the walls/ceiling of a room (eg Rushton, 2004 and Kalin, 2007)
- VOCs used in an occupational setting or present in the working environment (eg Jamieson *et al*, 2005 and Bernhard *et al*, 1995)
- consumer products used and stored within the air space (eg Crump, 1995)
- garages attached to a building, ambient air and other external sources (eg Brown and Crump, 1995, Dodson *et al*, 2008, Hawthorne, 2008 and Harrison and Holmes, 2001)
- kitchen appliances and building materials (eg Berry *et al*, 1995, Yu and Crump, 1998 and McHugh *et al*, 2006).

This is discussed further in Chapter 2, but background contribution to air quality from each of these sources can be significant, resulting in vapour intrusion or emission being determined as a risk where background sources are the greater contributor (false positive). Guidance on recommended information to record before and during indoor air quality sampling is provided in BS EN ISO 16000:1-2006, and includes environmental conditions such as the ventilation condition, room temperature and relative humidity, alongside an inventory to ascertain potential contribution from background sources.

For direct identification of sources of VOCs in air, including through background contribution, different methods can be used, with short-term sampling, such as the following recommended by BS EN ISO 16000-5:

- odour
- comparison between results of air measurements in the centre of the room and close to the potential source
- direct measurement of emissions from the building materials (BS EN ISO 16000-10) or removal of materials for laboratory testing.

Characteristic emission traces for VOC sources are provided in BS EN ISO 16000-5, distinguishing between sources that are continuous (such as PVC building sources) and intermittent (such as cooking or cigarette smoking).

In some cases, ratios of constituent concentrations can be used to distinguish between a subsurface source resulting in vapour intrusion compared to a source

originating from outside a building (for example, Hawthorne, 2008). Consideration of potential contribution can be critical when undertaking indoor air sampling, as concentrations of VOCs in ambient air outside of the house can be at least an order of magnitude higher than measured inside the house (for example, Harrison and Homes, 2001).

6.7 INVESTIGATING VOCS ASSOCIATED WITH NON-AQUEOUS PHASE LIQUID

When undertaking a ground investigation for VOCs, it is important to note the potential for non aqueous phase liquid (NAPL) to be present. As discussed in Table 2.2, these NAPLs may be LNAPLs (for example, some of the petroleum (non-halogenated) hydrocarbons) or DNAPLs (for example, some of the chlorinated hydrocarbons). In some cases, mixtures of different VOCs can result in compounds associated with LNAPL or DNAPL migrating differently in the environment to the behaviour that might otherwise be expected. It is noted that the density of the NAPL relative to water is different from the density of the gaseous phase of a mixture relative to air.

The investigation and sampling methods for NAPL are similar to those used to investigate other subsurface media (soil, groundwater or soil gas), with *in situ* probing and installation of monitoring wells being the most commonly used approaches. However, the assessor should always be aware of the fate and transport of the NAPL in the environment (for example, will it migrate with groundwater flow or along low-permeability geological boundaries?)

Questions the assessor should consider when investigating the presence, composition and extent of NAPL for the vapour intrusion/emission pathways include:

1 What is the relative density of the NAPL in comparison to its surroundings?
2 Is the NAPL likely to be mobile in the subsurface?
3 Is it present as residual NAPL (in soil pore space) and how can this be measured?
4 Could it be present beneath a building, or in contact with building foundations?
5 What types of VOCs could be present in the NAPL?
6 How will the mixture of VOCs affect the migration and volatilisation of VOCs from the NAPL?
7 What form of data is required to allow an assessment of the potential risk to human health from inhalation of vapours?
8 If ground works are undertaken which bring NAPL to the surface, how might it volatilise into an air space?

6.7.1 Assessing the presence, composition and distribution of NAPL

For many sites, the presence of NAPL is determined through site observations and presence of the NAPL on (or in) groundwater samples. Where LNAPL is present in a groundwater monitoring well, the thickness can often be recorded and NAPL samples collected for analysis. It should be noted that the thickness of LNAPL recorded in a groundwater monitoring well does not directly correlate

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to the thickness of LNAPL that may be present in the aquifer. Collection of soil gas samples above NAPL (for example, when present as an LNAPL on groundwater or where DNAPL is present in the unsaturated zone perched on a low permeability soil type) can help understanding of whether compounds are volatilising from the NAPL, and the level of contamination.

Where NAPL is no longer associated with groundwater or clearly recorded in the unsaturated zone, assessing the presence, extent and composition of NAPL can be difficult (for example, residual NAPL in soil pore spaces). A good CSM including an understanding of the potential source of contamination can help the assessor to determine whether residual NAPL is likely to be present in the unsaturated zone and whether it could represent a risk for vapour intrusion/emission alongside a combination of investigation/assessment techniques such as:

- visual observations during site investigation works
- use of surface or down-hole geophysical techniques
- use of *in situ* probing tools (eg LIF and Rapid Optical Screening Tool™) to assess presence of residual NAPL in soil pores
- use of modelling tools to predict the concentrations at which residual NAPL may form in soil.

Further information on designing a ground investigation to allow NAPL to be assessed and sampled is provided in BS 10175:2001.

6.7.2 Analysis of NAPL

Laboratory analysis can be performed on NAPLs, providing information ranging from the nature and likely age of the NAPL through to full-scale forensic testing. Forensic testing of the NAPL can provide the assessor with an understanding of the mixture of compounds present, and of the compounds that may have the potential to partition into soil gas or vapour phase.

6.8 OTHER INVESTIGATION TECHNIQUES

There is a range of ground investigation techniques that could be employed alongside other methods as part of an investigation considering the vapour intrusion/emission pathways. These include methods such as:

- near surface scanning of a surface source using a PID or similar tool
- vegetation surveys
- surface geophysical techniques (eg ground-penetrating radar used to help locate underground structures such as buried tanks).

6.9 QUALITY ASSURANCE/QUALITY CONTROL

Ensuring appropriate quality assurance/quality control is in place as part of any ground investigation is critical. Throughout this chapter, reference has been made to some specific QA/QC procedures that can be employed during a ground investigation, but the assessor should consider following points:

- assessing natural variability versus variability in investigation methods

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  - laboratory-based QA/QC processes, such as matrix spikes or matrix duplicates

- potential for contribution from a background sources
  - trip blanks
  - field duplicates
  - undertaking surveys before and during sampling

- sampling vessel material and construction
- sample preservation
- storage temperature
- degradation of VOCs in sample vessels before analysis
- loss of analytes to container walls/leaching of analytes from container walls.

Further guidance on specific QA/QC protocols can be found in existing guidance such as BS 10175:2001, the BS EN ISO 16000 series (2006–2007), ITRC (2007) and API (2005). The importance of ensuring appropriate QA/QC is in place for assessing vapour intrusion or vapour emission has been highlighted in recent research, for example, Crump *et al* (2008). Internal laboratory QA/QC procedures (such as efficiency of extraction) are not always reported as standard in the UK. It may be necessary to request not only the results of internal laboratory QA/QC testing, but also to provide sufficient sample to the laboratory if further QA/QC testing (such as matrix spikes) is needed.

Where the results of sampling indicate that the measured concentrations are close to the target concentration, the potential variability in site conditions as well as analytical results should be considered when interpreting the data.

6.10 EQUIPMENT FOR INVESTIGATING AND SAMPLING FOR VOCS

Several questions can be asked when considering which equipment to use:

1 Is the equipment intrinsically safe?

2 Will it measure the required parameters, or is more than one instrument needed?

3 Is the equipment robust?

4 Does the equipment have an independent power supply?

5 How heavy and what size is the equipment?

6 What is the required number of operators?

7 Are the operating instructions clear and are the operators adequately trained?

8 Does the equipment have an internal memory and computer logging facility?

9 How frequently should the instrument be serviced and calibrated?

Table 6.21, a modified and expanded version of Table 5.1 from Wilson *et al* (2007), illustrates a selection of equipment available for investigating and sampling for VOCs (and potential indicators of degradation, including oxygen and carbon dioxide) in soil gas and air, along with particular advantages and

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disadvantages of the equipment and when it should be used. Further discussion on particular exploratory techniques and equipment for investigating VOCs in soil gas is included in Appendix A7.

Table 6.21 ***Equipment for investigating and sampling for VOCs (based in part on Wilson et al, 2007)***

Equipment	Type of VOC	Advantages	Disadvantages	How it works and when to use
Field equipment to measure presence and concentration of VOCs				
Photo ionisation detector (PID) 	Wide range of VOCs, depending on the detector used, particularly the bulb	■ detects VOCs at low toxic thresholds ■ intrinsically safe ■ highly sensitive ■ hand-held site screening tool.	■ sample destroyed by sensor ■ can be affected by extreme temperatures and rain/ moisture ■ can be affected by cross-contamination ■ only semi-quantitative.	**Methodology** An ultraviolet light lamp is stored within the detector and used as a source of energy to remove an electron from neutrally charged VOC molecules. This produces an electrical current, which is proportional to the concentration of contaminant. **Application** For the semi-quantitative identification of VOCs in soil gas or other source media. A useful screening tool for many site investigations, although use of correct detector bulb is needed.
Flame ionisation detectors (FID)/GasTec 	Hydrocarbon contaminants, flammable soil gases/vapours	■ widely used for detection of hydrocarbon in soil gas and compounds that ionise in a hydrogen flame ■ highly sensitive (0–10 000 ppm) ideal for use as a primary investigating device for screening soils for many VOCs ■ presence of elevated concentrations indicates need for further investigation ■ the FID can be used in open air or in confined spaces.	■ require a minimum amount of oxygen in the sample to operate correctly ■ some versions may not be intrinsically safe (GasTec) so cannot be used in confined spaces or in flammable environments ■ responds to any combustible gas or vapours ■ sample destroyed by sensor ■ can be affected by extreme temperatures and rain ■ transportation (eg by courier) problematic due to the presence of hydrogen cylinder.	**Methodology** The FID measures the increase in ions produced when organic matter within the samples gas passes through a hydrogen flame. **Application** Soil vapour surveys (eg identification, delineation of hydrocarbon spills). Internal gas surveys of buildings and services to detect the ingress of methane. It is important that the sensitivity of the FID being used is suitable for the gases that need to be measured.

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Table 6.21 (contd) ***Equipment for investigating and sampling for VOCs (based in part on Wilson et al, 2007)***

Equipment	Type of VOC	Advantages	Disadvantages	How it works and when to use
Portable air analyser 	Wide range of VOCs	■ can be used to analyse for a wide range of VOCs in gaseous phase ■ good detection limits ■ portable.	■ relatively expensive and not widely used in the UK to date ■ needs experience to calibrate correctly.	**Methodology** The gas sample being measured is passed through the analyser. The sample is analysed using infrared spectroscopy. **Application** A range of scenarios, including as a screening tool, to delineate affected areas on site.
Laser induced fluorescence (LIF) detector 	Wide range of VOCs, in particular petroleum (non-halogenated) hydrocarbons	■ can be used to analyse the presence of a wide range of VOCs in the subsurface ■ can be used in combination with other detectors ■ real time results.	■ a detector/ sensor attached to a probing tool, expensive to set up relative to hand-held tools ■ needs experience to interpret the data.	**Methodology** The detector is progressed into the subsurface on a probe. A laser that fires short pulses of light into an optical fibre that runs through the probe. As the laser pulses pass into the soil through the probe window, contaminants in the soil respond by giving off a characteristic "glow." This emitted light is carried back to the surface over a second fibre, and it is measured with a detector. The optical screening method provides a nearly continuous profile of contaminant distribution as the probe is pushed into the ground. **Application** To investigate VOCs in the subsurface, including as a screening tool, to delineate of contaminated areas on site, primarily used to detect petroleum hydrocarbons.
Electrolytic conductivity detector (DELCD) 	Wide range of VOCs, in particular halogenated compounds	■ can be used to analyse for presence of a wide range of VOCs in the subsurface ■ can used in combination with other detectors to provide a good understanding of the contaminant distribution in the subsurface ■ real time results.	■ does not provide a quantitative analysis of concentrations in soil gas, but indicates the presence of certain VOCs in the subsurface ■ sample needs collection, usually using an *in situ* heated probe, with large equipment requirements ■ expensive to set up as part of probing tool relative to hand-held tools ■ needs experience to interpret the data.	**Methodology** Typically, sample is retrieved from the subsurface using a heated probe. The conductivity of gas is measured within the detector. **Application** To investigate VOCs in the subsurface, including as a screening tool, to delineate of contaminated areas on site, primarily used to detect halogenated compounds.

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Table 6.21 (contd) ***Equipment for investigating and sampling for VOCs (based in part on Wilson et al, 2007)***

Equipment	Type of VOC	Advantages	Disadvantages	How it works and when to use
Portable gas chromatography and portable mass spectrometer (GC-MS)	Wide range of VOCs	■ GC-MS is available in a reduced size ■ now available in portable carry case ■ the instrument is robust for use in field ■ offers the accuracy usually only obtained within a laboratory ■ individual compound quantified.	■ cost effective but only for long-term monitoring ■ limited battery life ■ need access to mains or generator power.	**Methodology** Sample is injected into a gas stream, which results in each compound separating. Each compound leaves the stream at a specific time. As it leaves the stream, it passes through a detector. The response of the detector is related to the concentration of the compound. By comparing the response of the detector to known standards, the concentration of the VOC in the soil gas sample can be calculated. The mass spectrometer is a type of detector for a gas chromatograph. **Application** This relatively new equipment offers the accuracy of the laboratory version but also mobility, this when transported to site the GC-MS can be ready to analyse samples within 30 minutes. However, to set up such equipment is expensive and would be cost effective only for long-term monitoring.
Sample containers				
Sampling bags 	Wide range of VOCs	■ wide range in bags available (such as Tedlar, Teflon, aluminium, rubber and Kevlar) ■ lightweight ■ relatively inexpensive ■ relatively inert ■ quick.	■ often fragile and easily punctured ■ hard to store safely when full ■ vacuum cleaning required in many bags ■ water vapour condenses in some bags ■ some potential for interaction/ loss of sample depending on the type of bag ■ limited sample volume and short sampling time.	**Methodology** A pump is used to draw the sample into the bag until full. The bag is sent to a laboratory for analysis. **Application** Can be used as a soil gas/air sample container where the VOCs are relatively non reactive, for short-term monitoring period. Recommended holding time for non reactive gases is 72–120 hours, but can be significantly less for reactive gases.

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Table 6.21 (contd) ***Equipment for investigating and sampling for VOCs (based in part on Wilson et al, 2007)***

Equipment	Type of VOC	Advantages	Disadvantages	How it works and when to use
Pressurised containers 	Wide range of VOCs	■ range in containers available (such as stainless steel bombs, copper, aluminium and glass) ■ robust ■ relatively easy to use ■ relatively inert.	■ not widely used in the UK so limited potential for analysis to be undertaken ■ relatively heavy ■ if pressure is lost, sample is lost ■ more expensive than bags.	**Methodology** A pump (or air pressure difference) is used to draw the sample into the container, usually at a set flow rate to give flexibility with time over which sample is collected. The container is sent to a laboratory for analysis. **Application** Can be used as a soil gas/air sample container for short to medium-term monitoring period. Not widely used in the UK to assess for VOCs, although more widely used in other countries.
Glass or stainless steel sampling tubes 	Range of VOCs and other gases in soil/air	■ relatively easy to use ■ robust ■ can be used with a manual pump ■ quick.	■ relatively heavy compared to bags or sorbent tubes ■ limited sample size, as such detection limits can be high ■ short sampling time.	**Methodology** A pump is used to draw the sample into the tube. The container is sent to a laboratory for analysis. **Application** Can be used as a soil gas/air sample container to collect indicate presence of VOCs at a point in time. Not widely used for VOCs as limited sample size means detection limits often high.
Chemical detector tubes 	Total hydrocarbons, gasoline/ petrol, diesel/ jet fuel, nitrogen oxides, carbon dioxide, hydrogen sulphide, carbon monoxide	■ used for a wide range of gases/vapours ■ wide detection range ■ simple to use without need for laboratory analysis.	■ time consuming if more than one gas being monitored for ■ potential for low accuracy ■ prone to interference effects ■ suitable for indication only.	**Methodology** Chemical detector tubes contain one or a mixture of chemicals that are reactive to certain gases. Gas sample drawn into tube and reacts with the chemical causing a change in colour. Either the resultant colour or length of colour in the tube can be related to a certain concentration of gas (Crowhurst *et al*, 1993). **Application** When there is a potential for toxic compounds. Indicator of soil gases/toxic compounds. All readings should be confirmed using laboratory analysis.

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Table 6.21 (contd) ***Equipment for investigating and sampling for VOCs (based in part on Wilson et al, 2007)***

Equipment	Type of VOC	Advantages	Disadvantages	How it works and when to use
Sorbent tubes 	Wide range of VOCs	■ small ■ robust ■ quantitative analysis of VOCs in soil gas, with potential for low detection limits sample obtained actively ■ can be used as a diffusive sampler without need for a pump ■ longer time to take sample.	■ for active sampling, requires use of a pump with well-calibrated flow rate for analysis to be meaningful ■ detection limit varies depending on the volume of air passed over sorbent ■ can be time consuming, as samples usually collected over a period of hours.	**Methodology** A pump is used to draw the sample into the tube, for active sampling. The gas passes over the sorbent material and VOCs in the gas are retained. The volume of air passing through the container is monitored. The container is then sent to a laboratory for analysis, with details of monitoring time/ volumes of air. **Application** Widely used to investigate the presence of a wide range of VOCs in soil gas/air, providing a quantitative analysis of concentrations of different VOCs if used correctly. Also used as a passive diffusion tube for air monitoring ("desorption tube", EA, 2004a)
Passive diffusion sampling devices	Wide range of VOCs	■ small and inexpensive ■ easy to use ■ can be left *in situ* to take measurements over a long-term time period ■ can be used for personal monitoring.	■ time-averaged sampling method so will not provide an indication on variation with time ■ uncertainty over the volume of air that passes over the sampling media (typically a sorbent) leads to difficulties in interpreting data.	**Methodology** Sample container is left *in situ* in the ground or air space for a period of time. Soil gas/air passes over the container and sampling medium (usually a sorbent material) records the presence of VOCs. The sampler is then sent for laboratory analysis, although some personal monitoring systems have in-built methods for showing detections (such as a change in colour). **Application** Widely used to investigate VOCs in air, less so in soil gas, as small and unobtrusive. Some forms also used to monitor personal exposure.
Pumps and flow meters				
Manual pumps 	Used to draw a sample of soil gas or air into a sample container	■ easy to use ■ widely available ■ no electrics used.	■ can only be used to collect "grab" samples ■ flow rate is not continuous as manually operated.	**Methodology** Pump is attached to the sampling system and pumped until the sample container reaches the desired pressure level. **Application** Widely used to collect "grab" samples, such as with glass or stainless steel sampling tube or bags.

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Table 6.21 (contd) ***Equipment for investigating and sampling for VOCs (based in part on Wilson et al, 2007)***

Equipment	Type of VOC	Advantages	Disadvantages	How it works and when to use
Automated pumps 	Used to draw a sample of soil gas or air into a sample container	■ easy to use ■ widely available ■ flow rate can be altered ■ can be used over a period of time.	■ may not be intrinsically safe in all cases ■ associated noise ■ requires calibration before use.	**Methodology** Pump is attached to the sampling system (sample container located between the sampling point and pump) and set to run at the desired flow rate and time. **Application** Widely used to collect samples over a longer time period than a manual pump, typically with sorbent tubes.
Gas flow pod 	Direct measurement of flow rate using a gas analyser	■ the flow pods comprise of robust aluminium ■ the flow range is 0.1 to 12 l/h and a flow resolution of 0.1 l/h.	■ the flow pod is not certified as intrinsically safe and cannot be used in confined spaces or in flammable environments.	**Methodology** This pod is available as an extra attachment to certain analysers. The flow pod directly measures the flow rate from a monitoring point. **Application** This instrument is now widely used and accepted for the measurement of gas flow. Used in conjunction with gas analyser. Cannot be used in confined spaces or in flammable environments.
Mass gas flow monitor 	Direct measurement of flow rate	■ measured directly at monitoring point ■ simple method ■ robust, hand-held monitor ■ flow measurement not affected by wind, steam or contaminants.	■ prone to dust and condensation build-up ■ correction factors should be applied if the gas composition is significantly different to that of air.	**Methodology** This sensor directly measures the flow rate from a monitoring point. **Application** This instrument is now widely used and accepted for the measurement of gas flow. The monitor can also be used to measure gas pressure in the borehole.

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Table 6.21 (contd) ***Equipment for investigating and sampling for VOCs (based in part on Wilson et al, 2007)***

Equipment	Type of VOC	Advantages	Disadvantages	How it works and when to use
Rotameters, vane anemometer, bubble-flow meters	Direct measurement of volume flow rate	■ measured directly at monitoring point ■ simple method ■ flow measurement not affected by wind, steam or contaminants.	■ can only be used where gas quantity (and pressure) are high ■ calibration is affected by the density, temperature and pressure of gas mixture ■ can underestimate ■ prone to damage ■ correction factors should be applied if the gas composition is significantly different to that of air.	**Methodology** Rotameters consist of a graduated vertical tube with a taper towards the lower end. Flow is represented by the position of a float within the tube. Bubble-flow meters are based on the time taken for a soap bubble to rise up a graduated tube with a known volume. The volume is recorded and converted to the volume flow of gas. Vane anemometers operate by counting the number of revolutions per unit-time of a vane, which rotates in the presence of a gas flow. **Application** These instruments have been widely used. Generally more appropriate for use on gassing landfill sites where the pressure and flow is greater. Soap bubble meters typically suffer from less resistance and are more appropriate for sites with low pressure and flow. However, the measurements can still be unreliable due to fluctuations.
Other equipment				
Explosimeters/lower explosive limit (LEL) detectors 	Flammable gases	■ easy to use ■ relatively small ■ used to detect ratios of different gases in air, and indicate when there is a potential risk of explosion.	■ only useful as an indicator, in combination with other techniques to mitigate risk ■ cannot be used for all environments or all VOCs.	**Methodology** The gas sample is drawn into the detector, and either a catalytic or catharometric sensor or infrared detector is used to record the ratio between the air/gas mixture. **Application** Used as an aid to mitigating risks to human health from explosion of flammables, for example, during investigations. Cannot be used as a tool to investigate the presence or concentrations of VOCs as part of a land contamination assessment.

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Table 6.21 (contd) ***Equipment for investigating and sampling for VOCs (based in part on Wilson et al, 2007)***

Equipment	Type of VOC	Advantages	Disadvantages	How it works and when to use
Semiconductors	Flammable soil gases, hydrogen sulphide, carbon monoxide	■ can be made very sensitive ■ long-term stability of measurements ■ good selection of some toxic gases.	■ lack of selectivity to combustible gases ■ not specific to any one material ■ accuracy and response depend upon humidity.	**Methodology** This sensor measures the change in electrical resistance of a solid state semiconductor as a gas sample passes through. The change in resistance is related to the concentration of combustible gas in a sample (Crowhurst, 1987). **Application** Generally unsuitable for environmental monitoring because they can react to any gas. Typically used for domestic purposes and leak detection.
Infrared gas analysers 	Methane, carbon dioxide and other gases	■ detects a wide range of gases ■ wide and sensitive detection range ■ widely used and proven within field ■ gas sample passes unchanged through the sensor ■ extra instrumentation can be added to the instrument to measure trace gases and flow.	■ readings affected by water in the system ■ selection of correct wavelength difficult ■ instruments may not be intrinsically safe ■ cross -sensitivity with hydrocarbons.	**Methodology** The gas sample being measured is stored in a cell within the analyser. Radiation is released and passed through the cell. The amount of radiation absorbed by the gas sample relates to the concentration of gas being measured (Crowhurst, 1987). **Application** The infrared analysers are generally the preferred soil gas monitoring instrument for all sites where methane and carbon dioxide are suspected/ They can also be used to detect the presence of gases that may be associated with degradation of certain VOCs or leakage into the sampling equipment from atmosphere.
Paramagnetic sensor	Oxygen	■ no interference from majority of other gases ■ accurate measurements ■ robust in the field.	■ accuracy can be affected by atmospheric changes ■ relatively expensive ■ prone to cross-contamination.	**Methodology** Paramagnetic sensors measure the changes in the magnetic susceptibility in the gas sample. Oxygen has a positive magnetic susceptibility whereas all other gases have a negative magnetic susceptibility, which enables the oxygen in a gas mixture to be measured (Crowhurst, 1987). **Application** For measurement of oxygen only, eg leakage tests.

6.11 ANALYTICAL TECHNIQUES

There are several methods that can be used to determine the presence of VOCs in environmental matrices. Some of these methods may be used in the field and include:

- bioluminescence kits for soil and groundwater (qualitative)
- PID headspace screening (qualitative/ semi-quantitative)
- immunoassay kits for soil and groundwater (semi-quantitative)
- headspace gas chromatography for soil and groundwater (quantitative)
- direct injection gas chromatography for gas samples (quantitative)
- flow through gas chromatography for gas samples (semi-quantitative)
- colorimetric tests for soils, liquids or gases (qualitative/semi-quantitative).

In the laboratory VOCs are usually analysed quantitatively following a standardised method. Most UK laboratories follow the 5000 and 8000 series of USEPA SW846, which have been modified for their own use. Specific UK guidance on the analysis of VOCs in soils is given in BS ISO 22155:2005. Laboratories undertaking soil chemical analysis should ideally be accredited under the EA's Monitoring Certification Scheme (MCERTS) for chemical testing of soil. Also note that for laboratory analysis of sorbent tubes to be considered quantitative, GC-MS should be used, comparing against compound-specific calibration curves.

There is existing guidance on analytical techniques for the gases oxygen, carbon dioxide and methane (for example, Wilson *et al*, 2007), which can be useful indicators of the degradation of certain VOCs in the unsaturated zone.

6.12 DATA INTERPRETATION

Guidance on the interpretation of the data collected as part of a ground investigation is provided in Chapter 7, including the development of assessment criteria to help assess the significance of the measured concentrations (see Chapters 7 and 8). Where site data are used within the assessment process, the assessor needs to understand not only the level of confidence with the dataset but also inherent uncertainties.

When assessing the vapour migration pathways covered by this publication, the use of multiple lines of evidence is recommended where possible. This could include the use of several investigation techniques (discussed in Chapter 5) the results of which need to be combined carefully to help refine the CSM. For example, if data collected from field screening combined with laboratory analysis indicates that VOCs are not present in the subsurface at detectable concentrations, these two lines of evidence could be used to illustrate that the risk from the vapour intrusion/emission pathways was acceptable due to an absence of a source. Different methods to exit the assessment process at an early stage in the process are discussed further in Chapter 7.

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6.13 SUMMARY

There are several exploratory and analytical tools that can be used to determine the presence, level and extent of VOC contamination in environmental matrices.

The selection of the appropriate tool for any survey depends on the CSM and the data collection objectives.

The advantages and disadvantages of the tool should be considered before selection for use, alongside the potential limitations/uncertainties associated with the data collected using the chosen tool.

It is important to have a considered sampling plan with an appropriate QA/QC plan.

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7 Vapour intrusion/emission generic quantitative risk assessment

7.1 INTRODUCTION

Generic quantitative risk assessment (GQRA) forms the second, more detailed stage within the vapour intrusion/emission assessment process (Figure 3.1), following the guidance defined within CLR11 (Defra and EA, 2004a). The objectives of undertaking a vapour intrusion/vapour emission generic quantitative risk assessment (v-GQRA) are:

1 To collect data on the site-specific ground conditions

2 To refine the CSM, to assess whether the vapour intrusion/emission/release pathways could present a potentially significant risk to human health receptors for the situations relevant to the project objective.

3 To establish whether use of generic assessment criteria (GAC), given the assumptions in their development, are appropriate for assessing the potential risks to human health. If so, they should be applied to determine whether the vapour intrusion/emission pathways require further assessment, or if the pathways can be screened out from further assessment (Defra and EA, 2004a).

The v-GQRA is the first time within the process that the potential risk is assessed not only qualitatively but also quantitatively. Figure 7.1 illustrates the different stages of the v-GQRA process, as listed in points 1 to 3, and described in detail in this chapter. As with all tiers of assessment in this guidance, the process can be applied flexibly and iteratively, but always keeping in mind other potentially active pollutant linkages.

The third point allows consideration of whether further work is needed to complete the v-GQRA, or whether a vapour intrusion/emission detailed quantitative risk assessment (v-DQRA) should be undertaken, for example, when GAC are not appropriate or sufficient to assess the risk (Defra and EA, 2004a). The result of the v-GQRA may lead the assessor to undertake a v-DQRA, consider remediation options or to exit the assessment process for the vapour intrusion/emission pathways.

Case study A3.1 shows how a v-GQRA was undertaken for a site in the UK following a v-PRA and site investigation. This case study is also referenced in Chapters 8 and 9.

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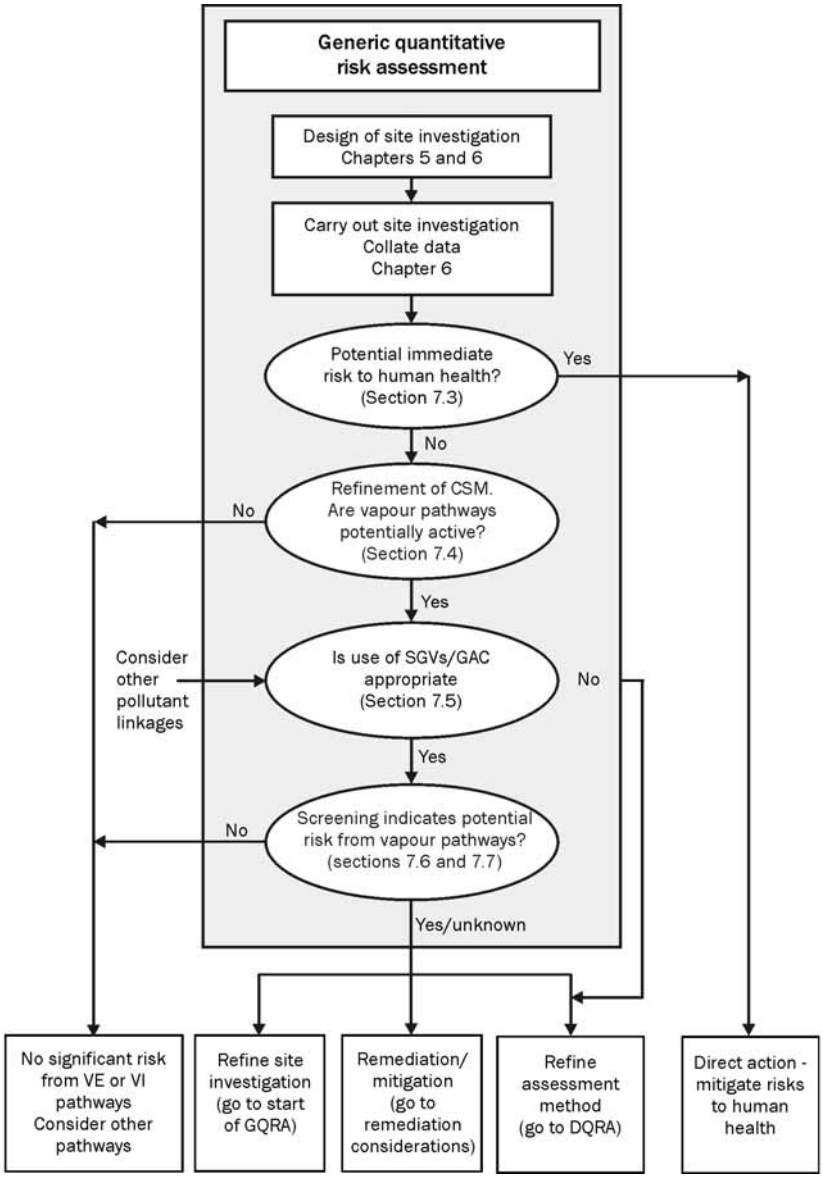

Figure 7.1 ***Generic quantitative risk assessment (extracted from Figure 3.1)***

7.2 SITE INVESTIGATION

7.2.1 Introduction

The first stage of the v-GQRA will typically comprise the design and carrying out of a site investigation, including intrusive works. The investigation is designed to allow further assessment of the vapour intrusion/emission pathways, and allow the CSM to be refined where appropriate. However, the investigation will often need to target extra pollutant linkages to the vapour intrusion/emission pathways, which should be noted during the design phase.

7.2.2 Objectives of the intrusive investigation

The primary objective of carrying out this type of intrusive investigation is to collect sufficient information to provide confidence in the conceptualisation of the vapour intrusion/emission pathways. This then allows the potential risks associated with the pathways to be assessed and further quantified.

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In Chapters 5 and 6, the design of the intrusive investigation, including potential investigative techniques, is discussed in detail. The intrusive investigation process is often iterative or "phased" (Defra and EA, 2004a) to meet the objectives of the assessment process. However, when designing the investigation(s), the assessor should note that the result of the v-GQRA is to determine whether there are potentially significant risks based on a set of generic, yet conservative, assumptions. Intrusive investigations designed to allow further consideration of the vapour intrusion/emission pathways for this type of assessment should not be expected to take the form of relatively complex investigation techniques, such as sub-slab soil gas sampling or sampling vapours in an indoor air space. However, it might include soil, groundwater and soil gas sampling and analysis.

The types of VOCs likely or known to be present at a site may influence the selection of investigation techniques. The levels of uncertainty, and in some cases conservatism, involved with modelling rather than measuring the intrusion/emission pathways vary depending on the site conditions and type of VOCs. This is discussed in further detail in Chapter 8 and Appendix A2. To reduce uncertainty in modelling these pathways, the assessor may wish to design an investigation that helps build up multiple lines of evidence even at a generic stage of assessment (for example, collection of soil gas data at the source as well as soil and/or groundwater data).

7.2.3 Building survey

For sites where a building or buildings are present and are to remain in place, and/or buildings are present on neighbouring sites, a survey of the buildings should be considered. The level of information gathered in the survey during the v-GQRA (or v-PRA) will depend on several factors, such as building ownership and access. It will not be possible to undertake a detailed building survey on all developed sites, due to access restrictions and/or difficulties with risk communication (for example, on a residential site). When entering an occupied building to undertake a building survey, or other forms of investigation, a risk communication plan is typically required.

An example of a building survey is presented as Appendix A5 and further discussion is provided in Chapter 4. Where access is unrestricted and the potential for causing undue stress to the building occupiers is minimal, the use of a building survey, such as that included in Appendix A5, is recommended to help the CSM development. Also, the information can be important in understanding how data collected from site can be interpreted (for example, which modelling tool is most appropriate for the building type present). Further discussion of how the building construction affects the vapour intrusion pathway is included in later sections of this chapter and also in Chapter 2.

7.2.4 Results from the site investigation(s)

The site investigation(s) should provide sufficient site-specific information that gives confidence in understanding the following typical factors, which relate to the vapour intrusion/emission pathways:

- the subsurface geology/soils
- the hydrogeological regime
- the nature and use of buildings on/adjacent to the site (present and known future use)

- the nature and condition of ground cover on/adjacent to the site (present and known future use).

The intrusive investigation would also typically provide an understanding of one or more of the following:

- the presence or absence of VOCs, or potentially volatile compounds in:
  - soil
  - in groundwater
  - in soil gas at the source depth or in the unsaturated zone
- the location of VOCs with respect to overlying buildings/outdoor air spaces.

7.3 REFINEMENT OF CONCEPTUAL SITE MODEL

Following completion of the site investigation works, the data should be collated to allow, where needed, refinement to the vapour migration/intrusion CSM.

A set of questions has been developed to help the assessor determine whether the vapour intrusion/emission pathways are likely to be active through refinement of the CSM. If the result demonstrates that a vapour intrusion and/or emission pollutant linkage is active, or potentially active, a decision needs to be made as to whether use of GAC is appropriate to assess the level of risk to human health.

The questions are included in the flow chart, presented as Figure 7.2, and are discussed in more detail in the following sections.

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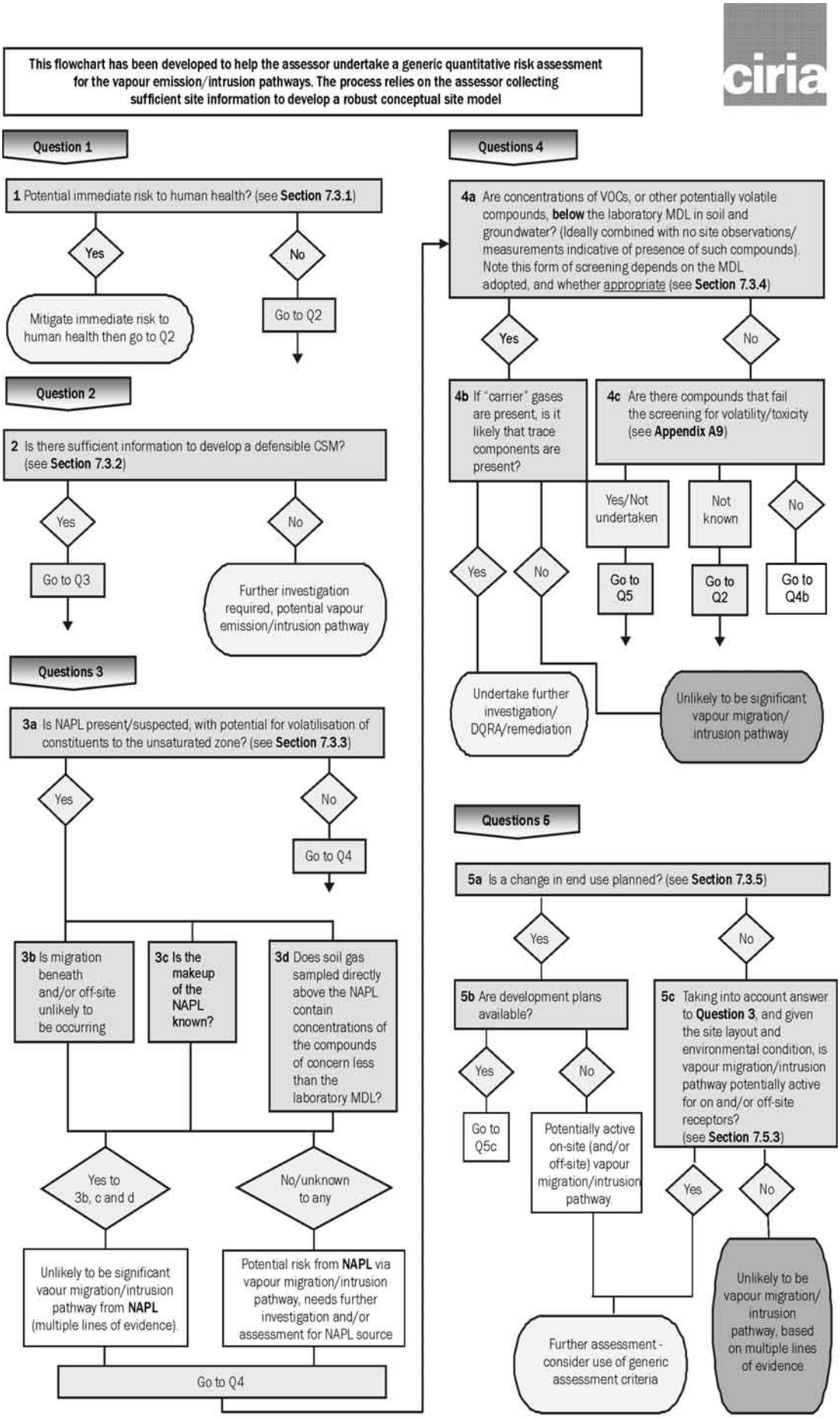

Figure 7.2 ***Flow chart to aid refinement of CSM***

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7.3.1 Question 1 (pollutant linkage assessment)

Is there a potential immediate risk to human health?

Once the initial site investigation has been undertaken, the first stage in reassessing the site is to question whether there is a potential immediate risk to human health. This concern may be raised by a range of factors, such as:

- olfactory evidence of contamination (for example, reports of odours during intrusive works or within manhole chambers or drainage routes) close to a receptor air space
- presence of VOCs at high concentrations in surface soils, which could be released through ground disturbance
- detections of VOCs known to have the potential to cause acute health effects, even at relatively low concentrations. An example of such a compound is hydrogen cyanide, for which short-term exposure to concentrations in the range 6–100 mg/m^3 can result in acute health effects (USEPA, 2008)
- detections of VOCs in a site setting where there is a potential risk of explosion.

Where an immediate risk is present, or suspected, direct action should be taken to mitigate the risk, and appropriate existing guidance should be followed (for example, HELA circulars). This could include the potential for acute health effects during future works (for example, through vapour release of a VOC during redevelopment) that need consideration at an early stage in the assessment process. Where the evidence for potential immediate risk is based on observations or complaints about odours, the odour threshold levels of the potential contaminant(s) can be reviewed against the toxicological threshold levels to help assess whether there is an immediate risk to human health. Once the immediate risk has been managed, it may be appropriate to continue through the process depending on the mitigating actions taken and/or the results of investigations.

Box 7.1 ***Assessing the potential for release of VOCs through ground disturbance***

There are many recognised techniques for estimating and modelling the migration of VOCs in soil gas through the unsaturated zone, such as the J&E model, which is used to model vapour intrusion (see Section 7.4.3). However, there is an absence of recognised techniques for estimating the likelihood for release of VOCs through ground disturbance. Research is ongoing, combining theoretical and empirical data, so as to understand how best to investigate and model the vapour release and emission pathways (for example, see Case studies 6.3, 8.3 and 9.1). Calculation methods for estimating the potential for vapour release range from a simple "back of the envelope" calculation through to more sophisticated modelling approaches (for example, DeVaull, 2001). One such "back of the envelope calculation" could be to estimate the concentration of a VOC in soil gas (for example, using the method for modelling partitioning included within EA, 2009b), and to assume that this could be released to (and diluted within) an overlying air space. The estimated concentration in the air space can then be compared with acceptable air quality levels (for example, derived from CLEA toxicological reports or workplace exposure limits as appropriate) to assess the potential risk to human health.

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7.3.2 Question 2 (pollutant linkage assessment)

Is there sufficient information on site conditions to develop a defensible CSM?

The CSM for the vapour intrusion/emission pathways cannot be refined unless there is confidence that sufficient site-specific data have been collected to conceptualise the appropriate pollutant linkages. This would typically include knowledge of the geology, hydrogeology, chemical/physical properties of the contaminants, and the level and distribution of contamination. The information used to refine the CSM depends on both the results of the v-PRA and the site investigation. Examples where the CSM may not be defensible could include:

- absence of groundwater monitoring wells installed in locations next to (or hydraulically down-gradient of) potential sources of contamination that could result in the presence of dissolved phase VOCs
- the number of sampling locations being too limited to allow a defensible understanding of the contaminant distribution to be formulated
- potentially significant preferential pathways identified but not investigated
- insufficient understanding of source or the nature of the contaminants.

If the assessor believes sufficient data have not been collected to conceptualise the vapour intrusion/emission pathways at a generic level, then further assessment and/or investigation will be required.

7.3.3 Questions 3a–d (source assessment)

3a Has NAPL been identified at the site, or could it be present?

For sites where NAPL (residual or free-phase) has been identified in the unsaturated or saturated zone (or is suspected) and there is the potential for volatilisation of the NAPL constituents into the unsaturated zone, consider the following:

1 Is the NAPL likely to be mobile (eg could the NAPL migrate beneath, or off site, including via preferential pathways)?

2 Are the properties of the NAPL understood (eg the types of compounds present in the NAPL)?

3 Are compounds of concern present, or likely to be present, in the gaseous phase directly overlying the NAPL (if resting on groundwater or in the unsaturated zone)?

These questions are included as 3b, 3c and 3d on Figure 7.2.

If the NAPL is of low mobility, has been well characterised and volatile compounds are not present in the gaseous phase directly overlying the NAPL, it could be concluded that there is unlikely to be a significant level of risk via the vapour intrusion/emission pathways. Assessing whether the presence of NAPL constitutes a potential risk from vapour intrusion/emission pathways also relies to an extent on professional judgement and a multiple lines of evidence approach, especially where the NAPL is residual, located in soil pore spaces in the unsaturated zone. However, often the presence of NAPL would lead to a more quantified assessment of the potential risks posed to human health via the vapour intrusion/emission pathways. Where NAPL is present on groundwater or in the unsaturated zone and may remain *in situ*, analysis of soil gas samples is likely to be required to enable assessment of risks from VOCs (originating from the NAPL) in the unsaturated zone (see Section 7.5).

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7.3.4 Questions 4a–c (source assessment)

4a Are concentrations of VOCs, or other potentially volatile compounds, below the laboratory reported method detection limit (MDL)?

The absence of detections (or reported detections) of VOCs, or other potentially volatile compounds, in the environmental media tested, can be used in many cases to conclude that there is unlikely to be a significant risk to human health via the vapour intrusion/emission pathways. Ideally this would be combined with site observations/measurements that correlate with the laboratory analysis, as multiple lines of evidence, although this is not possible for all types of VOC. Where the screening is passed (no detections), the assessor would proceed to Question 4b, otherwise the assessor would answer Question 4c.

The use of laboratory reported MDLs as part of the screening process needs to take into account the potential ranges in detection limits, the limitations with different analytical techniques, and whether the data collected is valid for such screening to be carried out. Is the reported MDL low enough given the contaminant(s) under assessment to be valid as a form of screening? It is worth noting that the reported MDL should be lower than screening criteria (such as generic assessment criteria, see Section 7.4), which may be employed as part of the risk assessment. Consideration should be given to appropriate laboratory reported method detection limits, which may influence the choice of the site investigation technique, sampling methodology and/or analytical methodology, during the design of the investigation as discussed in Chapter 5.

4b If "carrier" gases are present is it likely that trace components are present?

For some sites, VOCs and other potentially volatile compounds may not be detected in the subsurface. However, the presence and flux of "carrier" gases (for example, methane or carbon dioxide) could result in a flux of low volatility compounds through the unsaturated zone (discussed in more detail in Section 4.5.2). This is most commonly the case at landfill sites, where the EA has issued guidance on the types of compounds that could be present within the carrier gases, known as "trace components" (EA, 2004a). If the presence of trace component is likely, or suspected, Question 4a recommends the assessor undertake further investigation, more detailed risk assessment and/or remediation.

4c Are compounds present fail semi-quantitative screening based in volatility/toxicity?

If VOCs or other potentially volatile compounds have been detected, screening of the compounds for their volatility and toxicity via inhalation exposure can be undertaken. Screening compounds for volatility based on the Henry's law constant is a recognised procedure (for example, SNIFFER, 2003), but the screening has been extended to include an assessment of the likely toxicity of the compound. This dual form of screening was originally recommended within USEPA vapour intrusion guidance (USEPA, 2002), and an adapted form of this method is presented in Appendix A9. If the screening indicates that there are compounds of sufficient volatility and toxicity to present a potential risk via inhalation exposure, the assessor would proceed to Question 5. Note that this screening should be used with care. For compounds with an extremely low toxicological threshold for the inhalation pathway or where the compound is close to failing the screening, professional judgement and multiple lines of evidence may be required to exit the v-GQRA assessment process, especially if the concentrations are high at the ground surface and the risk via other pathways is likely to be significant.

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7.3.5 Questions 5a–c (pathway/receptor assessment)

5a Is a change in end use planned?

An assessment of the potential risk to human health associated with the vapour intrusion/emission pathways typically has a higher degree of uncertainty for a site where the end use will change than for a site where the end use will remain the same. If there is a proposed change in end use, the assessor should proceed to Question 5b, but if no change is planned, the assessor should proceed to Question 5c.

5b Are development plans available?

For a site where development plans are available, and show the locations and dimensions of proposed buildings and the type of building use, the assessor should answer Question 5c. If no development plans are available, it is unlikely that the vapour intrusion/emission pathways can be discounted without further quantitative assessment.

5c Given the site layout and environmental condition, is the vapour intrusion/emission pathway (from non-NAPL sources) likely to be active for on- and/or off-site receptors?

This question is designed to allow the assessor to use multiple lines of evidence to demonstrate whether vapour intrusion/emission is likely to be active, and whether they could present a significant level of risk to human health via inhalation exposure. Consideration should be given to factors including, but not limited to:

1 Is the geology/hydrogeology adequately characterised?

2 Is the source adequately characterised?

3 Which environmental medium/media is the source present in?

4 What is the known/likely lateral and vertical extent of the source?

5 Does a building lie close to or over the source (on- or off-site)?

6 Is hardstanding present on site, and if so, what is the nature/condition?

7 Are there potential routes for the contamination to migrate off-site? (such as dissolved phase VOCs in groundwater, flowing beneath the site)

8 Are there potential preferential pathways by which soil gas could migrate vertically or laterally to a receptor? (including naturally occurring, such as geological, or man-made, such as cross-site drainage routes or elevator shafts)

9 Are existing risk management measures already in place (such as an engineered building control) that would break the specific pollutant linkage?

Also the assessor should consider whether there could be a change in pathway during the site use (for example, excavations on site resulting in a vapour release).

Further forms of screening have been developed in other countries to help assess factors such as lateral offset between the source and receptor air space. For example, in the US, a range of exclusion distances are used by different states, depending on whether the state has elected to treat the different groups of VOC compounds (petroleum hydrocarbons, halogenated hydrocarbons and nitrogen/sulphur/oxygen-containing volatile compounds) differently. Where

VOCs are considered as one group, an exclusion distance of 30 m is typically promoted (for example, in California, Pennsylvania and Colorado). Where petroleum hydrocarbons are considered separately, exclusion distances of five to 10 m are used for petroleum hydrocarbons while 30 m is adopted for halogenated hydrocarbons (for example, in Utah, New Jersey and Indiana). These exclusion distances are only used where several starting criteria are met, such as the absence of significant potential for advective flow of soil gas in the subsurface. Further research in the UK may allow other forms of screening, such as the use of exclusion distances, to be adopted in future, as further lines of evidence for discounting the vapour intrusion/emission pathways from further assessment.

7.3.6 Summary

Following the process set out in the previous section should help the assessor to determine whether the vapour intrusion/emission pathways warrant further assessment, and allowing the CSM for this pathway to be refined. The results of some of the questions recommend that further investigative works, a v-DQRA or a remediation options appraisal is required. However, for many sites, the next stage in the process is to consider whether the use of GAC as a quantitative screening tool is appropriate (see Section 7.4). For some sites, it may be possible to exit the vapour intrusion/emission assessment process at this stage. The use of GAC, and their applicability under different circumstances, is discussed in the following sections.

7.4 USE OF GENERIC ASSESSMENT CRITERIA (VAPOUR INTRUSION/EMISSION)

The Contaminated Land Exposure Assessment (CLEA) methodology compiled by Defra and the EA encourages the development and use of GAC as a form of quantitative screening for land contamination sites, where appropriate. Within CLR11 (Defra and EA, 2004a), GAC are:

> *"criteria derived using largely generic assumptions about the characteristics and behaviour of sources, pathways and receptors. These assumptions will be [health protective] in a defined range of conditions".*

The UK Soil Guideline Values (SGVs) are a form of GAC developed by the EA as part of the CLEA framework (see Section 7.4.1). At the time of writing, there is a rolling programme of release for new SGVs.

As part of the CLEA methodology, Defra and the EA have provided guidance on the development of GAC to offer protection to human health via chronic exposure, with a focus on contaminants present in soil. Generic soil types, building parameters and parameters relating to chronic exposure (greater than one year of exposure) have been defined alongside recommendations for appropriate algorithms (EA 2009b and Jeffries, 2009) to calculate the GAC for several different land-uses (residential allotments, commercial/industrial).

Before using GAC to aid in assessing the potential risk via the vapour migration/intrusion pathways, the assessor should consider the following questions:

1 Are GAC available that include the pathways of concern?

2 Is the CSM used to develop the GAC appropriate, or suitably conservative, for the site?

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3 Are the vapour intrusion/emission models used to develop the GAC appropriate, or suitably conservative, for the site?

7.4.1 Are GAC (including Soil Guideline Values) available?

SGVs have been developed for a few compounds by the EA, although the SGVs are still in the process of review and update at the time of writing. Some of these compounds are VOCs. The SGVs are a screening tool describing:

> *"concentrations of contaminants in soil at which (in the Government's view)…would [represent] no appreciable/minimal risk to human health in… modelled generic land-use situations." (Defra, 2008).*

The SGVs are derived to be applicable as a screening tool for shallow, near-surface contamination in the unsaturated zone. The SGVs, including those for volatile compounds, consider several potentially active pollutant linkages, namely inhalation exposure, exposure via ingestion and exposure via absorption (including through skin). The potential risks via each pathway are then combined following EA guidance (EA, 2009b). Table 7.1 shows where SGVs lie within the human health risk assessment screening process, ie scenarios where a GAC may have to be developed by the assessor.

Table 7.1 ***SGVs within human health risk assessment***

Medium	On-site exposure	Off-site exposure
Soil	SGVs	None
Groundwater	None	None
Other (eg soil gas)	None	None

When assessing exposure from soil by a human health receptor it is generally accepted that SGVs are used where available and appropriate. The SGVs are not derived to be used where the receptor is distant from a soil source, but in many cases their use for this purpose is likely to be a conservative form of screening to protect off-site receptors. For example (assuming the use of SGVs is appropriate), comparison of an on-site concentration of a VOC to an SGV for residential end use where the site use is commercial but the adjacent land-use is residential would be a conservative assessment. Where no SGV has been developed, or extra pollutant linkages need considering (for example, where the source medium is not soil, shown in Table 7.1), assessors should decide whether to develop vapour intrusion/emission GAC (v-GAC) using similar assumptions used to develop the SGVs. The GAC may include other source media and pathways, such as inhalation of contaminated vapours in an indoor air space originating from a groundwater source. Further guidance on developing v-GAC is provided in Section 7.5 and Appendix A10. A concentration in excess of an SGV or GAC does not necessarily demonstrate a risk to human health, only that further consideration and assessment is warranted.

Where GAC/SGVs have not been developed, many stakeholders may choose to undertake a more detailed risk assessment, rather than develop GAC for a particular site.

Soil Guideline Values are developed assuming a generic land-use scenario. The derivation of the SGVs assumes a shallow, near-surface source in the unsaturated zone, which is infinite (non-reducing). Explicit in their derivation is the consideration that exposure will occur via more than one route of entry, including oral, dermal and/or inhalation. The SGVs only model exposure by a human health receptor located close to a soil source (typically on the site), and do not account for the potential for off-site migration of contaminants or the risk to other receptor types.

7.4.2 Is the CSM used to develop the GAC appropriate for the site conditions?

The guidance provided by the EA as part of the CLEA methodology gives a set of generic input values relating to the unsaturated zone soil type, building properties and exposure parameters for three different land-uses. Critical assumptions are made in the development of SGVs, which can be adopted in the later development of GAC for further compounds. For further details on the assumptions and parameter values used to develop the SGVs, reference should be made to the EA CLEA documentation. The assumptions and input parameters were designed to be applicable, or at least be reasonably conservative, for a large number of sites across the UK. However, where the assumptions or input parameters are not appropriate, or are too conservative for a site, a more detailed type of assessment should be considered. This would typically comprise calculation of site-specific assessment criteria, as part of a detailed quantitative risk assessment (DQRA). If the v-GAC are considered highly over-conservative for a site, the assessor may progress to a v-DQRA without undertaking a screening assessment.

7.4.3 Are the vapour intrusion/emission models used to develop the GAC appropriate?

This section focuses on the available vapour intrusion models, as the vapour intrusion pathway typically provides considerably smaller assessment criteria than the vapour emission pathway at a generic stage of assessment.

The sub-model used by the CLEA methodology to simulate the migration of soil gas through the unsaturated zone and migration into an indoor air space is based on the J&E model, which was developed following work by Nazaroff (1988). The model was developed on the basis that vapour intrusion occurs through cracks and openings in walls and foundations that convective transport is most significant in the region close to the foundation/basement, and that diffusion is the dominant transport mechanism away from the building influence (Johnson and Ettinger, 1991). Cracks and openings in a foundation (or basement if present) are conceptualised as a single crack running around the perimeter of the building, between the foundation slab and walls buried below the ground surface. A steady-state, one-dimensional solution is used to calculate transport of vapours through a porous medium (the crack) assuming constant uniform convective velocity (Johnson and Ettinger, 1991 and Johnson, 2002). Further description of the J&E model, including the associated algorithms, is provided by the EA (2009b). A similar solution was proposed by Waitz *et al* (1996), adopted within the modelling tool VOLASOIL (see Appendix A11). Alternative solutions to those presented by Johnson and Ettinger (1991) have been used to assess the vapour intrusion pathway, such as diffusion via pores in concrete or direct emission from uncovered basement soils (Brand *et al*, 2007), and a combination of diffusion (through building materials) and advective

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transport (limited by the permeability of the building floor) described by Ferguson *et al* (1995) and Krylov and Ferguson (1998).

Forms of the J&E model have been incorporated into several software packages, including USEPA J&E spreadsheet and other proprietary software packages such as RISC (developed by Spence and Walden, 2001, latest release in 2008) and RBCA *Toolkit for chemical releases* (developed by GSI, latest release in 2008). Following a review of available vapour intrusion models, Evans *et al* (2002) recommended the use of the J&E model within the CLEA methodology. It was then incorporated into CLEA 1.06 (released in October 2009) and later versions, which are being used to develop the SGVs for volatile compounds.

The version of the J&E model used within the CLEA methodology assumes the following (taken from several sources including EA, 2009b and ITRC, 2007):

- the source of contamination is infinite, and distributed evenly beneath the building
- steady state conditions exist (including flow into the building and building ventilation rates)
- the transport mechanism in the unsaturated zone is predominantly diffusion
- the transport mechanisms close to the building are advection and diffusion
- no degradation of the compound within soil gas occurs during transport
- transport into the building is via cracks in the foundation/walls
- the surface of the foundation slab lies at ground level, or a basement is present
- significant preferential pathways do not exist.

CLEA 1.04 (and the more recent version 1.06) also allows the user to model a depleting source for the vapour pathway if appropriate. When used to assess the risk of vapour intrusion associated with a soil source, assumptions are made when modelling partitioning to predict a concentration in soil gas. These include the assumptions that equilibrium conditions have been reached at the source and that organic matter in the soil is in the same form (see Chiou, 2002).

Recent guidance on the vapour intrusion pathway developed in the US (ITRC, 2007) summarises the physical conditions where the use of the J&E model is most and least suitable, as shown in Table 7.1:

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Table 7.2 ***Applicability of the J&E model (adapted from ITRC, 2007)***

More suitable scenario	Less suitable/inappropriate scenario
Homogeneous site geology/soil	Variable site conditions
Homogeneous contamination underlying building	Substantial lateral transport of soil gas
Uniform building construction (ie similar construction throughout the building)	Wet basements
No significant preferential pathways	Tall buildings in cold climates
	Large buildings with localised pockets of underlying contamination
	Shallow, fractured bedrock conditions

The assessor should consider whether use of the J&E model is appropriate before developing or using GAC/SGVs. In particular, the assessor should consider whether the J&E model is appropriate for the building construction (or planned for construction) at the site.

Quick reference 7.2 ***Critical assumptions in the use of the J&E model***

The J&E model is most suitable under the following conditions:

- **homogeneous geology/soils**
- **evenly distributed contamination beneath the building footprint**
- **uniform building construction (similar construction throughout building)**
- **absence of significant preferential pathways.**

Note that there are several vapour intrusion models used by the risk assessment community, all of which have associated advantages and disadvantages (see Appendix A11). The form of the J&E model adopted within the CLEA methodology is now the preferred option in the UK for developing v-GAC (and is being used to develop SGVs). However, alternative vapour intrusion models (or different forms of J&E) can be considered within a v-DQRA, if justified appropriately. This is particularly the case where the building construction differs significantly from that assumed in the J&E model. The different building construction types listed in Chapter 2 are considered further in Appendix A11 where the applicability of a range of vapour intrusion models is discussed based on the building construction. In some cases (for example, for certain building constructions), the use of the J&E model to predict concentrations of VOCs in an indoor air space could be highly conservative, due to the assumptions inherent in the model.

7.4.4 Comments on the J&E model

"The Johnson and Ettinger model is always conservative" is a phrase still commonly heard within the risk assessment community and the level of conservatism in the J&E model has been subject to considerable debate over the last fifteen years. However, data collected from a small number of high profile case study sites in the US lead to disagreement as to the level of conservatism, if present at all, within the J&E model. Much of the debate relates to the types of contaminants being assessed, for example, petroleum hydrocarbons versus chlorinated hydrocarbons, and how they behave in the environment. This is discussed in more detail in Appendix A2 and within EA (2009b), illustrating

which contaminants the J&E model is likely to be reasonably (or even highly) conservative, and which contaminants the J&E model is less conservative. An understanding of the limitations of modelling versus measuring this pathway, as there are also limitations with measuring, will help the assessor interpret the significance of VOCs in the subsurface.

7.5 DEVELOPMENT OF GENERIC ASSESSMENT CRITERIA (VAPOUR INTRUSION/EMISSION)

There is existing, relatively comprehensive guidance in the UK on deriving SGVs released by the EA (for example, EA, 2009a and 2009b), and many of the assumptions and parameter values provided within the CLEA methodology can be used to derive v-GAC for contaminants where no SGV is yet available, or for pathways not addressed with SGVs. Further guidance on development of v-GAC where no SGV is available is provided in Appendix A10. This includes guidance on methods to derive a GAC for groundwater from the vapour intrusion/emission pathways, though this publication does not specifically provide guidance on how to derive a GAC for other environmental media. Where soil gas data have been collected, including scenarios for potential risks associated with NAPL (see Section 7.3.3), the assessor may choose to develop GAC for soil gas or to progress to a v-DQRA where site-specific levels can be derived for soil gas (see Chapter 8).

7.6 OTHER SCREENING TOOLS – "ALPHA" FACTORS

The alpha factor (see Appendix A2) is a concept developed in the US whereby the level of attenuation (such as degradation, dispersion or dilution) between the source area and the point of exposure has been calculated from a dataset of measured values rather than using a modelling tool to predict the attenuation. For example, the ratio of the measured concentration of VOCs in the soil gas within the source area to that measured in an indoor air space results in a generic alpha factor provided for use as a screening tool. The concept of the alpha factor originated from work undertaken by Johnson (2002) whereby the ratio of the indoor air concentration to the source concentration calculated within the J&E model was identified as a critical parameter. This lead to the collection of empirical data, with the alpha factor measured using site data. Use of measured alpha factors may be a helpful screening tool for assessing sites where large numbers of measurements in multiple locations might otherwise need to be taken. This assumes that extrapolation of the measured alpha factor to locations where the same measurements have not been undertaken is appropriate (such as homogeneous soil or aquifer properties, similar building constructions or similar VOCs present). However, the use of measured alpha factors in place of derivation of GAC would need careful consideration, because alpha factors do not include the contribution to the overall risk from multiple pathways. Also, there is an absence of a UK-specific database on measured attenuation from different environmental source media. If this approach is adopted, the limitations with the method should be understood in the context of existing UK guidance on the assessment of land contamination.

7.7 COMPARISON OF MEASURED CONCENTRATIONS TO GAC/SGVS

Comparison of the measured concentrations of the compounds beneath the site against the GAC/SGVs helps the assessor to evaluate the likely risk to human

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health receptors from pollutant linkages, which include the vapour intrusion/emission pathways. The SGVs, and GAC developed using the same methodology, relate to potential risks via long-term exposure (more than one year).

The result of the v-GQRA, based on the potential risk via chronic inhalation exposure to VOCs, is likely to be one of the following:

- no exceedances of the SGVs/GAC
- no significant exceedances of the SGVs/GAC
- likely (or potentially) significant exceedances of the SGVs/GAC.

For the third result, there are then three options for how a site may progress further, namely further site investigation, a more detailed form of risk assessment or remediation.

Guidance has been released by Defra (2008) to help the assessor determine what represents a possibility of significant harm. The SGVs are derived to represent minimal risk. Measured concentrations of VOCs less than or close to an SGV (or GAC) indicate a minimal or non-appreciable risk to health, so the site can be screened out of the vapour intrusion/vapour emission assessment process (assuming no potential for shorter-term exposure causing adverse health effects – see Section 7.8). Measured concentrations of VOCs above the SGV (or GAC) indicate the possibility of a significant risk that should be further investigated.

The definition of whether exceedances of SGVs/GAC are significant has been subject to debate in the UK for several years, and what constitutes a "representative concentration" for the site or zoned area. There are several methods that likely significance of exceedances can be considered. However, the use of appropriate averaging areas and statistical analysis is a recognised technique for considering multiple data points, as opposed to single data points, which help to assess the potential significance of measured concentrations of compounds present beneath a site. Several guidance documents are available (for example, by USEPA) to help the assessor undertake statistical testing, the most recent being CL:AIRE and CIEH (2008) that focus on statistical testing for soils. It is recognised that there can be difficulties applying statistical tests to data where there is potential spatial and temporal variability. If using statistical techniques to assess the vapour intrusion/emission or release pathways considerable care should be taken, and in some cases the use of statistical testing will not be appropriate. For example, the building footprint may differ from the adopted averaging areas, or a preferential pathway(s) may be present in a localised area of contamination allowing vapour intrusion from that area into the building. The selection and use of statistical testing should be considered on each site, taking into account all relevant aspects of the CSM.

7.8 ASSESSING SHORTER-TERM EXPOSURE

Generic assessment criteria typically focus on the potential risks to human health from the vapour intrusion/emission pathway from relatively long-term (greater than one year) exposure durations. However, for some compounds, the potential for health effects from short-term exposure (while not presenting an immediate risk to human health – see Section 7.3.1) needs to be considered.

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Typically, this sort of exposure may be due to occupational practices, for example:

- a construction worker developing brownfield sites (occupational), for example, due to vapour emission
- a worker undertaking remediation works on sites affected by land contamination (occupational), for example, due to vapour release
- residents living on a developed brownfield site (non occupational, for example, through short-term vapour release events when tending the garden).

For each of the examples provided, the exposure period may be long-term (ie more than one year) or short to medium-term, depending on the frequency and duration of exposure events. In many cases where the short-term exposure is occupational in nature, potential risks can be managed by complying with pre-existing legislation/guidance, such as carrying out Control of Substances Hazardous to Health (COSHH) assessments or the use of regular air quality monitoring screened using workplace exposure limits (WELs). Use of Personal Protective Equipment (PPE) is recognised as a tool to be employed as an extra means of risk reduction, but ideally should not be solely relied upon to mitigate potential risks. Where the potential for shorter-term exposure could occur involving the general public/future site occupiers exists, a more detailed investigation and/or assessment is likely to be required (such as the potential for the multiple vapour release events in the example above). Reference to short to medium-term exposure toxicity data (such as produced by the Health Protection Agency) can help decision making, provided appropriate site data have been collected. However this form of assessment does not sit easily within the v-GQRA process. This is discussed further in Chapter 8.

7.9 POTENTIAL ODOUR EFFECTS

Some VOCs, and other volatile compounds, can be detected at relatively low concentrations. While a link between odour detection and adverse health effects has not been identified (Wilson *et al*, 2007), odours can cause potential nuisance effects such as nausea and a perception of adverse health effects. Under certain scenarios, odours can also be classed as a statutory nuisance under the Environmental Protection Act 1990. The potential for odour nuisance effects should not be discounted from the vapour intrusion/emission pathway assessment, even at a generic stage of assessment, and may warrant the need for further investigation/assessment or remediation. Note that there is often a large range in the reported odour threshold values, given the variability in perception at a receptor level. Examples of VOCs that are recognised as having the potential to cause odour nuisance effects as well as adverse health effects are carbon disulphide and naphthalene. Typical odour threshold values can be found on the HSE website <www.hse.gov.uk>, and in van Gemert (1999) and Nagy (1999). However, note that the origin of an odour may not be related to land contamination, instead being linked to above-ground work.

7.10 RESULT FROM THE V-GQRA

The result of the v-GQRA should allow the assessor to conclude that there is:

1 Unlikely to be significant risk to human health from vapour intrusion/emission.

2 Likely/potential for significant risk to human health from vapour intrusion/emission.

For the first result, the assessor can conclude that no further consideration of the vapour emission/intrusion pathway is needed within the assessment, but other pollutant linkages may still encourage the need for further works at the site.

For the second result, the next step (one of four) will depend on the level of certainty in the data collected/the assessment alongside a range of factors, including the regulatory requirements, timings or commercial factors (such as financial). The assessor may choose to undertake further intrusive investigation to refine the v-GQRA, to undertake a v-DQRA or to proceed to developing remediation options to help manage the identified (or potential) risk, on each site.

7.11 SUMMARY

The results of the v-GQRA should demonstrate whether further consideration of the vapour intrusion/emission (or release) pathways is required, or whether the site has been screened out of the assessment process.

As for the v-PRA, where an immediate risk to human health is known, or suspected, risk management and/or mitigation measures should be applied directly, before undertaking further investigative or risk assessment, to safeguard human health.

The v-GQRA is phased in approach:

1 The CSM is refined using the results of site investigations, in some cases allowing sites to be screened out of further assessment for the vapour intrusion/emission pathways without the use of quantitative screening levels.

2 Generic assessment criteria (v-GAC) are adopted where appropriate as a further form of screening.

Many sites affected by land contamination would be expected to be screened out of the vapour intrusion/emission assessment process at this stage. However, where a site warrants further consideration, the assessor can progress to the next stage in the assessment process (a v-DQRA) or may choose to consider remediation options.

For the majority of sites, the CSM will include further pollutant linkages to the vapour migration/intrusion pathways. These extra pathways should be considered before a decision of no further action can be taken for a site.

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7.12 FURTHER INFORMATION

CL:AIRE and CIEH (2008)
Guidance on comparing soil contamination data with a critical concentration
Published by CL:AIRE and the Chartered Institute of Environmental Health, with support from the Soil and Groundwater Technology Association (SAGTA) and the Royal Environmental Health Institute of Scotland (REHIS) (ISBN: 978-1-904306-79-5). Available from: <www.claire.co.uk/>

DEFRA (2008)
Guidance on the legal definition of contaminated land
PB 13149, Department for Environment Food and Rural Affairs. Available from: <www.defra.gov.uk/ENVIRONMENT/land/contaminated/pdf/legal-definition.pdf>

EA (2009b)
Updated technical background to the CLEA model
Science Report SC050021/SR3, Environment Agency, Bristol. Available from: <http://publications.environment-agency.gov.uk/pdf/SCHO0508BNQW-e-e.pdf>

EVANS, D, HERS, I, WOLTERS, R M, BODDINGTON, R T B and HALL, D H (2002)
Vapour transfer of soil contaminants
R&D Technical Report P5-018/TR, Environment Agency, Bristol

JOHNSON , P C and ETTINGER, R A (1991)
"Heuristic model for the intrusion rate of contaminant vapors into buildings"
Environmental Science and Technology, 25 **(8)**, American Chemical Society, Washington, USA, pp 1445–1452

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8 Vapour intrusion/emission detailed quantitative risk assessment

8.1 INTRODUCTION

Detailed quantitative risk assessment (DQRA) forms the third stage of the vapour intrusion/emission assessment process (Figures 3.1 and 8.1), following the general framework for risk assessment defined within CLR11 (Defra and EA, 2004a).

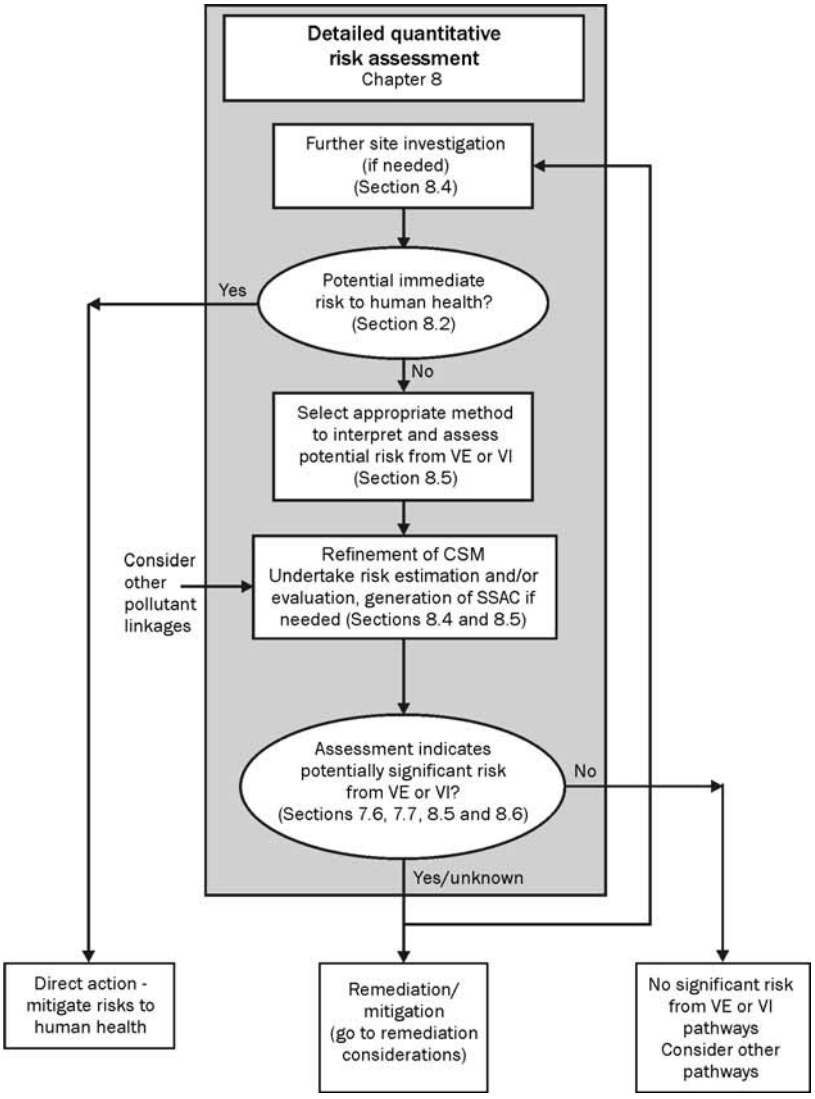

Figure 8.1 ***Detailed quantitative risk assessment (extracted from Figure 3.1)***

The level of detail incorporated in the vapour intrusion/emission DQRA (v-DQRA) will typically depend on the complexity of the site setting, the nature and extent of the contamination, and the overall objectives of the assessment process. Case study A3.1, which has already been used to show the progress of a site from v-PRA to a v-GQRA, illustrates a v-DQRA in practice. This case study is

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also referenced in Chapter 9. Whereas Case study A8.1 illustrates a site progressing from v-PRA to v-DQRA without undertaking a v-GQRA, due to the complexities of the CSM.

For the majority of sites, the v-DQRA can be viewed as an extension to the v-GQRA. However, further site-specific data are incorporated into the risk assessment process, typically requiring a higher level of experience in undertaking quantitative risk assessment than for a v-GQRA. Where the most complex form of v-DQRA (for example, requiring data collection over many months) is required, it would not be unusual for the assessor to choose to progress directly to remediation, though in many cases simpler forms of v-DQRA may only a few days or weeks to complete. Examples of situations where a v-DQRA would or may be undertaken are shown in Example 8.1.

Example 8.1 ***Reasons for undertaking a v-DQRA***

- the results of the v-GQRA indicated a likely or potentially significant risk, for example, compounds of concern were present in the subsurface at concentrations above the SGV/GAC
- the v-GQRA was not appropriate to determine the likely level of risk, for example:
  - no SGV/GAC were available for the compound(s) of concern
  - the SGV/GAC could not be used to assess the site, as the site setting/condition did not closely match the assumptions inherent in their derivation
  - no SGV/GAC were available for the source media
- NAPL has been identified, which is considered to present a potential risk from inhalation of vapours
- remediation is planned at the site, whereby SSAC are preferable to SGV/GAC.

For those sites where a more complex form of v-DQRA is undertaken, a higher level of data collection and data interpretation will often be required (see Example 8.2 for further details of these sites).

Example 8.2 ***Sites needing a more complex form of v-DQRA***

- highly complex geological/hydrogeological setting (for example, in Case study A8.1)
- "carrier" gases are likely to be transporting "trace" gases to the surface, for example, some landfill sites
- use of the J&E model for the vapour intrusion pathway is not appropriate (see Chapter 7)
- the results of the v-GQRA indicated a potentially significant risk
- detailed measurement to quantify the level of risk via the vapour intrusion/emission pathways is considered more appropriate than use of a modelling tool (for example, reports of odours in a property).

Several factors should be considered throughout the development of a v-DQRA, such as:

- the potential for immediate risk to human health
- the use of measurement and modelling, and how to combine them
- the value of collecting further site data, and whether it will affect decision making

- potential times involved in carrying out the assessment
- the regulatory context
- commercial factors (eg financial implications)
- level of experience needed
- community factors.

8.2 POTENTIAL IMMEDIATE RISK TO HUMAN HEALTH

As for earlier stages of assessment, where a potential immediate risk to human health is present or suspected, direct action should be taken to mitigate the risk (also discussed in Chapters 4 and 7), and should be considered throughout the investigation and assessment process. Often, the solution used to mitigate the risk may only be temporary, and further works are likely to be needed to find a permanent solution. Assessing the potential for immediate risk to human health from inhalation exposure, as opposed to the risk of explosion, can be difficult, especially where direct measurements (such as air quality data) cannot be taken. However, as part of the v-DQRA, modelling tools could in some cases be used to predict a concentration at the point of exposure (for example, an indoor air concentration) from measured concentrations of VOCs in the subsurface. This concentration can then be compared to air quality levels relating to acute health effects to assess whether there is a potential risk. Further information on air quality standards that give an indication of threshold levels associated with acute health effects can be found at:

Health Protection Agency <www.hpa.gov.uk>

Health and Safety Executive <www.hse.gov.uk>

European Chemicals Bureau <http://ecb.jrc.it/activities>

World Health Organisation <www.who.int>.

8.3 OBJECTIVES FOR V-DQRA

The objectives of undertaking a v-DQRA are:

1 To characterise the site using the site data (further data acquisition may be required), helping to confirm the presence/plausibility of a vapour pathway being active.

2 To refine the CSM by estimating and/or evaluating the risk from the vapour intrusion/emission (or release) pathways, often including the development of site-specific assessment criteria (SSAC) using an appropriate modelling tool(s).

3 To determine whether remediation is required based on vapour intrusion/emission pollutant linkages, on the basis of the refined CSM.

Figure 8.1 illustrates the different stages of the v-DQRA vapour intrusion/emission assessment process, as listed above and described in more detail throughout this chapter. As with all levels of assessment in this guidance, the process can be applied flexibly and iteratively, but other potentially active pollutant linkages should be noted.

An important decision in the v-DQRA process is considering when to collect further site data and how much reliance to place on modelling tools. A balance

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needs to be struck between the two, only collecting data if the assessor is clear as to how the data can be interpreted and evaluated, and only using modelling tools if the assessor understands whether the model is appropriate, in either case the associated limitations need to be understood. Multiple lines of evidence are often needed to provide confidence in the result of the assessment, and both measurement of the vapour intrusion/emission pathway and modelling of the pathways may be needed.

The result of the v-DQRA may lead to considering potential remediation options or to exit the assessment process for the vapour intrusion/emission pathways.

8.4 REFINEMENT OF THE CSM

8.4.1 Introduction

As shown in Figure 8.1 the first stage in the v-DQRA is to collect further site data (if needed) to help refine the CSM. For some sites, the collection of further site data may not be needed before undertaking a v-DQRA. Further data may be linked to additional intrusive site investigations, and could take the form of more detailed assessment of the site condition (for example, collating information on building construction), or could include further desk-based research or laboratory testing.

The assessor may choose to undertake further site investigation works for several reasons, such as:

- to improve the understanding of the contaminant distribution
- to provide site-specific data for input into modelling tools
- to reduce levels of uncertainty in modelling the vapour intrusion/vapour emission pathway
- to provide extra lines of evidence for inclusion/discounting the vapour intrusion/emission pathways.

8.4.2 Collection of extra investigation data

Before undertaking additional investigations, the assessor should consider how the data are going to be incorporated into the v-DQRA, how it might affect decision making and whether there are community concerns (such as causing undue stress) associated with the collection of further data. For some sites, it will be appropriate to use the data within a modelling tool to evaluate the risks associated with the vapour intrusion or vapour emission pathways. Where this is the case, the assessor should consider the parameters that may have the highest sensitivity. For example, several papers have been written documenting the most sensitive parameters within the J&E indoor air model, which should help with the design of the investigation (for example, Johnson, 2002 and Evans *et al*, 2002), as summarised in EA (2008b). For other sites, the use of modelling tools may not be appropriate. Further detail on the use of modelling tools is provided later in Sections 8.5.2 to 8.5.5.

Example 8.3 gives more information on the extra data that might be collected as part of the initial stages of a v-DQRA.

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Example 8.3 ***Data collection as part of v-DQRA***

- investigation of more sample locations
- collection and analysis of samples from different media (eg soil gas directly beneath a building or indoor air sampling)
- testing the physical properties of the unsaturated zone (eg organic matter content)
- collecting data to evaluate attenuation mechanisms in the unsaturated zone (eg biodegradation of VOCs)
- further investigation into existing building construction.

8.4.3 Design of further investigation works

The aim of further investigations is to refine the CSM by improving understanding of one or more of the processes in the migration pathway by:

- further investigation and assessment of the source
- migration through the unsaturated zone
- transport into an indoor or ambient air space
- dilution in an indoor or ambient air space
- inhalation exposure by a human health receptor.

The following sections outline several methods that can be employed to refine the understanding of the vapour intrusion and emission pathways. In some cases, for example, when undertaking a programme of indoor air sampling the assessor may need to develop a risk communication plan, and consider how best to share information with different stakeholders (for example, Petts *et al*, 2001, Petts *et al* 2003a and b, SNIFFER, 1999, NICOLE, 2002 and CL:AIRE 2007 and 2008). For many projects, good risk communication will be instrumental in successful delivery of a project.

Throughout the process, it should always be remembered that the intrusive investigation process is often iterative (or "phased"), in nature (Defra and EA, 2004a).

8.4.4 Further investigation and assessment of the source

The assessor should have a good understanding of the source nature, characteristics and distribution before completing any form of v-DQRA. The following physical input parameters are typically used to estimate the concentration of the compound of concern in soil gas where the presence of VOCs in soil gas has not been measured directly. This includes partitioning from a VOC sorbed to the soil or present in dissolved phase in groundwater. Many of the properties listed are used directly as input parameters within either the J&E model or the CLEA vapour emission model. Some properties can also be used to estimate the concentration in soil gas originating from an alternative source (for example, NAPL):

- properties of the environmental source medium
  - temperature at source
  - organic matter content
  - bulk density

- total porosity
- moisture content (which can vary with time)
- capillary fringe properties

- source composition and distribution
  - the source composition
  - the depth to source and location with respect to groundwater
  - extent and level of contamination on-site
  - extent and level of contamination off-site (known or estimated)
  - distance to nearest building (for vapour intrusion pathway).

Guidance is provided through the CLEA framework (for example, EA, 2008a) on selection of appropriate toxicological (health criteria values) and chemical data for compounds where no values have been provided to date.

Further investigation and assessment of the source may be needed as the assessor proceeds through the v-DQRA process, in particular for sites where knowledge about the nature of the likely compounds of concern is limited. The assessor may wish to undertake one or more of the following forms of further investigation to aid refinement of the CSM.

Toxicological studies

For some VOCs, limited data is available from common literature sources (for example, those recommended within EA, 2008a) relating to their toxicological properties. A more detailed literature review may be needed for certain compounds.

Installation of off-site monitoring points

The need to obtain relevant permissions to investigate off-site locations, alongside the need to consider developing a risk communication plan, often mean that off-site investigations are not undertaken on a regular basis during brownfield site assessments in the UK. As part of the more detailed form of assessment for the vapour intrusion/emission pathways, investigations in off-site locations may be preferable to relying on model predictions.

Carrier gases and trace components

For sites where a large flux of potential carrier gases (such as carbon dioxide or methane) has been identified, and trace components are also suspected to be present, sampling for the presence of trace components should be considered. This is unlikely to be needed for the majority of sites, but will be most common on landfill sites or adjacent properties. Guidance on the types of trace components that should be considered at landfill sites is provided by the EA (2004a), with a priority list of 25 "significant" components. For sites where considerable uncertainty is present with respect to the nature of the source material, and the types of volatile compounds present in soil gas, use of trace components soil gas analysis may help to identify indicator compounds of concern. A list of over 500 trace components has been reported in soil gas within landfills (EA, 2002).

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Forensic analysis of data

The concept of forensic data collection and analysis is discussed in existing guidance documents (for example, ITRC, 2007). Relatively sophisticated analytical techniques are applied to samples taken from the source zone (and from other points in the vapour intrusion/emission pathways), providing a "fingerprint" style assessment of the nature and source of the compounds of concern. Techniques applied include comparison of compound ratios, relating to degradation parent and daughter compounds and the use of isotope ratios to distinguish different sources where multiple sources are present (for example, Hawthorne, 2008).

8.4.5 Migration through the unsaturated zone

The following physical input parameters, for which data can be collected using relatively common investigation techniques, are typically used to model the migration of VOCs in soil gases through the unsaturated zone overlying the source zone (for example, within the J&E model):

- total porosity
- bulk density
- particle size analysis
- moisture content (which can vary with time)
- presence of lower-permeability strata within unsaturated zone, and properties
- organic matter content
- indicators of biodegradation (eg ratios between oxygen and carbon dioxide content).

There are several investigative techniques that can be used to obtain further information on the migration of VOCs in soil gas through the unsaturated zone:

Physical properties of the unsaturated zone

The properties listed above can be investigated using commonly adopted techniques (for example, collecting undisturbed samples for porosity testing). However, for some sites, it may be appropriate to collect further data relating to the physical properties of the unsaturated zone. If a modelling tool is used to assess the pathway, the assessor should consider the data requirements for the model, and whether site-specific data is needed or preferable to undertake the modelling. Ideally the sensitivity of the parameter within the model should be understood to help this decision making.

Case study 8.1 ***Measuring the soil vapour permeability***

For a site in central England, a potential vapour intrusion pathway was identified for VOCs entering residential properties. One important parameter in the modelling tool used to predict the indoor air concentration was identified as the soil vapour permeability of soils directly underlying the buildings. A soil vapour extraction system was applied to monitoring wells specifically designed (and screened) to target the relevant horizon, and the response monitored within neighbouring wells, enabling the site-specific soil vapour permeability to be calculated.

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A simple pneumatic test has also been developed (for example, Baehr and Hult, 1991, Switzer and Kossan, 2007, ITRC, 2007 and Ettinger, 2008) that can be used to estimate soil permeability, similar to a single well step drawdown test undertaken in a groundwater monitoring well. As for Case study 8.1, the design and screening of the well needs careful consideration.

Vertical profiling (contaminant distribution)

The installation of "nested" soil gas monitoring points provides information on the vertical distribution of VOCs in soil gases within the unsaturated zone, and the level of attenuation between the source and receptor air space. Sampling and analysis methodologies and monitoring techniques are described in Chapter 6, and should be referred to for further details. Where the vertical soil gas profile is likely to change over a period of time (for example, with large fluctuations in groundwater) the sampling programme needs to take this into consideration. Examples of scenarios where vertical profiling of the unsaturated zone could be useful include:

- significant thickness of unsaturated zone/deep source
- presence of horizons with variable permeability overlying the source
- to help demonstrate whether biodegradation of VOCs in soil gas is occurring.

Case study 8.2 ***Vertical soil gas profile using semi-quantitative techniques***

Vertical soil gas profiling was undertaken in the garden of a residential site in England. From laboratory analysis of soil samples collected from boreholes, the compound was known to be present in soils at a depth of around 1.5 m below ground level, but was also detectable using a PID and flame photometric detector (FPD). Preliminary screening of the vertical soil gas profile was originally undertaken by lowering a PID down a borehole, which indicated that concentrations of the compound were considerably lower at ground surface compared with the source zone. This was further confirmed within *in situ* probe holes, using an FPD, with readings taken at 0.015 m intervals. Typical results are plotted on the graph in Figure 8.2, illustrating that significant attenuation was occurring between the source zone and the ground surface.

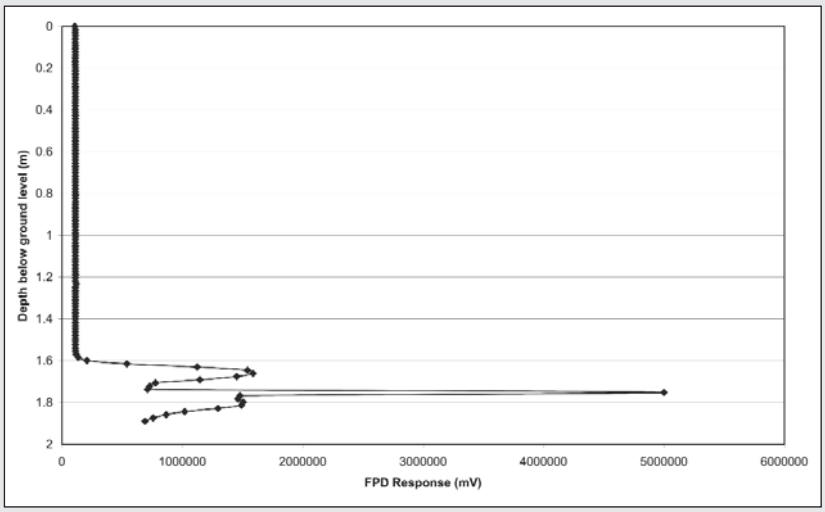

Figure 8.2 *Attenuation of a VOC, as measured with an in situ FPD probing tool*

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Analysis of samples from different horizons for typical degradation products as well as VOCs can help illustrate whether degradation is occurring, and the level of attenuation between the source and the ground level or building foundation. This is most commonly undertaken for the VOCs such as petroleum (non-halogenated) hydrocarbons, many of which undergo microbial aerobic degradation where sufficient oxygen is present in the subsurface (for example, Chaplin *et al*, 2002). Measurements of gases such as oxygen, methane and carbon dioxide with depth can provide an indication as to whether degradation of such compounds is occurring (see Appendix A2 for further details), typically using hand-held instruments on site.

Considerable care needs to be taken when collecting and interpreting data relating to the vertical soil gas profile for a site where new development is planned. Construction of a building or other form of cover over a previously open space can significantly affect the vertical profile of VOCs in soil gas (see Chapter 4).

Lateral profiling (contaminant distribution)

Alongside vertical profiling, and to understand the distribution of VOCs in the unsaturated zone, similar techniques can be used to assess the lateral distribution to build up a three-dimensional conceptualisation. The decision to undertake more detailed analysis to understand the lateral distribution within the unsaturated zone will depend on several factors, such as:

- the depth to, and extent of, the source with respect to the point of exposure
- the source media, and whether lateral transport is likely in the subsurface
- the presence of preferential lateral flow pathways requiring further assessment
- the level of certainty in data collected during earlier levels of investigation
- presence of relatively impermeable surface covers.

8.4.6 Transport into an indoor or outdoor air space

The following physical input parameters, for which site data can be collected using relatively common investigation techniques, are used to model the transport and dilution of VOCs in soil gases into/within an indoor or outdoor air space:

- indoor air space (for vapour intrusion)
- building type
- building dimensions
- foundation and substructure construction
- outdoor air space (for vapour emission)
- relative permeability and condition of surface cover if present
- typical prevailing wind direction
- mean annual wind speed
- rainfall and temperature.

The transport of VOCs in soil gases towards ambient air or a building, and the later migration into/dilution within the overlying air space, can be further investigated using several different techniques.

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Concentrations of VOCs in soil gas at the near-surface

For sites where buildings or areas of covered land (for example, concrete hardstanding) are present, sampling VOCs in soil gases just beneath the structure can in some cases reduce the degree of uncertainty (and in some cases, the degree of conservatism) associated with modelling the vapour intrusion/emission pathways. Use of this data, for example, within a modelling tool, in place of a source concentration removes the need to model the transport of the compound through the unsaturated zone, and may take account of bioattenuation processes.

Investigation techniques used to measure concentrations of VOCs in soil gas beneath a structure are typically referred to as sub-slab and near-slab sampling. Both techniques, and their associated merits and disadvantages, are discussed in detail in Chapter 6.

Use of tracer gases to measure vapour intrusion

The intrusion of vapours into an indoor air space typically occurs through joints, cracks and other unintentional openings in the building foundation (for example, Johnson and Ettinger, 1991, Waitz *et al*, 1996 and Danish Environmental Protection Agency, 2002). Studies have been undertaken to measure the migration of soil gas from the subsurface into an overlying indoor air space using tracer gases. While tracer gases, such as helium, are commonly used to assess whether soil gas sampling equipment is leaking, they can also be used to help the assessor quantify the level of vapour intrusion occurring at a site, and where intrusion is occurring. Tracer gases are also referred to as marker compounds within literature (for example, ITRC, 2007). The most commonly quoted tracer or marker compound is radon (where it is naturally occurring), although other inert marker compounds can be used where radon is not naturally occurring.

When choosing a tracer gas, the assessor should consider factors such as:

- if the tracer gas may already be present in the structure (eg whether the tracer gas may be used within typical consumer products)
- whether a tracer gas is present in the subsurface, or whether it needs to be introduced
- how it could interact with the existing VOCs if introduced
- the type of equipment and sampling techniques needed to undertake the test
- the limits of detection needed to allow valid interpretation of the data
- whether the data collected will allow a semi-quantitative or quantitative type of assessment
- the need to conduct the testing under different conditions (eg temporal changes, during winter and summer months)
- the existence of existing engineered controls (ie a synthetic membrane).

Existing guidance on undertaking tracer gas or marker compound investigations to assess the vapour intrusion pathway is limited, but examples are described by Wisbeck *et al* (2006) and McHugh *et al* (2008). Typically, tracer gas investigations include measurement of concentrations of the tracer gas in several sub-slab

locations alongside many locations within the structure. Similar techniques can be employed to assess the integrity of engineered controls (see Chapter 9 for further details).

Use of flux chambers

Flux chambers can be used both qualitatively and quantitatively to locate surface fluxes of VOCs, and are most typically used in the UK for sites where vapour emission is suspected (for example, landfill sites). Flux chambers are not designed for quantitatively investigating migration of VOCs from the subsurface into buildings. Guidance on the use of flux chambers is given in Chapter 6.

Measuring ventilation or air exchange rates

Vapours migrating into an indoor or outdoor air space are diluted within the air already present, before being inhaled at the point of exposure. Investigation techniques can be used to assess the level of dilution within the air space, and measured concentrations at the point of exposure.

The rate at which air present within an indoor or outdoor air space is replaced is used to assess the dilution of VOCs in soil gases originating from the source. For an outdoor air space, the degree of dilution is commonly modelled through wind effects (EA, 2008b). Site-specific data can be obtained on the average wind speed and direction if required, although there may be a cost implication (for example, from the MET Office). For indoor air spaces, the ventilation rate is used to model the dilution effect, but it can be harder to obtain site-specific data for this parameter. One technique is the use of a tracer gas, such as helium or sulphur hexafluoride (SF6). Either the decay of a defined release of the gas is monitored, or a constant release of the tracer gas is monitored over several air exchange periods. Further guidance on undertaking ventilation rate tests using tracer gases, and other forms of investigation for ventilation rates, is provided in documents such as BS EN ISO 12569:2001, BS EN 1524-1 and 2:2007 and BS ISO 16000-8:2007.

Indoor air sampling

When used as part of multiple lines of evidence, undertaking indoor air sampling and analysis for the presence of VOCs can in some, but not all, cases provide the definitive evidence that there is an active and significant pathway involving either vapour intrusion or emission linking the source and receptor via an inhalation exposure pathway. Investigation techniques for undertaking indoor air sampling are discussed in Chapter 5, but the main points to consider when developing an indoor air sampling and monitoring programme include:

- background sources for VOCs (eg consumer products)
- number and location (including height) of sampling points
- factors that could affect ventilation (such as air conditioning and opening of windows)
- risk communication plan (for occupied premises)
- levels of detection
- time taken for monitoring

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- uncertainties and likely errors in the data
- monitoring background conditions (eg ambient air outside the property).

An example pro-forma designed to be used before and during indoor air sampling is provided in BS EN ISO 160000-1:2006.

Case study A8.1 provides a detailed assessment of an indoor air monitoring programme. It illustrates the difficulties and benefits of undertaking indoor air sampling on a site with a complex geological setting and a source term with the potential to affect many overlying structures.

Outdoor air sampling

For some sites, the vapour emission pathway may require further evaluation, resulting in the need for the assessor to undertake outdoor air sampling. The source may be within the subsurface (for example, beneath a garden of a residential property) or could be present at the surface (for example, ex situ treatment of soils containing VOCs). Investigation techniques for undertaking outdoor air sampling are discussed in Chapter 6 but, as for indoor air sampling, main points to consider when undertaking an outdoor air sampling and monitoring programme include:

- background sources for VOCs (eg traffic fumes)
- number and location (including height) of sampling points
- risk communication plan (for some sites)
- levels of detection
- timings for monitoring
- prevailing wind direction.

Case study 8.3 ***Monitoring of ambient air quality during ex situ remediation of soils***

North west England

The site was formerly used for refining crude tar and fractioning chemicals, and had been in operation from the early 1900s up until around 1965. The process created several chemical intermediates (including benzol, creosols, phenols and naphthalene). From 1965 the site changed use and became a storage facility for heavy fuel oils, and a chemical manufacturer. Site investigations had revealed the presence of aliphatic and aromatic hydrocarbons in the range C10 to C35, benzene, toluene, xylenes, phenols and naphthalene in the subsurface soils and groundwater. Remediation criteria were developed for the site, and a remediation plan was developed comprising the use of multiple techniques including ex situ and *in situ* bioremediation, ex situ and *in situ* vapour extraction, multi phase extraction, groundwater pump and treat, ex situ chemical oxidation and *in situ* air stripping.

During progression of the unsaturated zone remediation works, an area of about 2500 m² was discovered with naphthalene concentrations several order of magnitude greater than the site investigation had previously encountered (up to 1000 mg/kg), with clear evidence of crystalline naphthalene in places. The remediation "treatment train" (ie the combination of remediation technologies employed) already in use at the site was sufficient to enable the treatment of this new area of contamination to the remediation criteria. Careful excavation and preparation of the soils for treatment was required and was started in accordance with already established method statements and emission levels for both off-site receptors beyond the site boundary and on-site remediation workers. The air quality was being monitored via sorbent tubes and on-site PID measurements over a rolling 28-day averaging period. However, it quickly became apparent that while operating within these levels the public surrounding site had some concerns over the strong odours being experienced. Due to the level of concern the remediation contractor, local regulatory authorities and the Health Protection Agency

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(HPA) convened a multi-agency group to address the concerns of the local public.

Following a review of the workplace exposure limit at the time of remediation, the HPA advised that for this site the 28-day average for the naphthalene concentration in air at the site boundary should be kept below 0.6 ppb. This target was developed taking into consideration the inhalation health criteria value for naphthalene (appropriate at the time of remediation), but was considerably lower than a target derived through modification of the workplace exposure limit to account for 24-hour exposure by more sensitive receptors (10 000 ppb).

Working with the EA and the HPA, and following site-based research, a monitoring protocol was developed to ensure that real time on-site PID monitoring, combined with quantitative laboratory analysis (active and passive sampling) for samples collected across the site, could be used to predict whether concentrations at the site boundary would exceed the recommended 0.6 ppb target. Predicting the emission and release of vapours using mathematical models proved unsuccessful for this site.

The monitoring protocol comprised the use of:



Figure 8.3

Monitoring ambient air quality during development of the monitoring protocol

- a "monitoring point" close to the excavation (monitored regularly using a PID to give real time indications of the potential off-site migration of vapours and identify the need for corrective action)
- two "compliance points" set between the site boundary and excavation, where the daily active (pumped) samples were collected using sorbent tubes, with a ppb detection limit
- "confirmation" sample locations at the site boundary and around the locality (eight in total) using a passive sampling technique (sorbent tubes left *in situ* over a 28-day period) with a sub-ppb detection limit. The results were incorporated into a rolling 28-day average concentration at the site boundary.

The protocol provided each of the stakeholders with confidence that remediation progressed in compliance with the newly proposed standards. However, due to the low level of the recommended air quality standard, using a hand-held PID alone would not have been sufficient to ensure continual compliance during the remediation works.

Where outdoor air sampling is undertaken as part of a wider investigation (such as to record background conditions while indoor air sampling), the outdoor air sampling should be undertaken at the same time as other samples are collected.

8.4.7 Exposure pathways and receptors

The EA have provided typical exposure values for a range of parameters in Updated technical background to the CLEA model (2009) and associated documents for different age ranges, including exposure duration, exposure frequency and inhalation rates. Where appropriate for the exposure scenario

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being modelled, EA (2009b) should be referred to for input parameters. If the exposure scenario being modelled does not closely match those presented in EA (2008b), alternative literature data sources should be considered, sensitivity testing undertaken and justification provided as to the selection of the final values.

For some exposure scenarios it will be appropriate to carry out a survey to identify the type of receptor at risk and the nature of the exposure. Case study 8.4 illustrates a site where such a survey was carried out.

Case study 8.4 ***Receptor and exposure scenario identification***

Active chemical plant, east England

A survey was carried out as part of further investigations undertaken at the site, due to the presence of multiple buildings with different use. Buildings used for manufacturing processing were distinguished from those used for laboratory analysis and breaks (for example, the canteen areas). Site staff were interviewed to ascertain the working patterns, which were shift-based, and used to develop site-specific exposure data for different parts of the site. Consideration was also given to whether occupational exposure to the same compounds of concern present in the subsurface was occurring due to working practices, in estimation of the level of risk via exposure to vapours.

8.5 RISK ESTIMATION AND RISK EVALUATION

The second stage of the v-DQRA is to collate the data, assess how best to use and interpret the data, and then estimate and evaluate the level of risk to human health via the vapour intrusion/emission pathways.

8.5.1 Data collation and interpretation

Methods of data collation should be considered during the assessment process. For some sites, collating large volumes of data within an electronic database can result in significant cost and time savings. In designing the database, the assessor should note factors such as:

- how the data will be used (what output is required from the database)
- the need to undertake statistical testing
- data ownership/confidentiality requirements
- storage requirements
- quality assurance/quality control (eg data entry).

Where sufficient data have been collected to allow statistical testing to be undertaken, and where the use of statistics has been determined as appropriate (see Section 7.7), suitable averaging areas and the choice of statistical test need to be considered. Further guidance on undertaking statistical testing on land contamination sites (soils) is included in documents such as CL:AIRE and CIEH (2008) and Nathanail (2004), with a wider range of statistical tests described by USEPA. As stated in Chapter 7, considerable care is needed in using statistical testing to evaluate site data relating to the vapour pathways.

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For any data collected, it is important to understand the limitations, uncertainties, likely margins of error, and the level of confidence in the results. For example, if concentrations of a compound have been recorded in indoor air, how do these relate to "typical" background concentrations? Not only collecting air quality measurements with appropriate detection levels, but interpreting the data can be difficult, ie the differences between contributions from a subsurface source and ambient/background conditions. If the limitations and uncertainties associated with different types of data are not taken into account, the result of the risk evaluation may not represent the true site conditions and level of risk.

Case study 8.5 ***Understanding uncertainties and limitations with data***

Active industrial site, central England

A site in central England was found to be contaminated by halogenated hydrocarbons (notably trichloroethene, 1,2-dichloroethene and vinyl chloride). The level of the contamination varied across short lateral distances, due to the composition of the underlying geology, which comprised weathered mudstones. This made the collection of soil gas samples for VOCs analysis difficult due to the potential for saturation of the sorbent where the contamination was highest. As a result, a balance had to be achieved between obtaining a low detection level where contamination levels were low (or where the degradation products 1,2-dichloroethene and vinyl chloride were not present at high concentrations) and obtaining quantitative data on the compounds present at high concentrations. Figure 8.4 illustrates the results of the first round of soil gas sampling, with the arrows indicating sample locations where the sorbent tube was effectively saturated.

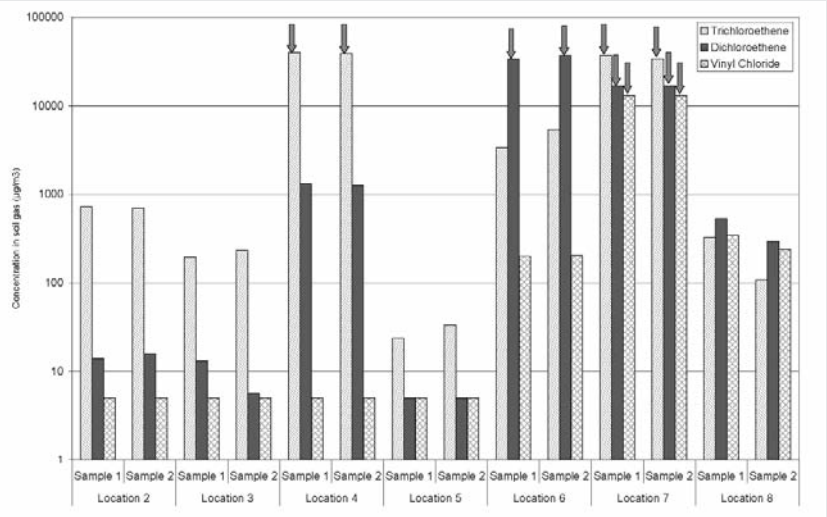

Figure 8.4 *Results of the soil gas sampling*

The results indicate not only the importance of understanding the limitations with data that can be present due to varying ground conditions and the contaminant distribution, but also the uncertainty in laboratory analysis results (as shown by the varying results from the duplicate samples). The data collected for this site enabled the limitations and uncertainties with the data to be understood, helping to refine the investigation and assessment method used for the second round of soil gas monitoring. Use of more than one sorbent tube in series would have been one method to test whether saturation and breakthrough of the first tube in the series is occurring.

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8.5.2 USE OF MODELLING TOOLS

Modelling tools can be useful to help the assessor estimate and evaluate the risk to human health, given specific site conditions. Some modelling tools have the ability to predict the level of risk from a measured concentration, or concentrations, in soil, groundwater or another source media, by comparing a predicted daily dose with the tolerable daily dose or health criteria value. This form of risk estimation is sometimes referred to as "forward risk assessment" and provides a ratio commonly termed a "hazard index". The CLEA methodology requires that the hazard index for each potentially active pathway for an environmental source medium is summed to provide an indication of overall risk, provided that there is no toxicity evidence to suggest it is inappropriate to do so. A total hazard index (or hazard quotient) of greater than unity indicates a potentially significant risk. Several commonly used modelling tools have the capability to undertake this form of "forward risk assessment".

The CLEA methodology also promotes the development of site-specific assessment criteria (SSAC). The majority of modelling tools commonly used have the ability to calculate SSAC, allowing evaluation of the level of risk by comparison of the SSAC with measured concentrations of the compound of concern in the source medium. This form of risk assessment is sometimes referred to as "backward risk assessment". Figure 8.5, adapted from EA (2008b), illustrates both forms of assessment.

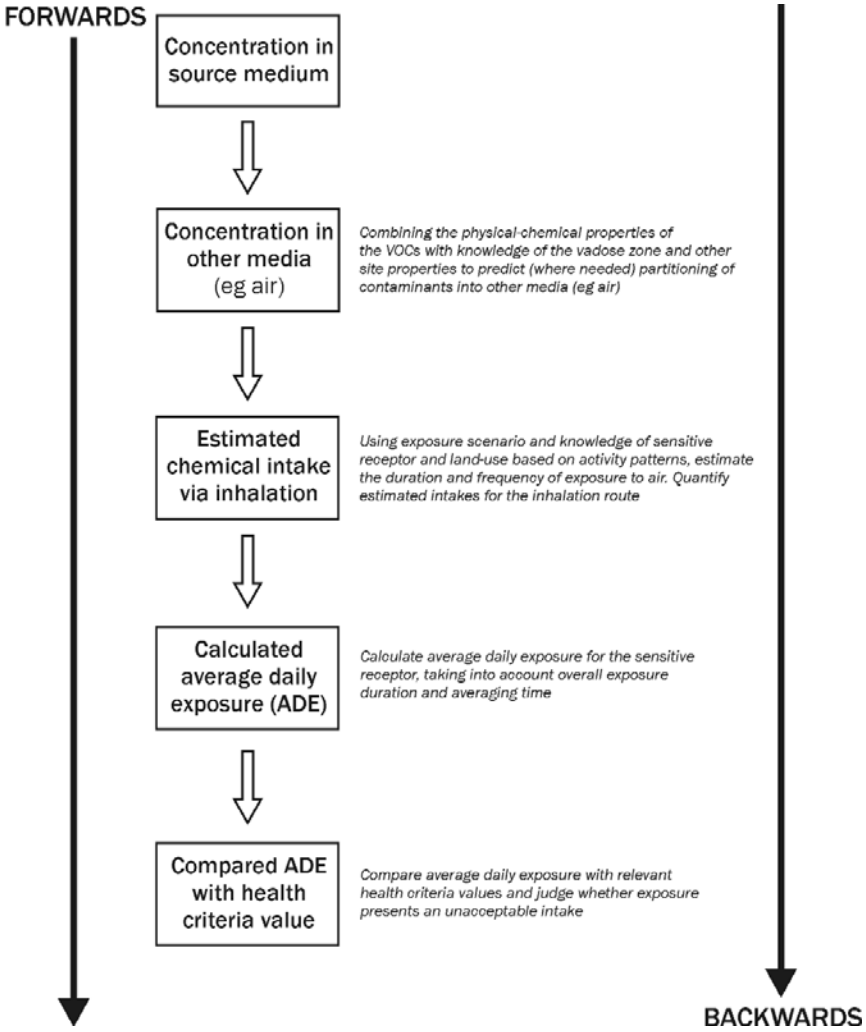

Figure 8.5 ***"Forward" and "backward" risk assessments (adapted from EA, 2008b)***

For many sites, the use of modelling tools to estimate and evaluate the level of risk from measured concentrations (from a variety of source media) will be appropriate. For some sites, the use of modelling tools will be less appropriate, or modelling tools may not be easily applied, which may require calculations to be done external to a model (see Example 8.4).

Example 8.4 ***Measurement versus modelling***

The following are examples of situations where measurement may be more appropriate than modelling:

- the modelling assumptions are not appropriate for the CSM
- a preferential pathway through the natural soils/geology has been identified
- a programme of indoor air sampling has been undertaken
- *ex situ* remediation of soils, requiring monitoring of outdoor air quality
- presence of a large flux of potential carrier gases (eg an actively gassing landfill).

8.5.3 Different types of modelling tools

Where the use of one or more modelling tools is appropriate, the choice of tool needs consideration.

As for developing GAC, the type of vapour intrusion/emission model present within the modelling tool is important. Being the current vapour intrusion model recommended for use in the UK (EA, 2008b), the J&E model (including the steady-state, continuing source form recommended by Evans *et al*, 2002) should be adopted to assess the risk to human health, where appropriate for the site setting. Section 7.4.3 gives some criteria to help the assessor decide whether using the J&E model is appropriate, and in some cases reasonably conservative, for the site assessment. Similarly, the relatively simple CLEA vapour emission model should be adopted, where appropriate for the site setting, to assess the risk via inhalation of outdoor air.

For some sites, the J&E model (steady-state, continuing source form) or the CLEA vapour emission model will not be appropriate for the site setting because of assumptions inherent in the models that could result in the level of risk either being highly overestimated or, in some cases, underestimated. In many cases the J&E model is inappropriate because of the building construction. Where this is the case, alternative modelling tools can be used, provided the assessor has the experience to understand the implications of using a different tool, and can justify it appropriately. Examples of different types and uses of modelling tools are provided in the following sections, and a range of vapour intrusion models (and how they relate to different building constructions, as discussed in Chapter 2) are discussed further in Appendix A11. Whatever the type of modelling tool used, it needs to be flexible enough to incorporate site-specific data alongside relatively standard input values recommended by the EA, such as chemical or toxicological properties. Consideration always needs to be given to multiple potential pollutant linkages, as the CLEA methodology recommends additivity of risk across the different exposure pathways.

It is recognised that some risk assessment practitioners have developed custom-built software packages based on the guidance presented in the CLEA methodology. Provided custom-built models are transparent and have undergone suitable quality assurance/quality control testing, and it is clear which guidance documents have been followed during the model development, they can be considered as potential alternatives to existing software packages.

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Modifications to J&Ettinger model (1991)

Modifications to the original form of the J&E model include:

- inclusion of a depleting source (although the use of this form does not account for potential higher intake at the start of the exposure period, and instead average over the exposure period, and should be used with caution)
- inclusion of degradation of the compound in gaseous phase (unsaturated zone)
- inclusion of a lower permeability lens (or lenses) of material overlying the source zone.

Appendix A11 highlights the commonly used modelling tools that incorporate modified versions of the J&E model.

Other forms of vapour intrusion models

There are other vapour intrusion models that can be used to assess this pathway, provided appropriate justification is given. Several of these (such as VOLASOIL within Risc-Human) are discussed in Appendix A11. New models are under development that may be appropriate for future use. These include modelling codes that simulate the degradation of VOCs during transport through the unsaturated zone (for example, Lahvis, 2006 and DeVaull, 2007), alongside models that consider biodegradation alongside sink terms (for example, Turczynowicz and Robinson, 2007).

Direct emission from soils

The vapour emission model included within the CLEA methodology is designed to model the migration of volatile compounds from the surface to an overlying air space. The software package RBCA Toolkit v2.0 is another example of a modelling tool that includes an algorithm to model the direct emission of soil gas from a surface source (see Appendix A11), and, alongside tools such as RISC, can also model the emission from a subsurface source.

Air dispersion modelling

The modelling of air dispersion is recognised as a form of assessment requiring a relatively high level of expertise. Modelling packages most commonly used to predict the transport of VOCs via air dispersion include AEROMOD PRIME (as used by the EA) and ADMS3. Even more sophisticated models, such as CALPUFF, are also used, but have high input requirements. Such forms of modelling are unlikely to be required for the majority of sites as part of a land contamination assessment.

Lateral transport of VOCs in soil gases in the subsurface

The majority of modelling tools used to assess either the vapour intrusion or vapour emission pathways consider the vertical transport of VOCs in soil gas upwards towards the point of exposure. For some site settings, the potential for lateral transport of soil gases through the unsaturated zone also needs to be

considered. The software package GasSim 2 (Golder Associates, 2006), developed primarily to assess the potential risks associated with landfill sites, allows the user to simulate the lateral transport of soil gases via advective and diffusion-driven flow, but does not account for attenuation mechanisms such as degradation or retardation. Further details on the use of GasSim 2, and its predecessor GasSim, is included in existing guidance documents, such as Wilson *et al* (2007). Another modelling code designed to simulate the lateral transport of soil gases is VapourT (Mendoza, 1992), and further works on this subject are being undertaken that may result in the development of new modelling tools (for example, Abreu and Johnson, 2005 and Robinson and Turczynowicz, 2005). Where there is considered to be a high likelihood for significant lateral transport of VOCs in soil gases (for example, where degradation of the VOC is considered unlikely to be significant during transport), undertaking direct measurement may be more appropriate than use of modelling alone.

Lateral transport in groundwater beneath the subsurface

The transport of VOCs in the dissolved phase beneath off-site land or property, and then the volatilisation and transport to the point of exposure, can be modelled by several software tools, including RISC v4.0 and RBCA Toolkit v2.0. Other software packages, such as the EA of England and Wales' *Remedial targets worksheet* (RTW) v3.1 or ConSim v2.2 (Golder Associates, 2003) can be used to predict concentrations in groundwater at an off-site location. The output of the assessment can then be used within a different modelling tool to assess the potential risk following volatilisation from the groundwater, such as the J&E model. However, for sites with a complex hydrogeological setting and/or complex source (for example, multiple sources), the use of a more sophisticated groundwater flow/contaminant fate and transport model may be required. Examples of such models include FLOWPATH II (Groundwater Services Inc) and MODFLOW (USEPA) (used with various commercially available graphical interfaces). Such models require a high degree of user training and experience, can take weeks or months to develop, and rely on a significant level of site-specific data for the purposes of model validation.

Presence of NAPL

The most commonly used software packages likely including CLEA 1.06 (January 2009), do not directly model the risks associated with NAPL, but account for the likely presence of residual phase product given the site setting and level of effects. For a soil source, the saturated gaseous phase concentration is calculated and from this the maximum concentration of a compound in soil, representing the theoretical concentration above which residual phase begins to form is calculated (as described by ASTM, 1995). Similarly for groundwater, the gaseous phase concentration associated with the theoretical maximum solubility of a compound can be calculated. When assessing a NAPL comprising a mixture of compounds (notably for petroleum hydrocarbons), the concentration of each constituent in soil gas will, theoretically, reach the concentration defined by Raoult's Law (Evans *et al*, 2002), depending on the mole fraction of the constituent in the NAPL. See EA (2009) for further discussion.

In CLEA 1.06 a screening system is used to highlight sites for which the calculated assessment criteria are below, close to, or significantly higher than the theoretical residual concentration. In the software packages RISC v4.0 and RBCA Toolkit v2.5, where the saturated gaseous phase concentration (or

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solubility concentration in groundwater) is not sufficient to result in a risk via the modelled pathway, no assessment criteria are developed as no further assessment of the pathway is assumed to be necessary (ASTM, 1995). Where using models where no assessment criteria are developed under this circumstance, the assessor should consider the potential contribution to the overall risk whether NAPL is, or is likely to be, present (including residual NAPL in soil pores) and whether further forms of assessment are required. Models that allow the assessor to directly assess the potential risks from NAPL include a USEPA spreadsheet model (2003), and the Dutch model VOLASOIL included within Risc-Human v3.2 (Waitz *et al*, 1996).

Where NAPL has been identified beneath the subsurface, multiple lines of evidence are likely to be required to assess the potential level of risk. The assessor should note the other pollutant linkages that may be active due to the presence of the NAPL, and how its presence might be dealt with under different regulatory settings.

8.5.4 Modelling tool input data

The use of site-specific data is preferable to literature data for many input parameters for modelling tools. However, for some input parameters the assessor is likely to rely on literature sources for the majority of assessments, due to the complexity in collecting site-specific data and the sensitivity of the input parameter within the modelling tool. Where a parameter is sourced from literature data that is not specific to the UK because appropriate data are not available, a range of potential input values should be considered, and sensitivity testing may need to be undertaken to show the relative sensitivity of different parameters. This may relate to unusual exposure scenarios (for example, land-use not considered within the CLEA methodology). If sensitivity testing is undertaken, the effect on other pollutant linkages should also be considered before the final value is selected.

8.5.5 Model validation using measurements

The collection of site-specific data, when combined with appropriate forms of modelling, can be a powerful tool for providing confidence on the result of the assessment.

In some cases, the collection of site data will allow refinement of the modelling to better represent the level of risk to the identified receptors (see Case study 8.6). For example, use of measured concentrations of compounds in soil or groundwater may indicate a potential risk, but use of soil gas quality data collected in the source zone may indicate that the level of risk is much lower than originally predicted. For petroleum hydrocarbons, this is often likely to be the case due to the acknowledged over-prediction of soil gas concentrations when using the Henry's law constant (see Appendix A2) and the influence of biodegradation.

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Case study 8.6 ***Predicted versus measured concentrations of VOCs in soil gas***

Operational petrol stations, UK-wide

Soil and groundwater investigations were performed on over 100 petrol filling stations, as part of a due diligence assessment of a large site portfolio. Assessing the vapour intrusion risks using the J&E model indicated potential health risks from the inhalation of soil-derived hydrocarbon vapour in overlying and adjacent buildings in more than 30 per cent of the sites. A programme of source gas sampling was carried out using dedicated gas wells for over 40 sampling events. Soil gas samples were collected using low flow air sampling pumps and sorbent tubes, with laboratory analysis for benzene, toluene, ethylbenzene, xylenes (BTEX), methyl tert-butyl ether (MTBE) and petroleum hydrocarbon bands for TPHCWG equivalent carbon ranges, C4 through to C16. The recorded soil vapour concentrations were compared to the model predicted source gas concentrations derived from adjacent groundwater source concentrations. This is illustrated in the data obtained from four representative sites in Figure 8.6.

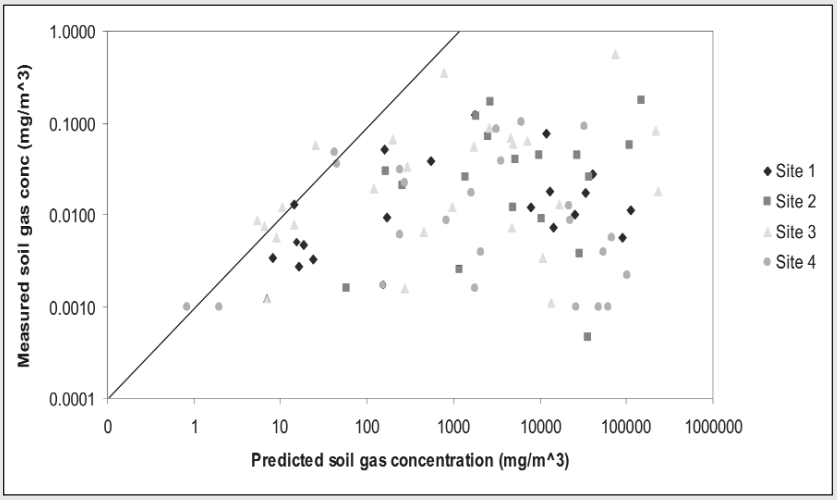

Figure 8.6 *Predicted versus measured concentrations of BTEX/MTBE and volatile hydrocarbons in soil gas*

The trend line in Figure 8.6 represents a factor of 0.001 (10^{-3}) between the model predicted concentration and the measured gas concentration. The 95th percentile upper confidence limit of the ratio of recorded to predicted soil gas concentration of the larger dataset was 0.0003 (3×10^{-4}), indicating that in the majority of cases, the measured soil gas concentrations of BTEX, MTBE and volatile petroleum hydrocarbons were 30 000 times lower than those predicted by the theoretical partitioning equation used in the model. Modelling the risks using the measured soil gas concentrations resulted in no predicted indoor health risks.

For other sites, collection of a dataset from part of the site affected by the land contamination could be used to validate modelling tool inputs and outputs thereby allowing use of the model over the remainder of the site (or even off-site) with increased confidence. For example, if a dissolved phase plume of a VOC is present beneath several properties, collection of sub-slab, indoor air and outdoor air samples from a select few of the properties and then model validation (or in some cases "reality checking" the modelling output) could allow the potential risk to the remaining properties to be estimated based on measured groundwater concentrations. This approach would rely on relatively homogeneous aquifer and unsaturated zone properties, and similar building construction overlying the plume (see Case study 4.1).

Where extra iterations of site investigation and data interpretation are undertaken to refine the understanding of the vapour intrusion/emission pathways, the assessor should acknowledge the uncertainties and limitations associated with different types of measurement and models before reaching

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conclusions as to whether the level of risk is significant. As for each stage of assessment, where possible, multiple lines of evidence should be presented.

8.5.6 Mitigation measures

For many sites, mitigation measures may have been installed, or are planned, to address the potential risk of explosion and/or asphyxiation from the build-up of soil gases in enclosed air spaces such as carbon dioxide or methane. In some cases, mitigation systems installed to protect against these gases will reduce the potential for vapour intrusion of VOCs. In other cases, the presence of a mitigation system will not significantly reduce the likelihood of vapour migration, and in some cases the mitigation system could result in a higher level of risk from inhalation of VOCs in vapours. See Example 8.5 for details of each case.

Example 8.5 ***Different mitigation systems***

The following mitigation systems are often used for carbon dioxide/methane:

Open void beneath building – likely to reduce the potential for intrusion of VOCs into an indoor air space due to dilution within the air space.

Synthetic membrane – often used in conjunction with a vented void. Degradation of certain, but not all, synthetic membranes from exposure to VOCs can result in limited reduction in potential for intrusion of VOCs into an indoor air space.

Vertical gas extraction – typically used on landfill sites, active venting of soil gases can provide a preferential migration path for VOCs in soil gas to enter atmosphere, potentially increasing the likelihood of exposure.

Further details on remediation techniques, including mitigation systems, which are designed to limit the migration of VOCs in soil gas into an indoor or outdoor air space are provided in Chapter 9. Details on typical mitigation techniques used to reduce the risks of explosion or asphyxiation from the build-up of gases such as methane or carbon dioxide can be found in Wilson *et al* (2007), NHBC (2007), BS 8485:2007 and Wilson *et al* (2008). The assessor should consider the effect, if any, a pre-existing or planned gas mitigation system may have on the potential for vapour intrusion/emission during modelling.

8.5.7 Development of SSAC

Site-specific assessment criteria (SSAC) can be developed for sources present in soil and/or groundwater using the same approach outlined in Chapter 7 for GAC. However, where data have been collected for further source media (for example, soil gas, indoor or outdoor air) more experienced assessors may choose to develop SSAC specifically for that media. Assessors need to consider the contribution from the different modelled exposure pathways to the overall risk level. Methods to consider contribution from multiple pathways may take the form of qualitatively reviewing the contribution from the vapour intrusion/emission pathways (for example, reviewing the hazard indices) or may take a more quantitative form by assigning a percentage of the overall acceptable risk level to each pathway.

Often, SSAC are used as remediation criteria. Where appropriate, the effect of additivity across multiple exposure pathways should be considered in their development. The need to consider additivity due to contribution from different environmental source media will be site-specific in nature. For example, where a building overlies contamination by VOCs in both soils and groundwater,

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estimating for the contribution to VOCs in soil gas from each source is unlikely to be viable. The assessor should note the type of VOC present (for example, petroleum hydrocarbons versus halogenated hydrocarbons) and any levels of conservatism incorporated into the assessment when undertaking the risk evaluation and the need to consider contributions to the overall risk from different source media.

8.5.8 Comparison of measured concentrations to SSAC

As for use of SGVs/GAC, comparison of the measured concentrations of the compounds beneath the site against the SSAC is one method that allows the assessor to evaluate the likely level of risk to human health receptors from pollutant linkages, which include the vapour intrusion/emission pathways. The SSAC are typically calculated to consider potential chronic health risks associated with long-term exposure but may also need to consider health effects associated with shorter-term exposure events, and should take into account the potential for occupational exposure (for example, during remediation works) where needed.

Where appropriate, the use of statistical testing can be used in the risk estimation and evaluation, as discussed in Chapter 7.

8.5.9 Assessing shorter-term exposure

As for the earlier stages of assessment, the potential for shorter-term exposure events should be considered when evaluating the risk to human health. This is also discussed in Chapter 7, alongside potential odour nuisance effects.

As part of a v-DQRA, the potential risk from shorter-term exposure events could be assessed in several ways. Using the examples provided in Chapter 7, Example 8.6 illustrates methods by which the risk could be estimated.

Example 8.6 ***Potential methods of evaluating risk from shorter-term exposure***

Scenario	Potential method of assessment for a site
A construction worker or remediation worker undertaking works on sites affected by land contamination (occupational)	❑ measure and/or estimate (using modelling tools) VOC concentrations in air, through either vapour emission (over the construction period) or through vapour release events ("instantaneous releases") ❑ compare measured or predicted concentrations in air to air quality standards. These may include WELs where appropriate. A range of quality standards may need to be adopted to account for acute health effects and chronic health effects. Note this may indicate the potential for immediate risk to human health, or risk of acute health effects if works were to proceed without risk management measures being employed.
Residents living on a developed brownfield site (non occupational)	❑ estimate VOC concentrations in air, through vapour release events (for example,while tending the garden) ❑ compare predicted concentrations in air to air quality standards. As for the occupational example, a range of quality standards may need to be adopted to account for acute health effects and chronic health effects.

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8.5.10 Potential odour nuisance effects

As discussed in Chapter 7, the potential for odour nuisance effects from VOCs associated with land contamination may need consideration. Similar risk estimation assessment methods can be used as for the shorter-term exposure events, such as prediction of a concentration in air and comparison to an air quality standard (in this case, an odour threshold).

8.6 RESULT OF THE ASSESSMENT

The result of the v-DQRA will be one of the following:

1 Unlikely to be significant risk to human health from vapour intrusion/emission.

2 Known/potential for significant risk to human health from vapour intrusion/emission.

For the first result, the assessor can conclude that no further consideration of the vapour intrusion/emission pathway is needed within the assessment, but that other pollutant linkages may still result in the need for further works at the site.

For the second result, the next step will depend on the level of certainty in the data collected/the assessment, as for the v-GQRA. The assessor may choose to undertake further intrusive investigation to refine the v-DQRA, or to proceed to developing remediation options to help manage the identified (or potential) risk.

8.7 SUMMARY

The results of the v-DQRA should demonstrate whether further consideration or remediation to manage the risks associated with the vapour intrusion/emission (or release) pathways is required, or whether the site has been screened out of the assessment process.

As for the v-PRA and v-GQRA, where an immediate risk to human health is known, or suspected, risk management and/or mitigation measures should be applied directly, before undertaking further investigative or risk assessment, to safeguard human health.

The v-DQRA enables the assessor to employ a large range of investigation techniques and assessment tools to focus on the vapour intrusion, emission and release pathways in details providing confidence in the estimation and evaluation of the risk to human health.

The focus of the v-DQRA is on refinement of the CSM using the results of site investigation alongside modelling tools (as required) to highlight the sites where the pathways of concern are known or likely to be active. In many cases, the v-DQRA involves a balance between assessing the risk using site measurements in combination with modelling tools.

For the majority of sites, the CSM will include more pollutant linkages to the vapour migration/intrusion pathways. These extra pathways should be considered before a decision of no further action can be taken for a site.

8.8 FURTHER INFORMATION

BAEHR, A L and HULT, M F (1991)
"Evaluation of unsaturated zone air permeability through pneumatic tests"
Water Resources Research, 27 **(10)**, American Geophysical Union (AGU), Washington, USA, pp 2605–2617

DANISH ENVIRONMENTAL PROTECTION AGENCY (2002)
Guidelines on remediation of contaminated sites
Environmental guidelines no 7, Copenhagen

EA (2009b)
Updated technical background to the CLEA model
Science Report SC050021/SR3, Environment Agency, Bristol. Available from: <http://publications.environment-agency.gov.uk/pdf/SCHO0508BNQW-e-e.pdf>

HAWTHORNE, S B (2008)
"Tracing contributions of benzene from outdoor to indoor air"
Environmental Forensics, 9, Taylor and Francis, USA, pp 99–106

JOHNSON , P C and ETTINGER, R A (1991)
"Heuristic model for the intrusion rate of contaminant vapors into buildings"
Environmental Science and Technology, 25 **(8)**, American Chemical Society, Washington, USA, pp 1445–1452

SNIFFER (1999)
Communicating understanding of contaminated land risks
Project SR97(11)F, Scotland and Northern Ireland Forum For Environmental Research, Edinburgh (update in preparation)

TURCZYNOWICZ, L and ROBINSON, N I (2007)
"Exposure assessment modeling for volatiles – towards an Australian indoor vapor intrusion model"
Toxicology and Environmental Health Part A, 70, Taylor and Francis, USA, pp 1619–1634

WAITZ, M F W, FREIJER, J I, KREULE, P and SWARTJES, F A (1996)
The VOLASOIL risk assessment model based on CSOIL for soils contaminated with volatile compounds
Report 715810014, National Institute of Public Health and the Environment (RIVM), The Netherlands

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9 Remediation considerations

9.1 INTRODUCTION

This chapter provides an overview of different remediation strategies that can be used to help manage risks to human health from inhalation of VOCs. The overall framework for identifying and selecting remediation of the options, and the work carried out and its verification, is provided within CLR11 (Defra and EA, 2004a). There are also several existing guidance documents that can be referred to for information on remediation technologies, for example, Evans *et al* (2001), Harris *et al* (2005), Mallet and Beale (2008) and Strange and Landon (2007).

Remediation strategies will typically involve one or a combination of the following mechanisms for breaking a pollutant linkage:

- source treatment (removal/reduction of source)
- pathway management/breakage
- receptor management/removal.

There are also several common factors that should be considered when deciding which of these is most appropriate for the site, as discussed in the following sections.

Before spending time considering remediation strategies it is important to understand whether there are immediate safety risks and if emergency action, for example, evacuation, is required. Also, the development of health and safety plans associated with carrying out the remediation strategy should include measures to be taken if a situation arises where there are immediate safety risks presented to those on site, or in the surrounding area.

9.2 SETTING REMEDIATION OBJECTIVES

Defining the objectives for remediation is a crucial step in enabling scopes of work and remediation end-points to be established. Guidance on setting remediation objectives is presented in CLR11 (Defra and EA, 2004a), where it is acknowledged that there are several different factors that will require consideration to ensure the acceptability of the remediation strategy to the range of relevant stakeholders. A summary of these factors is presented in Table 9.1.

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Table 9.1 ***Summary of factors influencing remediation objectives (adapted from Defra and EA, 2004a)***

		Options		
Factor	**Points to consider**	**Source treatment/ removal**	**Pathway management/ breakage**	**Receptor management/ breakage**
Effectiveness	The result of the risk assessment process will be instrumental in defining the degree to which risks need to be controlled and may have resulted in site specific remediation criteria that can be used to assist in defining objectives. When considering the effectiveness of the remediation strategy several questions can be asked: ■ can the remediation standard be achieved using the options being considered? ■ is one option likely to be stand alone or used in combination with others? ■ what are the likely timescales within which the remediation standard can be achieved?	A well designed source treatment/removal remediation option should be effective. However relies on the results of the risk assessment to determine the level of treatment required. Residual risks may be managed by combining with pathway management/breakage	Different pathway management/breakage techniques are more effective than others, and may need to be combined with other remediation techniques. Does not specifically rely on the outcome of the risk assessment (target levels) to determine level of treatment required. Can require long-term monitoring to ensure effectiveness.	An effective technique, as removes the receptor from the pollutant linkage, but not necessarily effective long-term due to difficulties in managing receptor (ie human) behaviour.
Reasonableness	Considering the cost of the proposed strategy is important when determining that objectives are successfully achieved (for example some stakeholders may prefer costs to be spread out over a longer term strategy whereas others may prefer a different balance). The parties funding the remediation should also be kept in mind, particularly if they are not the people making the decision about the strategy. Transparency in the way the costs have been developed will be vital in these circumstances. In considering the reasonableness of the remediation strategy one should be able to demonstrate that the cost of the option(s) is likely to be justified by the benefits.	A reasonable solution for many sites. Timescales and costs involved that depend on the nature of the problem, may be prohibitive for some sites, especially development sites.	A reasonable solution for many sites, especially development sites where timescales may be important. Can require long-term monitoring that is not always a reasonable solution	Reasonable where there is flexibility in how the land can be used, otherwise unlikely to be a reasonable long-term solution for many sites.
Practicability	Technology will affect the objectives leading to several questions: ■ can the option(s) be carried out given the source location? ■ can the option(s) be carried out where site constraints (area and access, existing infrastructure) are present? ■ can the option(s) be integrated with other works proposed or in progress?	A practical solution on many sites, delivery beneath buildings/ structures may be difficult, particularly if technology may change soil properties. Effective in combination with construction works, either excavating or installing system infrastructure	A practical solution on many sites, particularly new developments with retrofitting beneath existing structures. The practicality of undertaking long-term monitoring on certain sites may be key – complete elimination of vapour intrusion is difficult to achieve	Restruction on land-use. May not be practical on many sites
Durability	The required lifetime of a proposed strategy needs to be factored into the selection and design process such that the solution will be robust for the necessary period of time: ■ what is the typical lifetime of the option(s)? ■ for how long would the option typically be effective?	Potential risks generally managed with period of system operation, typically several years that are easily incorporated into system design	The source term is still in place, so the durability of the remediation depends on the technique adopted. Typically requires long-term monitoring to ensure durability	Restriction on land-use. May not be a durable solution on many sites
Residual liabilities	What residual liabilities are likely to remain following adoption of the remediation strategy and are these likely to be acceptable to the client/landowner/ developer?	Residual liability typically minimised or reduced with source treatment/removal	Residual liability can remain relatively high, as source is left in place	Residual liability can remain relatively high, as source is left in place

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Table 9.1 (contd) ***Summary of factors influencing remediation objectives (adapted from Defra and EA, 2004a)***

		Options		
Factor	**Points to consider**	**Source treatment/ removal**	**Pathway management/ breakage**	**Receptor management/ breakage**
Verification	The feasibility, costs and timescales associated with verifying the remediation strategy should be considered in: ■ what techniques are typically used to verify the remediation strategy? ■ how long would verification typically take?	Verification techniques are often similar to those used to investigate the site and are wide ranging. It may be easier to verify source treatment/removal on development/ underdeveloped sites	Limited range of verification techniques, generally point of exposure (indoor/outdoor air) sampling or testing efficiency of barrier during development	Not generally applicable. Monitoring of site use
Stakeholder issues	The legislative and regulatory context within which remediation is being considered should be managed and understood to ensure relevant objectives are defined. Perception and communication issues may be important in demonstrating to various stakeholders that their interests are being considered	For many stakeholders this may be the preferred option as hazard is reduced, however factors such as risk communication and disruption to site use may be vital	Good communication of management of risks using this option is important, especially if long-term monitoring is required	Upfront communication between different stakeholders needed when employing receptor management/removal option. Often may not be the preferred solution for many stakeholders

These considerations may not be exhaustive and it is important to note limitations of the strategy, as well as the need to be flexible, particularly if multiple stakeholders are to be satisfied.

Quick reference 9.1 ***Important factors influencing remediation objectives***

The following should be considered when selecting a remediation technology/technique and designing a risk management plan:

- ❑ **effectiveness**
- ❑ **reasonableness**
- ❑ **practicability**
- ❑ **durability**
- ❑ **residual liabilities**
- ❑ **verification**
- ❑ **stakeholder issues.**

9.3 MANAGING RISKS FROM SHORT-, MEDIUM- AND LONG-TERM EXPOSURE

The result of the risk assessment process may have identified a potential risk to human health via either short-, medium- or long-term exposure, with associated acute or chronic health effects. A remediation strategy may needed to address one or all of these exposure scenarios, taking into account the receptor at risk.

Short to medium-term exposure scenarios (ie typically less than one year) will generally require a short response time and remediation over a short-term, including risk mitigation measures to address immediate risk to human health, as the health effects relating to shorter-term exposure are often acute in nature.

Long-term exposure scenarios (ie greater than one year) are more typically (but not always) associated with the potential for chronic health effects. In the absence of an immediate risk to human health, remediation may be done and verified over a longer period of time.

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9.3.1 Risks associated with short to medium-term exposure and acute health effects

Potentially significant risks of acute health effects may have been identified during the risk assessment process. There are several scenarios in which risks could be present that may affect remediation considerations, as highlighted in Example 9.1. The first two scenarios illustrate where risks can be managed proactively, whereas in the third scenario reactive measures may be required. In the fourth scenario some preventative remediation considerations are highlighted.

Example 9.1 ***Examples of short to medium-term exposure scenarios with potential for acute health effects***

During remediation works (for example due to vapour emission or vapour release)

In this scenario action is specifically being undertaken to manage potential vapour emission risks during remediation works. During the remediation works exposure can be minimised and controlled, but would often be difficult to avoid.

Before starting remediation appropriate risk assessments for the works would be undertaken (as for investigation, see Chapter 5), which may highlight several mitigating steps that should be taken to control and monitor risks during remediation works, for example:

- control of working hours
- air quality monitoring (including at site boundary)
- health surveillance/personal monitoring
- monitoring for explosive limits
- development of an emergency action plan
- use of appropriate Personal Protective Equipment (as a precautionary measure).

During construction (for example due to vapour emission or vapour release)

In this scenario construction may be being undertaken concurrently with remediation in which case reference should be made to the example above and allowances for control of acute risks should be made.

Alternatively it may be that remediation has already taken place, before construction, so there may be an expectation that measures to control risks are not required. However, some contingency should always be made for dealing with acute risks on construction sites, for example, there may be an instantaneous release of vapours from a pocket of contaminated material that only became evident as the ground was disturbed. Remediation will not always have reduced VOC concentrations to a level such that acute risks during ground disturbance will not occur, unless specifically considered within the risk assessment/remediation process.

During routine site operation (for example due to a spill event)

In this scenario reactive measures are likely to be required to mitigate against immediate risks to human health. These may include:

- evacuation of areas or limiting access to affected areas
- spill response
- vapour extraction/control
- communication plans
- personal monitoring
- use of PPE (as an extra precautionary measure).

Maintenance workers may be exposed to contaminated materials during routine work. Risks associated with such exposure will typically be acute based on the time taken for the works. As with remediation and construction works appropriate health and safety plans and risk assessments should be prepared and should include consideration of the potential for workers to be exposed.

Neighbouring properties (for example due to construction works on an adjacent brownfield site)

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Example 9.1 (contd) ***Examples of short to medium-term exposure scenarios with potential for acute health effects***

During any of these scenarios consideration also needs to be given to occupants of neighbouring properties and the risks to which they are exposed. This may lead to specific design elements being built into the remediation strategy, for example:

- excavations may need to be tented to manage and control vapour releases
- monitoring may be undertaken to confirm that risks are being appropriately managed
- a vapour treatment plant may be required
- emergency plans may include evacuation procedures or advising occupants to stay indoors.

Case study 9.1 illustrates how the release and emission of volatiles was monitored and assessed on a site undergoing remediation works. Case study 8.3 gives a further example of a site where such monitoring was undertaken during remediation works in north west England.

Case study 9.1 ***Monitoring and assessing vapour release and emission during remediation***

Fullerton, USA

The site was used in the 1940s for the disposal of refinery sludges in several sumps, now covered with a layer of soil. The sludge was investigated and found to contain compounds, many of which were VOCs with the high potential for volatilisation during ground disturbance. USEPA (1990) undertook experiments to assess the rate and extent of volatilisation during excavation works, by enclosing the area under investigation and measuring the rate of emission and concentration of VOCs and sulphur dioxide. DeVaull (2001) developed a modelling tool to predict the rate and extent of emission, and used these data to assess the validity of the model. The model was reported to capture the major relevant parameters and features involved in estimating the rate and extent of release/emission of VOCs, providing a good prediction of rates of emission and concentrations when appropriately applied. The model illustrated that volatile releases/emissions during the excavation were dominated by the generation rate of new surface area and the associated period of surface flux emissions. For further information, see DeVaull (2001) and USEPA (1990).

9.3.2 Risks associated with long-term exposure and chronic health effects

For many sites, the known (or suspected) risk to human health will be associated with the long-term exposure to VOCs in an indoor or outdoor air space, with the potential for chronic health effects. The primary difference between remediating (or mitigating) in this scenario compared to where the health effects are acute in nature is the time over which remediation is likely to be carried out and verified. Example 9.2 provides some commonly encountered scenarios where a potential risk to human health from long-term exposure may be identified. Remediation strategies likely to be adopted to reduce the exposure and the risk of chronic health effects are discussed further in Section 9.6.

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Example 9.2 ***Examples of long-term exposure scenarios with potential for chronic health effects***

During routine site operation

A commercial or industrial property may have been developed on a site with an industrial history, with VOCs present in the ground due to historical spillages/releases or poor waste management practices. The vapour intrusion/emission pathways could be active, subjecting the site workers to exposure over a long-term. While the potential for exposure under normal occupational practices should be considered, remediation works could still be recommended on the basis of potential for chronic health effects.

New housing development

A new housing development planned for a site affected by land contamination could require remediation (including mitigation) works to reduce the potential for long-term exposure from vapour intrusion and emission. Where mitigation measures are employed, the potential for risk to neighbouring sites may still need to be considered, as the source is still left in the subsurface.

Neighbouring properties

Properties located near to a site affected by land contamination may have the potential for vapour intrusion (for example, through migration of dissolved phase VOCs in groundwater and then later volatilisation). Where the health effects are shown to be chronic in nature (related to long-term exposure) remediation may not be actively undertaken beneath the neighbouring properties, instead focusing on reducing the source beneath the site and relying on natural attenuation effects to reduce off-site concentrations with time. In some cases, remediation will be required to actively prevent cross-boundary migration of VOCs, reducing the risk to off-site receptors.

9.4 TIMING OF REMEDIATION

The timing of remediation with respect to the status of the site (undeveloped, in development, or operational/occupied) will affect the feasibility of available remediation options.

9.4.1 Pre-development

Risk assessments undertaken on sites before development often include generalised assumptions regarding the eventual site layout. This lack of certainty restricts the ability to tailor both risk assessment and remediation strategies to a development.

When remediation is undertaken before development it is often the case that those undertaking remediation will not be responsible for the development itself. This can reduce the number of available remediation options for several reasons, for example:

- the timings for remediation may be limited
- the developer may not expect to make provisions for remediating
- the party remediating the site may wish to manage liabilities for themselves and not be prepared to rely on a future developer carrying out further remediation.

One point to consider if undertaking remediation pre-development is whether the future development works will alter the soil gas regime significantly. In this case, further works (such as monitoring) may be required during the development process.

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9.4.2 Remediating during development

There are advantages and disadvantages to undertaking remediation during development, as shown in Table 9.2.

Table 9.2 ***Advantages and disadvantages of undertaking remediation during development works***

Advantages	Disadvantages
Remediation during development can present opportunities to access sources requiring treatment.	The nature of development sites means that the time taken for remediation is often one of the most critical factors and time frames are often short. This can restrict the cost-effectiveness of many remediation technologies.
Costs of remediation may be lower where plant and equipment already on site can be used.	Conflicts with contractor's time can result in escalation of remediation costs.
Pathway management measures (discussed further in Section 9.6) can be incorporated during the development design and when the work is carried out.	Verification can be difficult in terms of access, techniques and timing.
Designing site layouts with remediation requirements in mind can be beneficial in controlling risks.	Damage to remediation infrastructure may occur increasing time and costs.

Verification of the success of remediation works either during or after the construction works needs to be considered (see Section 9.7).

9.4.3 Remediating occupied/operational sites

Sites being used for either industrial/commercial purposes or for housing present complex problems, both technically and commercially when developing remediation strategies. Factors to consider are similar regardless of whether the contamination occurred pre-development or during operation. For example:

1 Health and safety considerations can escalate, often requiring the use of site permitting systems, which can affect timing.

2 Access – some areas of the site might be restricted for operational reasons, or owners may be unwilling to grant access in the first instance.

3 Timing – works may often need to be undertaken in less busy periods on operational sites, such as evenings or weekends, or at a time of convenience in residential areas.

4 Feasibility of remediation – it may not be possible to access areas where the source is present unless buildings or structures are demolished or removed.

5 Presence of structure above and below ground may prevent successful or safe application of source or pathway management technologies.

6 Do available technologies and the building design enable mitigation measures to be retrofitted, for example, membranes, increased ventilation (either active or passive)?

7 Can the buildings remain occupied during the works?

8 Who owns the buildings and does there need to be a change in ownership?

9 How best can the perceptions of all stakeholders be managed?

10 Can the site be re-instated to the layout before remediation (such as site level and ground cover)?

11 Are there any long-term licensing issues and/or monitoring programmes required, and who will be responsible for ensuring they are followed?

12 What is the level of residual liability following the works?

9.5 COST-BENEFIT ANALYSIS

The relative costs and benefits of remediation should be considered during the process of selecting appropriate remediation options and technologies. The EA has developed some guidance on this subject, for example EA (2000b).

The concept of cost-benefit analysis is also promoted by Defra and the EA (2004a).

9.6 REMEDIATION OPTIONS

The UK recommended process for selecting appropriate remediation options is set out in Defra and EA (2004a). Further guidance is also provided by Harris *et al* (2005). Within this process feasible options are identified and evaluated and a remediation plan is developed by combining options.

The following sections discuss the options for breaking an identified pollutant linkage and the factors that may be considered in developing a remediation plan. Many strategies will involve more than one option, ie a "treatment train" approach. It is not the aim of this chapter to discuss advantages and disadvantages of specific remediation technologies, guidance on specific technologies can be found in a range of references including Harris *et al* (2005), EA (2001) and ITRC (2007).

9.6.1 Source treatment/removal

Source treatment or removal can be thought of as removing or reducing the identified compounds presenting a risk, in this case VOCs.

Removal of the source may leave the site contaminant-free, though in the majority of cases some residual contamination will remain in the ground.

There are a wide range of technologies that can be used to undertake source treatment that can be broadly categorised by process, such as:

- physical processes – the physio-chemical properties of the contaminant and the affected soil and groundwater are exploited to transfer the contamination into a phase that can either be removed from the ground, (for example, soil vapour extraction, air sparging and soil washing) or encapsulated in the ground (for example, cement-based stabilisation)
- chemical processes – contaminants are transformed or destructed via reactions with chemical reagents, for example, chemical oxidation
- biological processes – contaminants are transformed or attenuated by promoting microbial degradation, for example, biopiling, and land farming.

The feasibility of source treatment/removal will depend on several different factors, such as those summarised in Table 9.1.

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9.6.2 Pathway management/breakage

In managing potential risks associated with the vapour intrusion/emission of VOC pathway management/breakage is often via some form of building controls/vapour barrier, which may be either passive or active. The document by ITRC (2007) provides an overview of a range of pathway management/breakage options used to mitigate the vapour intrusion pathway, and are summarised in Table 9.3.

Table 9.3 ***Types of mitigation system (adapted from ITRC, 2007)***

Type of system	Points of consideration
Passive systems	■ barriers are materials or structures installed below a building to physically block the entry of vapour. In reality it is considered to be very difficult to completely prevent the entry of vapours into a building by passive barriers alone (ITRC, 2007) ■ venting involves the incorporation of a layer below the floor slab that allows soil gas to move laterally beyond the building footprint and is only generally feasible on new developments. Because venting is partially reliant on soil gas venting laterally before it can enter the building, it should be used in conjunction with passive barriers.
Active systems	■ active sub-slab depressurisation systems function by creating a pressure differential across the foundation slab. This favours movement of indoor air down into the subsurface by pulling soil gas from beneath the slab and venting to atmosphere. These systems are widely considered to be the most practical vapour intrusion mitigation strategies for most existing structures and for new structures, where they are similar to passive venting except a fan is used to draw soil gas through the venting layer. Similar systems can be installed sub-membrane where there are crawl spaces and no slab. Systems can also be pressurised rather than depressurised, such that fans are used to push fresh air into the venting layer rather than pulling it out, which prevents the ingress of soil gas. These types of systems can be effective, but their performance can be difficult to monitor and maintain ■ an alternative system is the use of a network of soil vapour extraction (SVE) points to extract vapours as they migrate close to the surface/beneath a building. The use of an SVE network relies on factors such as the zone of influence achievable, the access points and building size ■ where soil gases are vented to the atmosphere, treatment of the off-gas may be required.
Building pressurisation	These systems use mechanical means to positively pressurise the building interior. It may be possible to achieve this by optimising heating, ventilation and air conditioning (HVAC) systems.
Indoor air treatment	Air within the structure would be directed to air pollution control equipment. This technique is not widely employed because it allows the collection of vapours within the structure and relies on the continuous operation of the system to control risks.

Of the options in the table, subsurface features such as barriers and venting layers cannot be easily retrofitted and are more suited to new developments, although depressurisation technologies have been shown to be effective without these features. It is preferable to install pathway management/breakage methods at the time of construction (ITRC, 2007).

The feasibility of pathway management or breakage will depend on several different factors, such as those described in Table 9.1. The potential need for long-term monitoring of the effectiveness of the solution is important to the use of pathway management/breakage techniques (see Section 9.7). In particular, it is noted that the zero carbon agenda is resulting in new housing and other buildings

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being constructed with minimal air leakage, making it vital that where pathway management/breakage solutions are employed, they are sound in the long-term.

9.6.3 Receptor management or removal

This option could include several measures to restrict the use of buildings or land, for example:

- the building(s) may be evacuated or taken out of use altogether
- the use of the building may be changed so that it is used less often for shorter periods of time
- access to the building may be restricted
- deed restrictions to limit the type of development on a site (eg restriction to commercial development).

These options would typically be short-term measures and the latter two may be difficult to enforce unless restrictive covenants are placed on the use of the site. This scenario may develop when land changes ownership and could be an effective way of managing the level of remediation required.

The feasibility of receptor management or removal will depend on several different factors, such as those summarised in the Table 9.1.

9.7 REMEDIATION VERIFICATION

The processes involved in remediation comprise development of a remediation strategy, which includes remediation plan, and critically, verifying the success of the remediation (Defra and EA, 2004a). Existing guidance provides advice on verifying remediation works, but questions to consider may include:

Source treatment/removal:

1 Have sufficient data have been collected to demonstrate a suitable reduction in the source?

2 Could the concentrations increase in the future?

3 Is long-term monitoring needed to demonstrate the success of the remediation?

Pathway management/breakage:

1 Has the mitigation measure been installed appropriately?

2 Can tests be undertaken to ensure the pathway is broken?

3 What long-term measures are required to monitor the effectiveness of the mitigation measure?

4 Could the pathway become active again in the future?

Receptor management/removal:

1 Can the mitigation approach be maintained in the long-term?

2 Do other risk management measures need to be employed alongside receptor management/removal?

3 Are there any procedures that need to be adopted to ensure mitigation is successful?

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9.8 POTENTIAL ODOUR NUISANCE EFFECTS

In some cases, remediation (including mitigation measures) may be required to address potential odour nuisance effects, related to transient conditions or long-term odour issues. Similar considerations may be required as for remediation to reduce risks to human health, such as:

1 What techniques could be used to reduce/remove the odour nuisance?

2 How can the techniques be used?

3 How can the success of the work done be monitored?

4 How can community concerns be alleviated throughout the process?

9.9 FUTURE CHANGES TO THE DEVELOPMENT AND EFFECT ON THE SOIL GAS REGIME

The potential effects of changes to the soil gas regime due to a future development should be considered not only during the risk assessment process, but also during design, the carrying out and verification of a remediation plan. Several scenarios that may need consideration when designing the remediation plan are discussed in Table 9.4.

Table 9.4 ***Potential development scenario changes***

Scenario	Points of consideration
Existing gas protection measures	The presence of existing gas protection measures (typically for sites where bulk ground gases such as carbon dioxide or methane are present) at a development may affect the remediation plan for a site where risks from a potential vapour intrusion or emission pathway have been identified.
Changing the site use	Changes to the soil gas regime can occur because of the site development (such as construction of a building on a previously undeveloped site) or modification to the existing layout, such as extending the building footprint, as discussed in earlier chapters. This needs consideration before carrying out and verifying remediation works.
Future changes to the site layout	Future changes to the site layout should be reassessed through the planning regime. However, for certain remediation technologies (in particular use of pathway breakage/removal) the design needs to consider whether changes to the site use in the future could reduce the effectiveness of the chosen technique (eg puncturing of an engineered vapour barrier)
Effects resulting from changes off-site	Changes in off-site land-use may, under certain circumstances (for the more mobile and persistent VOCs), affect the soil gas regime beneath a site, which should be considered during development of the remediation plan. This is unlikely to be a significant problem for sites contaminated by more readily degradable compounds such as petroleum hydrocarbons.

9.10 SUMMARY

Remediation to minimise the risks from the vapour intrusion, emission or release pathways can be required based on a wide range of exposure scenarios, related to short, medium and long-term exposure and associated health effects.

Three potential forms of remediation can be adopted, namely source treatment/removal, pathway management/breakage or receptor management/removal. The selection of an appropriate technique depends on the CSM and the overall objectives to undertaking the remediation.

The remediation works need to be planned, carried out and verified before the risks to human health can be said to be effectively managed. In some cases, this requires long-term monitoring of the success of risk mitigation measures.

9.11 FURTHER INFORMATION

DEFRA and EA (2004a)
Model procedures for the management of land contamination
Contaminated Land Report 11 (CLR11), Environment Agency, Bristol (ISBN: 1-84432-295-5). Available from: <http://www.environment-agency.gov.uk/static/documents/SCHO0804BIBR-e-e(1).pdf>

ITRC (2007)
Vapor intrusion pathway: a practical guideline
ITRC vapor intrusion team, Interstate Technology And Regulatory Council, Washington DC, USA. Available from: <http://www.itrcweb.org/Documents/VI-1.pdf>

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10 Recommendations for research

1 This publication has highlighted different scenarios in which degradation of VOCs present as part of soil gas could, and often occur, based on studies presented in literature. In many cases, the degradation occurs under aerobic conditions, linked to the presence of oxygen in the subsurface. However, there is a need for further research in the UK into the conditions required for degradation of certain VOCs to occur.

2 The results of the literature review demonstrated that there have been limited studies into the effects of placing a low permeability medium such as concrete hardstanding (or a building) over soils on distribution and migration of VOCs in soil gas in the unsaturated zone. Further research in this area would help in understanding the importance of ground conditions on the presence and distribution of VOCs in the unsaturated zone in soil gas.

3 Separate guidance documents have been developed in several countries for the assessment and mitigation of risks associated with landfill gases such as methane and carbon dioxide (principally through risk of explosion), and the assessment and management of risks associated with VOCs (principally through inhalation exposure). However limited research has been undertaken to assess the interaction between these gases and compounds in the subsurface. Further research is recommended to investigate their interaction and the effect this could have on the transport of VOCs in the subsurface (Chapters 3 to 8).

4 Further work should be undertaken to develop a UK standard for undertaking soil gas investigations for VOCs, as has already been developed for investigations of other environmental media (Chapter 6).

5 There is debate within literature as to whether a soil gas monitoring well should be purged before sampling, because of the potential time involved in reaching close to steady-state conditions. Further research is recommended to assess whether, and under what scenarios, purging the sampling point is appropriate.

6 Potential mitigation systems that can be adopted to break the vapour intrusion pathway have been discussed briefly in this publication. However, the development of further, more detailed guidance relating to this topic, for example, as prepared by ITRC (2007), would be a valuable document for stakeholders involved in mitigating risks associated with vapour intrusion of VOCs (Chapter 9).

7 Considerable research has been undertaken in the US to create a database of empirical data relating to the vapour intrusion of VOCs. This has provided valuable information on how different VOCs migrate in soil gas through the subsurface and into indoor air spaces. Further research should be undertaken in the UK to develop a similar database, based on UK datasets (Appendix A2).

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References

ABREU, L D V and JOHNSON, P C (2005)
"Effect of vapor source – building separation and building construction on soil vapor intrusion as studied with a three-dimensional numerical model"
Environmental Science and Technology, 39, American Chemical Society, Washington, USA, pp 4550–4561

ABREU, L D V and JOHNSON, P C (2006)
"Simulating the effect of aerobic biodegradation on soil vapor intrusion into buildings: Influence of degradation rate, source concentration and depth"
Environmental Science and Technology, 40, American Chemical Society, Washington, USA, pp 2304–2315

ABREU, L D V, ETTINGER, R and McALARY, T (2007)
"Application of 3D numerical modeling to assess vapor intrusion screening criteria for petroleum hydrocarbon sites"
Proc vapor intrusion: learning from the challenges. Presentation at air and waste management association conference, Providence, RI, 26–28 September 2007

ALLEN, D J, BREWERTON, L J, COLEBY, L M, GIBBS, B R, LEWIS, M A, MacDONALD, A M, WAGSTAFF, S J and WILLIAMS, A T (1997)
The physical properties of major aquifers in England and Wales
Technical Report WD/97/34, British Geological Survey, Wallingford, Oxford (ISBN: 6-00000-572-5)

API (1998)
Assessing the significance of subsurface contaminant vapor migration to enclosed spaces, site-specific alternatives to generic estimates
API Publication 4674, American Petroleum Institute, Washington, USA. Available from: <www.api.org/>

API (2005)
Collecting and interpreting soil gas samples from the unsaturated zone. A practical strategy for assessing the subsurface vapor-to-indoor-air migration pathway at petroleum hydrocarbon sites
API Publication 4741, American Petroleum Institute, Washington, USA. Available from: <www.api.org/>

ASTM (2003)
Standard practice for cone penetrometer technology characterization of petroleum contaminated sites with nitrogen laser-induced fluorescence
ASTM D6187-97, American Society for the Testing of Materials, Pennsylvania, USA. Available from: <www.astm.org/>

ASTM (2004)
Standard guide for site characterization for environmental purposes with emphasis on soil, rock, the unsaturated zone and ground water
ASTM D5730-04, American Society for the Testing of Materials, Pennsylvania, USA. Available from: <www.astm.org/>

ASTM (2006)
Standard guide for sampling waste and soils for volatile organic compounds
ASTM D4547-06, American Society for the Testing of Materials, Pennsylvania, USA. Available from: <www.astm.org/>

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ASTM (2008)
Assessment of vapor intrusion into structures on property involved in real estate transactions
ASTM E 2600, American Society for the Testing of Materials, Pennsylvania, USA. Available from: <www.astm.org/>

AUER, L H, ROSENBERG, N D, BIRDSELL, K H and WHITNEY, E M (1996)
"The effects of barometric pumping on contaminant transport"
Journal of Contaminant Hydrogeology, 24, Elsevier BV, pp 145–166

BAEHR, A L and HULT, M F (1991)
"Evaluation of unsaturated zone air permeability through pneumatic tests"
Water Resources Research, 27 **(10)**, American Geophysical Union (AGU), Washington, USA, pp 2605–2617

BARCELONA, M J, WEHRMANN, H A and VARLJIEN, M D (1994)
"Reproducible well-purging procedures and VOC stabilization criteria for groundwater sampling"
Ground Water, 32, Elsevier BV, pp 12–22

BARRY, D L, SUMMERSGILL, I M, GREGORY, R G and HELLAWELL, E (2001)
Remedial engineering for closed landfill sites
C557, CIRIA, London (ISBN: 978-0-86017-557-5)

BERNHARD, C A, KIRSHNER, S, KNUTTI, R and LAGOUDI, A (1995)
"Volatile organic compounds in 56 European office buildings"
Healthy Buildings, 95 **(3)**, pp 1347–1352

BERRY, R W, BOXALL, J and CRUMP, D R (1995)
"Health hazards of building materials"
Building Issues, 7 **(1)**, Lind Centre for Habitat Studies, Lund University. CombiGrafic, Sweden

BERRY, R W, BROWN, V M, COWARD, S, CRUMP, D R, GAVIN, M, GRIMES, C P, HIGHAM, D F, HULL, A V, HUNTER, C A, JEFFREY, L G, LEA, R G, LLEWELLYN, J W and RAW, G J (1996)
Indoor air quality in homes: the BRE indoor environment study, parts 1 and 2
BRE Reports BR299 and BR300, CRC Press, London

BOLTZE, U and DE FREITAS, M H (1996)
"Changes in atmospheric pressure associated with dangerous emissions from gas generating disposal sites. The 'explosion risk threshold' concept"
Geotechnical Engineering, 119, pp 177–181

BOSZE, S L, RIHA, B, ROSSABI, J and HYDE, K (2001)
"Treatment of a unsaturated zone plume using barometric pumping: a passive soil vapour extraction study at the Miscellaneous Chemicals Basin, Savannah River site, South Carolina"
Proc abstracts from the American Geophysical Union Fall meeting 2001, San Francisco, 10–14 December 2001

BOYLE, R AND WITHERINGTON, P (2007)
Guidance on evaluation on development proposals on sites where methane and carbon dioxide are present, incorporating "traffic lights"
Report reference 10627-R01-(02), National House Building Council, Milton Keynes

BRADLEY, A D, JOHNSTON, A G and EDWARDS, J S (2002)
"NMVOC to methane ratios from flux box measurements"
Proc Integrated waste management and pollution control: research, policy and practice. Waste 2002, Stratford upon Avon, UK, September 2002, pp 121–130

© COPYRIGHT CIRIA 2009 NO UNAUTHORISED COPYING OR DISTRIBUTION PERMITTED

BRAND, E, OTTE, P F and LIJEN, J P A (2007)
CSOIL 2000: an exposure model for human health risk assessment of soil contamination. A model description
Report 711701054, National Institute of Public Health and the Environment (RIVM), The Netherlands

BRE (2007)
Radon: protective measures for new dwellings
Report BR211, BRE Press, Building Research Establishment, Bootle (ISBN: 1-86081-328-3)

BROWN, V M and CRUMP, D R (1998)
"The influence of indoor and outdoor sources on concentrations of benzene, toluene and undecane in 173 UK houses"
Proc Healthy Buildings 1995, Milan, 10–14 September 1995, 1, pp 385–391

BROWN, V M and CRUMP, D R (1998)
"The use of diffusive samplers for the measurement of volatile organic compounds in the indoor air of 44 homes in Southampton"
Indoor and Built Environment 7, International Society of the Built Environment, Sage Publications, USA, pp 245–253

CARD, G B (1995)
Protecting development from methane
Report 149, CIRIA, London (ISBN: 978-0-86017-410-3)

CAREY, M A, MARSLAND, P A and SMITH, J W N (2006)
Remedial targets methodology: hydrogeological risk assessment for land contamination
GEHO0706BLEQ-E-E, Environment Agency, Bristol

CARLTON, C (ED) (2007)
Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonization
EUR 22805-EN, European Commission, Joint Research Centre, Ispra

CHAPLIN, B P, DELIN, G N, BAKER, R J and LAHVIS, M A (2002)
"Long-term evolution of biodegradation and volatilization rates in a crude oil-contaminated aquifer"
Bioremediation Journal, 6 **(3)**, Taylor and Francis, London, pp 237–255

CHIOU, C T (2002)
Partition and absorption of organic contaminants in environmental systems
John Wiley & Sons (ISBN: 978-0-47123-325-1)

CL:AIRE (2007)
Communicating risk on contaminated sites: how best to engage with local residents
CL:AIRE SUBR:IM bulletin 6. Available from: <www.claire.co.uk>

CL:AIRE (2008)
Community engagement, urban regeneration, and sustainability
CL:AIRE SUBR:IM bulletin 8. Available from: <www.claire.co.uk>

CL:AIRE and CIEH (2008)
Guidance on comparing soil contamination data with a critical concentration
Published by CL:AIRE and the Chartered Institute of Environmental Health, with support from the Soil and Groundwater Technology Association (SAGTA) and the Royal Environmental Health Institute of Scotland (REHIS) (ISBN: 978-1-904306-79-5). Available from: <www.claire.co.uk/>

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COHEN, Y (1996)
"Volatile organic compounds in the environment: a multi-media perspective"
In: W Wang, J Schnoor and J Doi (eds), *Volatile organic compounds in the environment*, ASTM STP 1261, American Society for the Testing of Materials 1996, pp 7–32

COWARD, S K D, LLEWELLYN, J W, RAW, G J, BROWN, V M, CRUMP, D R and ROSS, D I (2001)
Indoor air quality in homes in England
BRE Report 433, BRE Press, Bootle (ISBN: SBN 978-1-86081-530-0)

COWARD, S K D, BROWN, V M, CRUMP, D R, RAW, G J and LLEWELLYN, J W (2002)
Indoor air quality in homes in England: volatile organic compounds
BRE Report 446, BRE Press, Bootle (ISBN: 978-1-86081-566-9)

CROWHURST, D (1987)
Measurement of gas emissions from contaminated land
BRE Press, Bootle. **Out of print**

CROWHURST, D and MANCHESTER, S J (1993)
The measurement of methane and other gases from the ground
CIRIA Report 131, CIRIA, London (ISBN: 978-0-86017-372-4)

CRUMP, D R (1995)
"Volatile organic compounds in indoor air"
In: R E Hester and R M Harrison (eds), *Volatile organic compounds in the atmosphere, issues in environmental science and technology*, 4, pp 109–124

CRUMP, D R and WILKINSON, G (2000)
"The assessment of land contaminated with hexachlorobutadiene and the role of measurement in assessing the indoor air quality in properties in the immediate vicinity"
Proc Competing precisely with the environment, Runcorn, 21 November 2000

CRUMP, D R, BROWN, V, ROWLEY, J, LLEWELLYN, J, WILKINSON, G and MOSS, R (2002)
"Sampling of hexachlorobutadiene in the air of homes at a site contaminated by industrial waste in England"
Proc Indoor air, Monterey, California, 30 June to 5 July 2002, pp 944–949

CRUMP, D R (2003)
"VOCs in buildings from contaminated land"
Clean Air, 33 **(2/3)**, Begell House Inc, Connecticut, pp 39–43

CRUMP, D R, BROWN, V, ROWLEY, J and SQUIRE, R (2004)
"Reducing ingress of organic vapours into homes situated on contaminated land"
Environmental Technology, 25, Taylor and Francis Ltd, London, pp 443–450

CRUMP, D R, HARTLESS, R, ROSS, D, SCIVYER, C, DAVIDSON, M and POUT, C (2005)
Review of building parameters for the development of a soil vapour intrusion model
R&D Project Record P5-079/PR, Environment Agency, Bristol

CRUMP, D R, BROWN, V, ROWLEY, J, SQUIRE, R, QUARTERMAN, P and HAFKENSCHEID, T (2008)
"Development and application of a sorbent tube method to determine carbon disulphide in indoor and ambient air"
Proc Indoor air, 516, Copenhagen, 17–22 August 2008

DANISH ENVIRONMENTAL PROTECTION AGENCY (2002)
Guidelines on remediation of contaminated sites
Environmental guidelines no 7, Copenhagen

DAVIS, G B, TREFRY, M G and PATTERSON, B M (2004)
Petroleum and solvent vapours: quantifying their behaviour, assessment and exposure
CSIRO land and water report to the Western Australian Department of the Environment, Perth

DAVIS, R (2006)
"Vapor attenuation in the subsurface from petroleum hydrocarbon sources: An update and discussion on the ramifications of the vapor-intrusion pathway"
LUSTLine Bulletin, 52, May 2006

DEFRA (2006)
Environmental Protection Act 1990: Part 2A. *Contaminated land*
DEFRA Circular 01/2006

DEFRA (2008)
Guidance on the legal definition of contaminated land
PB 13149, Department for Environment Food and Rural Affairs. Available from: <www.defra.gov.uk/ENVIRONMENT/land/contaminated/pdf/legal-definition.pdf>

DEFRA and EA (2004a)
Model procedures for the management of land contamination
Contaminated Land Report 11 (CLR11), Environment Agency, Bristol (ISBN: 1-84432-295-5). Available from: <http://www.environment-agency.gov.uk/static/documents/SCHO0804BIBR-e-e(1).pdf>

DEFRA and EA (2004b)
Contaminants in soil: collation of toxicological data and intake values for humans – vinyl chloride
Research and Development Publication TOX 18, Department for Environment, Food and Rural Affairs and Environment Agency

DEFRA and EA (2004c)
Contaminants in soil: collation of toxicological data and intake values for humans – tetrahloroethene
Research and Development Publication TOX 23, Department for Environment, Food and Rural Affairs and Environment Agency

DEFRA and EA (2004d)
Contaminants in soil: collation of toxicological data and intake values for humans – trichloroethene
Research and Development Publication 24, Department for Environment, Food and Rural Affairs and Environment Agency

DoE (1994)
Sampling strategies for contaminated land
Contaminated Land Report 4 (CLR4), DEFRA Publications. Prepared by the Centre for Research into the Built Environment, Nottingham Trent University.

DoE (1995)
Industry profiles
Department of the Environment, Belfast. Available from: <http://www.environment-agency.gov.uk/research/planning/33708.aspx>

DEVAULL, G E (2001)
"Estimation of volatile emissions during the excavation of soil or waste"
Environmental Science Technology, 35, American Chemical Society, Washington, USA, pp 3974–3980

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DEVAULL, G E (2007)
"Indoor vapor intrusion with oxygen-limited biodegradation for a subsurface gasoline source"
Environmental Science Technology, 41, American Chemical Society, Washington, USA, pp 3241–3248

DODSON, R E, LEVY, J I, SPENGLER, J D, SHINE, J P and BENNETT, D H (2008)
"Influence of basements, garages, and common hallways on indoor residential volatile organics compound concentrations"
Atmospheric Environment, 42, pp 1569–1581

ELECTRIC POWER RESEARCH INSTITUTE – EPRI (2005)
Reference handbook for site-specific assessment of subsurface vapor intrusion to indoor air
Document 1008492, Palo Alto, California

ENGLISH PARTNERSHIPS (2006)
The Brownfield Guide: a practitioners guide to land reuse in England
English Partnerships GD100018768

EA (2000a)
Secondary model procedure for the development of appropriate soil sampling strategies for land contamination
R&D Technical Report P5-066/TR, Monitor Environmental Consultants Ltd under contract to Environment Agency, Bristol (ISBN: 1-85705-577-2)

EA (2000b)
Cost-benefit analysis for remediation of land contamination
R&D Technical Report P316, Environment Agency, Bristol

EA (2000c)
Technical aspects of site investigation in relation to land contamination
Report P5-065/TR, two volumes, Environment Agency, Bristol

EA (2000d)
Non-intrusive investigation techniques for groundwater pollution studies
R&D Technical Report P403, Environment Agency, Bristol

EA (2001)
Remedial treatment datasheets
Environment Agency, Bristol. Available from:
<http://www.environment-agency.gov.uk/commondata/acrobat/rtas.pdf>

EA (2002)
Investigation of the composition, emissions and effects of trace components in landfill gas
R&D Technical Report P1-438/TR1, Environment Agency, Bristol

EA (2003)
Guidance on monitoring of landfill leachate groundwater and surface water
TGN02, Environment Agency, Bristol

EA (2004a)
Guidance for monitoring trace components of landfill gas
TGN04, Environment Agency, Bristol

EA (2004b)
An illustrated handbook of DNAPL transport and fate in the subsurface
R&D Publication 133, Environment Agency, Bristol

EA (2005)
Guidance on requirements for land contamination reports
Version 1, July 2005, Environment Agency, Bristol

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EA (2008)
Compilation of data for priority organic pollutants for derivation of Soil Guideline Values
Science Report SC050021/SR7, Environment Agency, Bristol. Available from:
<http://publications.environment-agency.gov.uk/pdf/SCHO1008BOVO-e-e.pdf>

EA (2009a)
Human health toxicological assessment of contaminants in soil
Science Report SC050021/SR2, Environment Agency, Bristol. Available from:
<http://publications.environment-agency.gov.uk/pdf/SCHO0508BNQY-e-e.pdf>

EA (2009b)
Updated technical background to the CLEA model
Science Report SC050021/SR3, Environment Agency, Bristol. Available from:
<http://publications.environment-agency.gov.uk/pdf/SCHO0508BNQW-e-e.pdf>

ETTINGER, R, McALARY, T and CREAMER, T (2008)
"Comments on the DTSC/LARWQCB soil gas sampling advisory"
Cal-EPA Soil Gas Advisory Forum, Los Angeles, California, 4 March 2008

EVANS, D, JEFFERIS, S A, THOMAS, A O and CUI, S (2001)
Remedial processes for contaminated land – principles and practices
C549, CIRIA, London (ISBN: 978-0-86017-549-0)

EVANS, D, HERS, I, WOLTERS, R M, BODDINGTON, R T B and HALL, D H (2002)
Vapour transfer of soil contaminants
R&D Technical Report P5-018/TR, Environment Agency, Bristol

FERGUSON, C C, KRYLOV, V V and McGRATH, P T (1995)
"Contamination of indoor air by toxic soil vapours: a screening risk assessment model"
Building and Environment, 30 **(3)**, Elsevier BV, pp 375–385

FISCHER, M L, BENTLEY, A J, DUNKIN, K A, HODGSON, A T, NAZAROFF, W W, SEXTRO, R G and DAISEY, J M (1996)
"Factors affecting indoor air concentrations of volatile organic compounds at a site of subsurface gasoline contamination"
Environmental Science and Technology, 30 **(10)**, American Chemical Society, Washington, USA, pp 2948–2957

FITZPATRICK, N A and FITZGERALD, J J (2002)
"An evaluation of vapor intrusion into buildings through a study of field data"
Soil and Sediment Contamination, 11, pp 603–623

FOLKES, D J, JEFFREY, P K and SANPAWANITCHAKIT, C (2007)
"Vapor intrusion as a function of lateral distance from a groundwater plume boundary"
Proc Air and Waste Management Association Vapor Intrusion conf, Providence, RI, September 2007

GARDNER, M, HAYWARD, H, BAKER, K, POLETTI, E, GILL, J and HOULDEN, L (2004)
Risk assessment comparison study
Compiled by ARCADIS Geraghty and Miller International. Published by NICOLE/ISG (Network for Industrially Contaminated Land in Europe Industrial Sub-Group). Executive summary report available from:
<www.nicole.org/news/downloads/NICOLE%20RA%20MODELS%20PROJECT%20EXECUTIVE%20SUM.PDF>

GEOPROBE SYSTEMS INC (2006)
"Direct-push installation of devices for active soil gas sampling and monitoring"
Technical Bulletin, 3099, May 2006

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GOLDER ASSOCIATES (2006)
Influence of bioattenuation on vapor intrusion into buildings – model simulations using semi-analytical one-dimensional model
Report prepared by T H Rees, and I Hers for the New Jersey Department of Environmental Protection

HARRIS, M R, HERBERT, S M and SMITH, M A (2005)
Remedial treatment for contaminated land
CIRIA SP164, volumes I–XII, CIRIA, London (ISBN: 978-0-86017-408-0)

HARRISON, P and HOLMES, P (2001)
Indoor air quality in the home: final report on DETR contract EPG 1/5/12
Institute of Environmental Health (IEH) web report W7, November 2001

HARTMAN, B (2002)
"Reevaluating the upward vapor migration risk pathway"
LUSTLine Bulletin, 41, June 2002

HARTMAN, B (2004)
"How to collect reliable soil-gas data for risk-based applications – specifically vapor intrusion"
LUSTLine Bulletin, 48, November 2004

HAWTHORNE, S B (2008)
"Tracing contributions of benzene from outdoor to indoor air"
Environmental Forensics, 9, Taylor and Francis, USA, pp 99–106

HEALTH CANADA (2004)
Final draft report on soil vapor intrusion guidance for health Canada Screening Level Risk Assessment (SLRA)
Golder Associates, Burnaby, British Columbia, Canada

HERS, I, SMITH, L, HEALEY, N and MIASEK, P (2007)
"Evaluation of petroleum hydrocarbon vapor bioattenuation and implications for intrusion guidance"
Proc AWMA 3rd specialty conference on vapor intrusion, Providence, Rhode Island, September

HSE (2000)
Recommendations in the report into the Bontddu petrol incident
HELA LACOTS PETEL 65/28, HSE Books, Bootle

HSE (2005)
Workplace exposure limits: containing the list of workplace exposure limits for use with the Control of Substances Hazardous to Health Regulations 2002 (as amended)
EH40/2005 Workplace Exposure Limits. For table of WELs, as of October 2007: <http://www.hse.gov.uk/coshh/table1.pdf>

HSE (2008)
Controlling airborne contaminants at work. A guide to local exhaust ventilation (LEV)
HSG 258, HSE Books, Bootle

INSTITUTE OF WASTE MANAGEMENT (1998)
The monitoring of landfill gas
Second edition, Institute of Waste Management, Northampton

ITRC (2007)
Vapor intrusion pathway: a practical guideline
ITRC vapor intrusion team, Interstate Technology And Regulatory Council, Washington DC, USA. Available from: <http://www.itrcweb.org/Documents/VI-1.pdf>

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ITRC (2007)
Vapor intrusion pathway: investigative approaches for typical scenarios
ITRC vapor intrusion team, Interstate Technology And Regulatory Council, Washington DC, USA

JAMIESON, S, DIMITROULOPOULOU, S, BROWN, V, APSIMON, H and COLVILLE, R (2005)
"Levels of indoor VOCs in workplaces in a polluted urban area of London"
Indoor Built Environment, 14 **(3–4)**, pp 255–268

JEFFRIES, J (2009)
A review of body weight and height data used within the Contaminated Land Exposure Assessment (CLEA) model
Science Report SC050021 (Technical Review 1), Environment Agency, Bristol

JOHNSON , P C and ETTINGER, R A (1991)
"Heuristic model for the intrusion rate of contaminant vapors into buildings"
Environmental Science and Technology, 25 **(8)**, American Chemical Society, Washington, USA, pp 1445–1452

JOHNSON , P C (2002)
"Identification of critical parameters for the Johnson and Ettinger (1991) vapor intrusion model"
API Bulletin 17, May 2002, American Petroleum Institute, Washington DC, USA

JOHNSON, P C, ETTINGER, R A, KURTZ, J, BRYAN, R and KESTER, J E (2002)
"Migration of soil gas vapors to indoor air: Determining vapor attenuation factors using a screening-level model and field data from the CDOT-MTL Denver, Colorado site"
API Bulletin 16, April 2002, American Petroleum Institute, Washington DC, USA

JOHNSON, R (2001)
Protective measures for housing on gas-contaminated land
BRE Report 414, BRE Press, Watford (ISBN: 1-86081-460-3)

JONES, H K, MORRIS, B L, CHENEY, C S, BREWERTON, L J, MERRIN, P D, LEWIS, M A, MacDONAL, A M, COLEBY, L M, TALBOT, J C, McKENZIE, A A, BIRD, M J, CUNNINGHAM, J and ROBINSON, V K (2000)
The physical properties of minor aquifers in England and Wales
Technical Report WD/00/4, British Geological Survey, Oxford
(ISBN: 6-00000-573-3)

KALIN, R (2007)
"Vapour intrusion modelling – a UK update"
Proc Risk assessment in the real world, brownfield briefing conference, 22–23 May 2007

KRYLOV, V V and FERGUSON, C C (1998)
"Contamination of indoor air by toxic soil vapours: the effects of subfloor ventilation and other protective measures"
Building and Environment, 33 **(6)**, Elsevier BV, pp 331–347

KURZ, D W (2000)
"Estimating residential indoor air impacts due to groundwater contamination"
Proc 2000 conference on hazardous waste research, Denver, Colorado, 23–25 May 2000

LAHVIS, M A and BAEHR, A L (1999)
"Quantification of aerobic-biodegradation and volatilisation rates of gasoline hydrocarbons near the water table during natural-attenuation conditions"
Water Resources Research, 35, American Geophysical Union (AGU), Washington, USA, pp 753–765

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LAHVIS, M (2006)
"Alternative model-based approach for assessing vapor intrusion at petroleum hydrocarbon sites"
Geological Society of America Abstracts with Programs, 38 **(7)**, the Geological Society of America, Colorado, USA, p373

LAPHAM, W W, WILDE, F D and KOTERBA, M T (1997)
Guidelines and standard procedures for studies of ground-water quality: selection and installation of wells and supporting information
Investigation Report 96-4233, US Geological Survey Water-Resources

LYMAN, W J, REEHL, W F and ROSENBLATT, D H (1982)
Handbook of chemical property estimation methods
American Chemical Society publication, Washington, DC
(ISBN: 978-0-84121-761-4)

ODPM (2004)
Planning policy statement 23: *planning and pollution control*
Office of the Deputy Prime Minister (now Communities and Local Government), London

OVAM, (2008)
Ontwerpversie standaardprocedure beschrijvend Bodemonderzoek – January 2008
OVAM, (Public Waste Agency of Flanders), Belgium

MALLET, H and BEALE, L (2008)
Guidance for the safe development of housing on land affected by contamination
R&D Publication 66, National House-Building Council (NHBC) <www.nhbcbuilder.co.uk>, Environment Agency (EA) <www.environment-agency.gov.uk> and the Chartered Institute of Environmental Health (CIEH) <www.cieh.org> (ISBN: 978-1-904306-82-5)

MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL PROTECTION (MADEP) (2004)
Proposed changes to the MCP Numerical Standards GW-2 Groundwater Standards
Office of Research and Standards, Boston

McALARY, T, DOLLAR, P, DEHAVEN, P, WILKINSON, G, MOSS, R, LLEWELLYN, J and CRUMP, D (2002)
"Assessment of subsurface vapour transport through Triassic sandstone and quarry fill into indoor air in Weston Village, Runcorn, UK"
Proc Indoor air, Monterey, California, 30 June to 5 July 2002, pp 902–907

McALARY, T, DOLLAR, P, DEHAVEN, P, WILKINSON, G, LLEWELLYN, J and CRUMP, D (2002)
"Subsurface vapour intrusion into indoor air; a case study"
Proc Remediation of chlorinated and recalcitrant compounds (2002). Third international conference on remediation of chlorinated and recalcitrant compounds, Monterey, California, May 2002. Paper 1D-08, A R Gavaskar and A S C Chen (eds), Batelle press, Columbus, OH, USA (ISBN: 1-57477-132-9)

McALARY, T, NICHOLSON, P, BERTRAND, D, ABREU, L and JOHNSON, R E (2007)
"A case study on the influence of aerobic biodegradation on vapor intrusion at a former refinery property"
Proc AWMA specialty conf on vapor intrusion, Providence, RI, September 2007

McHUGH, T E, CONNOR, J A and AHMAD, F (2004)
"An empirical analysis of the groundwater-to-indoor –air exposure pathway: The role of background concentrations in indoor air"
Environmental Forensics, 5, Taylor and Francis Ltd, USA, pp 33–44

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McHUGH, T E, DE BLANC, P C AND POKLUDA, R J (2006)
"Indoor air as a source of VOC contamination in shallow soils beneath buildings"
Soil and Sediment Contamination, 15 **(1)**, Taylor and Francis, USA, pp 103–122

McHUGH, T E, HAMMOND, D F, NICKELS, T and HARTMAN, B (2008)
"Use of radon measurements for evaluation of volatile organic compound vapour intrusion"
Environmental Forensics, 9, Taylor and Francis, USA, pp 107–114

McMAHON, A, HEATHCOTE, J, CAREY, M and ERKSINE, A (2001)
Guide to the good practice for development of conceptual models and the selection and application of mathematical models of contaminant transport in the subsurface
Report NC/99/38/2, National Groundwater and Contaminated Land Centre, Environment Agency, Bristol

MENDOZA, C A (1992)
VapourT users guide
Department of Geology, University of Alberta, Edmonton

NAGY, G Z (1991)
"The odour impact model"
Air and Waste Management Association, 41, pp 1360–1362

NATHANAIL, C P (2004)
"The use and misuse of CLR7 acceptance tests for assessment of risk to human health from contaminated land"
Quarterly Journal of Engineering Geology and Hydrogeology, 37, Geological Society, London, pp 361–367

NAZAROFF (1988)
"Predicting the rate of 222Rn entry from soil into the basement of a dwelling due to pressure-driven air flow"
Radiation Protection Dosimetry, 24 **(1/4)**, Oxford University Press, pp 199–202

NICOLE (2002)
Communication on contaminated land
Network for Industrially Contaminated Land in Europe, Reading, Berkshire.
Go to: <www.nicole.org>

NEW HAMPSHIRE DEPARTMENT OF ENVIRONMENTAL PROTECTION (NHDES) (2006)
Vapor intrusion guidance
New Hampshire Department of Environmental Services Site Remediation Programs, Waste Management Division

NJDEP (2005)
Vapor intrusion guidance
Site remediation and waste management program, New Jersey Department of Environmental Protection <www.nj.gov/dep/srp/guidance/vaporintrusion>

NZMfE (1999)
Guidelines for assessing and managing petroleum hydrocarbon contaminated sites in New Zealand
ME245 New Zealand Ministry for the Environment, Wellington, New Zealand

NIELSON, D M and NIELSEN, G L (2006)
"Groundwater sampling"
Practical handbook of environmental site characterisation and groundwater monitoring, second edition, D M Nielsen (ed), CRC-Taylor & Francis, pp 959–1112

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PETTS, J, HORLICK-JONES, T and MURDOCK, G (2001)
Social amplification of risk: the media and the public
HSE Contract Research Report 329/2001, Health and Safety Executive, Bootle

PETTS, J, HOMAN, J and POLLARD, S (2003a)
Participatory risk assessment: involving lay audiences in decisions on risk: literature review and stakeholder interviews
R & D Technical Report E2-043/TR/01, Environment Agency, Bristol

PETTS, J, GRAY, A-J and POLLARD, S (2003b)
Participatory risk assessment: characterising Environment Agency decisions on risk
R & D Technical Report E2-043/TR/02, Environment Agency, Bristol

POLSON, C J and MARSHALL, T K (1975)
The disposal of the dead
Third edition, the English University Press Ltd, London

ROBINSON, N I and TURCZYNOWICZ, L (2005)
"One- and three-dimensional soil transportation models for volatiles migrating from soils to house interiors"
Transport in Porous Media, 59, Springer, Netherlands, pp 301–323

ROGGEMANS, S, BRUCE, C L, JOHNSON, P L and JOHNSON, R L (2001)
"Vadose zone natural attenuation of hydrocarbon vapors: An empirical assessment of soil gas vertical profile data"
API Bulletin 15, December 2001, American Petroleum Institute, Washington DC, USA

RUDLAND, D J, LANCEFIELD, R M and MAYELL, P N (2001)
Contaminated land risk assessment: a guide to good practice
C552, CIRIA, London (ISBN: 978-0-86017-552-0)

RUSHTON, L (2004)
"Health impact of environmental tobacco smoke in the home"
Reviews on Environmental Health, 19 **(3–4)**, Freund Publishing House Ltd, London, pp 291–309

SEPA (2003)
Guidance on monitoring of landfill leachate groundwater and surface water, version 2
Scottish Environment Protection Agency, Stirling. Available from: <www.sepa.org.uk>

SCOTTISH GOVERNMENT (2000)
Planning Advice Note 33: *Development of contaminated land*
Available from: <www.scotland.gov.uk>

SCOTTISH GOVERNMENT (2006)
Environmental Protection Act 1990: Part IIA *Contaminated land – statutory guidance*: Edition 2
Available from: <www.scotland.gov.uk>

SLOCOMBE, R T, BUCHANAN, J and LAMONT, D R (2002)
"A management system for protecting compressed air tunnelling workers during operations through contaminated soil"
Proc 2nd int conf on engineering and health in compressed air work, St Catherine's College, Oxford, 25–27 September 2002, Thomas Telford (ed), London, 2003

SMITH, J A, TISDALE, A K AND CHO, J H (1996)
"Quantification of natural vapour fluxes of trichloroethylene in the unsaturated zone at Picatinny Arsenal, New Jersey"
Environmental Science and Technology, 30 **(7)**, American Chemical Society, Washington, USA, pp 2243–2250

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SNIFFER (1999)
Communicating understanding of contaminated land risks
Project SR97(11)F, Scotland and Northern Ireland Forum For Environmental Research, Edinburgh (update in preparation)

STEEDS, J E, SHEPHERD, E and BARRY, D L (1996)
A guide for safe working on contaminated sites
Report 132, CIRIA, London (ISBN: 978-0-86017-451-6)

STEEDS, J E, SLADE, N J and REED, M W (2000)
Technical aspects of site investigation in relation to land contamination
R&D Technical Report P5-065/TR, Environment Agency, Bristol (ISBN: 1-85705-545-4)

STONE, K, MURRAY, A, COOKE, S and FORAN, J (2009)
Unexploded ordnance (UXO) – a guide for the construction industry
C681, CIRIA, London (ISBN: 978-0-86017-681-7)

STRANGE, J and LANGDON, N (2007)
Contaminated land: investigation, assessment and remediation
Second edition, Institution of Civil Engineers, London (ISBN: 978-0-72773-482-2)

SWARTJES, F A (2002)
Variation in calculated human exposure: comparison of calculations with seven European human exposure models
Report 711701030, National Institute of Public Health and the Environment (RIVM), The Netherlands

SWITZER, C and KOSSON, D S (2007)
"Evaluation of air permeability in layered unsaturated materials"
Journal of Contaminant Hydrology, 90 **(3–4)**, Elsevier BV, pp 125–145

TILMAN, F and WEAVER, J W (2005)
Review of recent research on vapor intrusion
EPA/600/R-05/106, Office of Research and Development, US Environment Protection Agency, Washington DC, USA

TILMAN, F and WEAVER, J W (2006)
"Subsurface soil conditions beneath and near buildings and the potential effects on soil vapor intrusion"
Proc *18th annual national tanks conference, Memphis*, 20–22 March 2006

TREFRY, M G and BEKELE, E (2004)
"Structural characterization of an island aquifer via tidal methods"
Water Resources Research, 40 **(1)**, American Geophysical Union (AGU), Washington, USA

TURCZYNOWICZ, L and ROBINSON, N I (2007)
"Exposure assessment modeling for volatiles – towards an Australian indoor vapor intrusion model"
Toxicology and Environmental Health Part A, 70, Taylor and Francis, USA, pp 1619–1634

USACE (2007)
"Vapor intrusion and TCE update"
Army IRP/MMRP workshop, December 2007, in conjunction with ITRC, United Stated Army Corps Of Engineers

UNITED STATES DEPARTMENT OF ENERGY (1996)
100-FR-3 groundwater/soil gas supplemental limited field investigation report

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USEPA (1990)
Technology evaluation report: SITE program demonstration of a trial excavation at the McColl superfund site
Air and Engineering Research Laboratory, Risk Reduction Engineering Laboratory, region IX, US Environment Protection Agency, Washington DC, USA

USEPA (2000)
Office of emergency and remedial response user's guide for the Johnson and Ettinger (1991) model for subsurface vapour intrusion into buildings (revised)
Prepared by Environmental Quality Management Inc, December 2000 for United States Environmental Protection Agency, Washington DC, USA

USEPA (2001)
RCRA (Resource Conservation and Recovery Act) draft supplemental guidance for evaluating the vapor intrusion to indoor air pathway (vapor intrusion guidance)
United States Environmental Protection Agency, Washington DC, USA

USEPA (2002)
OSWER (Office of Solid Waste and Emergency Response) Draft guidance for evaluating the vapor intrusion to indoor air pathway from groundwater and soils (subsurface vapor intrusion guidance)
United States Environmental Protection Agency, Washington DC, USA

USEPA (2003)
Soil-gas measurement. Guidance document for soil-gas surveying
EPA EMSL-LV contract no 68-03-3245, C L Mayer (ed), Lockheed Engineering and Sciences Company, Las Vegas, NV, United States Environmental Protection Agency, Washington DC, USA

USEPA (2003)
A USEPA spreadsheet model:
<www.epa.gov/oswer/riskassessment/airmodel/johnson_ettinger.htm)>

USEPA (2008)
Brownfields technology primer: vapor intrusion considerations for redevelopment
EPA 542-R-08-001, Office of Solid Waste and Emergency Response, United States Environmental Protection Agency, Washington DC, USA

VAN GEERT, K, GEVAERTS, W, LAURYSSEN, K, VANDEN BOER, E, PROVOOST, J and CORNELIS, C (2003)
"Relation between concentrations in soil, groundwater, soil vapour concentrations and indoor air concentrations: field experiments"
Proc of ConSoil 2003, Bordeaux, France, 12–16 May 2003

VAN GEERT, K, GEVAERTS, W, LAURYSSEN, K, VANDEN BOER, E, PROVOOST, J and CORNELIS, C (2004)
"Relation between soil, groundwater concentrations, soil gas and indoor air: measurements and models"
Nicole SPG, published by NICOLE <www.nicole.org> October 2004

VAN GEMERT, L J (1999)
Compilation of odour threshold values in air and water
Division for Nutrition and Food Research TNO, Netherlands Organization for Applied Scientific Research

VENN, A J, COPPER, M, ANTONIAK, M, LAUGHLIN, C, BRITTON, J and LEWIS, S A (2003)
"Effects of volatile organic compounds, damp, and other environmental exposures in the home on wheezing illness in children"
Thorax, 58, BMJ Publishing Group, pp 955–960

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WAITZ, M F W, FREIJER, J I, KREULE, P and SWARTJES, F A (1996)
The VOLASOIL risk assessment model based on CSOIL for soils contaminated with volatile compounds
Report 715810014, National Institute of Public Health and the Environment (RIVM), The Netherlands

WEALTHALL, G P, STEELE, A, BLOOMFIELD, J P, MOSS, R, and LERNER, D N (2001)
"Sediment filled fractures in the Permo-Triassic sandstones of the Cheshire Basin: Observations and implications for pollutant transport"
Journal of Contaminant Hydrogeology, 50, Elsevier BV, pp 41–51

WELSH ASSEMBLY GOVERNMENT (2002)
Planning Policy Wales
The Publications Centre, Cardiff. Available from: <http://www.wales.gov.uk>

WELSH ASSEMBLY GOVERNMENT (2006)
Part 2A *Statutory guidance on contaminated land*
Available from: <http://chwaraedysgutyfucymru.gov.uk>

WIEDEMEIER, T H, RIFAI, H S, NEWELL, C J and WILSON, J T (1999)
Natural attenuation of fuels and chlorinated solvents in the subsurface
John Wiley and Sons, New York

WIJNEN, H J VAN and LIJEN, J P A (2006)
Validation of the VOLASOIL model using measurements from Dutch contaminated sites – concentrations of four chlorinated compounds
Report 711701041, National Institute of Public Health and the Environment (RIVM), The Netherlands

WILKINSON, G, MOSS, R, CRUMP, D, BROWN, V, ROWLEY, J, HAFKENSCHEID, T, KEARN, R, CARP, A, and KRISTENSON, J (2002)
"Quality control and quality assurance procedures used during the indoor air monitoring in Weston Village, Runcorn"
Proc Indoor air, Monterey, California, 30 June to 5 July 2002 pp 950–955

WILSON, S, OLIVER, S, MALLETT, H, HUTCHINGS, H and CARD, G (2007)
Assessing risks posed by hazardous ground gases to buildings
C665, CIRIA, London (ISBN: 978-0-86017-665-7)

WILSON, S, CARD, G and HAINES, S (2008)
The ground gas handbook
Chartered Institute of Environmental Health, London

WISBECK, D, SHARPE, C, FRIZZELL, A, LUTES, C and WEINBERG, N (2006)
"Using naturally occurring radon as a tracer for vapor intrusion: a case study"
Proc Society for Risk Analysis annual meeting, Baltimore, Maryland, 3–6 December 2006

YU, C W F and CRUMP, D R (1998)
"A review of the emission of volatile organic compounds from polymeric materials used in buildings"
Building and Environment, 33 **(6)**, Elsevier BV, pp 357–374

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British Standards

BS 5925:1991 *Code of practice for ventilation principles and designing for natural ventilation*

BS 5930:1999 *Code of practice for site investigations*

BS 10175:2001 *Investigation of potentially contaminated sites. Code of practice*

BS EN ISO 12569:2001 *Thermal insulation in buildings. Determination of air exchange in buildings. Tracer gas dilution method*

BS EN ISO 16017-1:2001 *Indoor, ambient and workplace air. Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/ capillary gas chromatography. Pumped sampling*

BS ISO 10381-1:2002 *Soil quality. Sampling. Guidance on the design of sampling programmes*

BS ISO 10381-2:2002 *Soil quality. Sampling. Guidance on the design of sampling techniques*

BS ISO 10381-3:2002 *Soil quality. Sampling. Guidance on safety*

BS EN ISO 16017-2:2003 *Indoor, ambient and workplace air. Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography. Diffusive sampling*

BS ISO 22155:2005 *Soil quality. Gas chromatographic quantitative determination of volatile aromatic and halogenated hydrocarbons and selected ethers. Static headspace method*

BS EN ISO 5667-1:2006, BS 6068-6.1:2006 (and related series) *Water quality. Sampling. Guidance on the design of sampling programmes and sampling techniques*

BS ISO 12569:2007 *Indoor air. Determination of local mean ages of air in buildings for characterising ventilation conditions*

BS ISO 15175:2004 *Soil quality. Characterization of soil related to groundwater protection*

BS EN ISO 16000-1:2006 *Indoor air. General aspects of sampling strategy*

BS EN ISO 16000-9:2006 *Indoor air. Determination of the emission of volatile organic compounds from building products and furnishing. Emission test chamber method*

BS EN ISO 16000-10:2006 *Indoor air. Determination of the emission of volatile organic compounds from building products and furnishing. Emission test cell method*

BS EN ISO 16000-5:2007 *Indoor air. Sampling strategy for volatile organic compounds*

BS ISO 16000-8:2007 *Indoor air. Determination of local mean ages of air in buildings for characterising ventilation conditions*

BS 8485:2007 *Code of practice for the characterization and remediation from ground gas in affected developments*

BS EN 15241:2007 *Ventilation for buildings. Calculation methods for energy losses and infiltration in commercial buildings*

BS EN 15242:2007 *Ventilation for buildings. Calculation methods for the determination of air flow rates in buildings including infiltration*

Acts/Regulations

Building Regulations (England and Wales) 2000: Part C (Site preparation and resistance to contaminants and moisture – 2004) and Part F (Ventilation – 2006) (SI 2000, no 2531)

Building Regulations (Scotland) 2004

Contaminated Land (Wales) Regulations 2001

Contaminated Land (Scotland) Regulations 2005

Contaminated Land (England) Regulations 2006

The Control of Substances Hazardous to Health Regulations 2002 (COSHH) (SI No 2677)

Environmental Permitting Regulations 2007

Environmental Protection Act 1990: Part 2A Contaminated Land (inserted by Section 57 of the Environment Act 1995)

Pollution Prevention and Control (England and Wales) Regulations 2000

Pollution Prevention and Control (Scotland) Regulations 2003

Town and Country Planning Act 1990

Town and Country Planning Act (Scotland) 1997

Waste and Contaminated Land (Northern Ireland) Order 1997

Waste Management Licensing (Scotland) Regulations 1994, amended in 2003

Water Environment and Services (Scotland) Act 2003

Water Resources Act 1991

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A1 Trace components

Significant trace components of landfill gases, as identified in EA (2004a), are:

- 1,1-dichloroethane
- 1,1-dichloroethene
- 1,2-dichloroethene
- 1,3-butadiene
- 1-butanethiol
- 1-pentene
- 1-propanethiol
- 2-butoxy ethanol
- Arsenic (as As)
- Benzene
- Butyric acid
- Carbon disulphide
- Chloroethane
- Chloroethene (vinyl chloride)
- Dimethyl disulphide
- Dimethyl sulphide
- Ethanal (acetaldehyde)
- Ethanethiol
- Ethyl butyrate
- Furan (1,4-epoxy-1,3-butadiene)
- Hydrogen sulphide
- Methanal (formaldehyde)
- Methanethiol
- Tetrachloromethane
- Trichloroethene.

Other components that the Environment Agency suggest could be monitored for are:

- 1,2-dichloroethane
- 1,1,2,2-tetrachloroethane
- Dichloromethane.

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A2 Background information – vapour intrusion

In the past ten years, the measurement and modelling of the vapour intrusion pathway has been the subject of considerable debate, with a range of guidance documents developed globally to help practitioners assess the pathway.

A2.1 GLOBAL PRACTICES – ASSESSING THE VAPOUR INTRUSION PATHWAY

In 1995, USEPA developed the risk-based decision making (RBDM) and risk-based corrective action (RBCA) methodologies, in part to provide a clearer and consistent framework for the assessment of risks to human health from the intrusion of volatile compounds into indoor air spaces (Davis *et al*, 2004). The RBCA concepts and methodology were adopted, and adapted, by many countries. Other similar risk-based frameworks were later adopted in countries such as The Netherlands. Computer software packages were developed to assess the pathway and develop screening levels (for example, the J&E vapour intrusion model, the Dutch CSOIL model and the later VOLASOIL model). In the UK, vital work was undertaken in the 1990s into how to assess and model the vapour intrusion pathway by Ferguson *et al* (1995) and Krylov and Ferguson (1998).

In the last five years several guidance documents have been developed. This is primarily following the collation of site-specific data regarding the vapour intrusion pathway (such as USEPA's groundwater-indoor air empirical dataset), but also from concerns about ensuring that computer modelling is only applied under appropriate circumstances,

Vapour intrusion in the USA

McHugh *et al* (2004) provide a summary of the vapour intrusion guidance development in the USA, and help to explain the route taken in the USA to assess this pathway (adapted from McHugh *et al*, 2004):

- RBCA was adopted in the mid nineties at corrective action sites using the J&E model (1991)
- the focus was on developing vapour intrusion screening levels for groundwater
- in the late nineties, two Colorado sites with "chlorinated solvent" (halogenated hydrocarbon) groundwater plumes, and with measured concentrations in the air within overlying buildings, became apparent at a national level in the USA
- largely as a response to this, USEPA released the RCRA (Resource Conservation and Recovery Act) *Draft supplemental guidance for evaluating the vapor intrusion to indoor air pathway* (vapor intrusion guidance) (USEPA, 2001) for RCRA corrective action facilities. In 2002, this was extended to superfund and other corrective action sites with the release of the OSWER (Office of Solid Waste and Emergency Response) *Draft guidance for evaluating the vapor intrusion to indoor air pathway from groundwater and soils (subsurface vapor intrusion guidance)* (USEPA, 2002)

- there has now been a move towards sampling and collection of data as opposed to use of models, because of uncertainties as to whether the J&E model was sufficiently conservative to develop screening levels. This has culminated in the recent development of a USEPA database documenting alpha factors (see Section A2.2).

In 2005, the American Petroleum Institute (API) released a guidance document to provide more practical advice on the assessment of petroleum hydrocarbons, and the collection of soil gas samples (API, 2005). Following this, the International Technology and Regulatory Council (ITRC) compiled a comprehensive practical guidance document and supplement for the vapour intrusion pathway (as undertaken in the USA), after consultation with regulators, industry, consultants and other stakeholders:

- *Vapor intrusion pathway: a practical guideline* (ITRC, 2007)
- *Vapor intrusion pathway: investigative approaches for typical scenarios* (ITRC, 2007).

Following the ITRC document, the American Society for the Testing of Materials (ASTM) finalised the standard practice document to assess vapour intrusion into structures for property involved in real estate transactions (2008). USEPA released a guidance document for brownfield sites undergoing redevelopment (2008).

In the last five years, the guidance developed in the USA, and also in Canada (for example, Health Canada, 2004), has focused on collection of groundwater and soil gas data, with recommendations made against the use of soil data for the assessment of risks via the vapour intrusion pathway. There appear to be many reasons for the move away from the use of soil data, including:

- uncertainty associated with modelling of partitioning from soil to soil gas (level of conservatism and cases where modelling under-predicts the level of partitioning), potential for loss of volatiles during soil sampling, resulting in a poor correlation between soil measurements and soil gas data (ITRC, 2007), and uncertainty in the analysis (reproducibility and discrete nature of sample)
- many of the sites of concern in the USA overlie "off-site" groundwater plumes, where soil sources are not present
- the regulatory/legislative framework in place.

Vapour intrusion in Australia and New Zealand

Both Australia and New Zealand have adopted risk-based assessment frameworks, which consider the vapour intrusion pathway.

In 2004, the Australian Commonwealth and Scientific Research Organisation (CSIRO) released a document that reviewed the status of research and investigation techniques and knowledge in the area of soil gas/vapour intrusion and potential exposure assessment. The report focused on petroleum (non-halogenated) hydrocarbons and halogenated hydrocarbons (chlorinated solvents), their different behaviour in the environment (namely biodegradation in the unsaturated zone), and several case studies from across Australia (Davis *et al*, 2004).

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Work has been undertaken in the last five years to develop an Australian vapour intrusion model. Most recently, Turczynowicz and Robinson (2007) provided an update on progress for the model development, alongside a summary of regulatory perspectives on vapour intrusion modelling from North America and Europe. The use of health-based soil investigation levels (HILs) for the vapour intrusion pathway has been proposed for petroleum hydrocarbon compounds.

The New Zealand Ministry for the Environment (NZMfE, 1999) has also developed guidance on the assessment of petroleum hydrocarbon compounds, which includes the soil to indoor air inhalation exposure pathway.

Vapour intrusion in Belgium

The Belgian authorities have been considering the vapour intrusion pathway for the last five years in a similar level of detail to the USA. The Public Waste Agency of Flanders (OVAM) commissioned studies to assess the relationship between soil, groundwater and soil gas concentrations due to its effect on indoor air spaces. A new guidance document, adopted in June 2008 (OVAM, 2008) recommends the use of soil and groundwater data to assess the pathway, although extra measurements (such as soil gas or indoor air) could be collected to provide further lines of evidence if desired. Research funded by OVAM, and carried out by the Flemish Institute for Technological Research (VITO), ARCADIS Gedas and Soresma compared different soil gas measurement techniques, the presence of a slab at the surface and the relationship between soil measurements and soil gas (Van Geert *et al*, 2003 and 2004). The conclusion reached by the studies was that large uncertainties could be present with soil gas measurements, and collection of useful and defensible data required an experienced investigator. The guidance in Flanders relies first on the use of soil and groundwater data, and secondly on alternative methods of assessment (multiple lines of evidence, if required).

Vapour intrusion in The Netherlands

The Dutch authorities have undertaken research into the vapour intrusion pathway for over 15 years, with much of the work reported by the National Institute for Public Health and the Environment (RIVM). A vapour intrusion sub-model was included in the modelling tool CSOIL (see Brand *et al*, 2007 for a description) used within the software model Risc-Human) which assumed that vapours entered crawl spaces beneath buildings, either through an open basement floor or through porosity in concrete foundation slabs. Further research was later undertaken to assess the pathway, with the vapour intrusion model VOLASOIL developed and included in Risc-Human (Waitz *et al*, 1996). This vapour intrusion model considered the influence of pressure-driven flow, drawing soil gas from the subsurface into a crawl space and then into an overlying living space. Work has been done more recently to validate the VOLASOIL model (Wijnen and Lijen, 2006).

Vapour intrusion in other countries

General risk assessment guidance documents have been developed by countries globally (such as France and Brazil), but these are not specific to the vapour intrusion pathway. Typically, both soil and groundwater data are used at the screening or generic quantitative type of assessment, in some cases using default "attenuation" factors to develop generic screening levels (for example, Sweden).

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A2.2 PROCESSES OF MODELLING

Within literature, three processes of the modelling of the vapour intrusion pathway have been considered in the greatest detail:

- partitioning of contaminants from soil/groundwater to soil gas
- migration via the unsaturated zone
- the intrusion of vapours into the overlying building.

Partitioning of contaminants

The mechanism by which VOCs partition into gaseous phase, and how to model the partitioning, has been subject to debate within literature. This is primarily due to the observed differences between predicted concentrations of compounds in the gaseous phase (originating from either a soil or groundwater source, via theoretical/laboratory studies) when compared to data from empirical studies. It is generally recognised that there are limitations and simplifications involved when modelling processes taking place in a complex and heterogeneous medium such as soil, which is discussed in detail in Chiou (2002). Points to consider include the effect the moisture content has on concentrations of organic contaminants in gaseous phase, the level of dissolved organic carbon and co-distillation effects. Relatively simple partitioning equations are most commonly used to predict the concentration of an organic compound in gaseous phase (for example, EA, 2009b).

There are relatively few peer-reviewed papers that assess the partitioning of contaminants from soil/groundwater to soil gas using data collected from actual sites. In 2002, Fitzpatrick and Fitzgerald presented a systematic examination of cases on file with the Massachusetts Department of Environmental Protection relating to VOC contaminated sites near to buildings. Indoor air, soil gas and/or groundwater data from each site were compiled and assessed. The appropriateness of using Henry's law constant to model partitioning was assessed, with the measured value compared to the theoretical value as a percentage (%Hc). In total, data from 24 sites were reviewed for this purpose. The results were as follows:

Table A2.1 ***Summary of results of the study by Fitzpatrick and Fitzgerald (2002)***

Site type	# Sites	%Hc range	Mean (%)	Std. deviation
All	24	7×10^{-3} – 10	0.661	1.73
High confidence	16	2×10^{-3} – 10	0.721	1.66
PCE	6	0.025 – 1	0.48	0.56
TCE	14	2×10^{-3} – 10	1.15	2.4
DCE	3	0.03 – 1.4	0.671	0.73
Benzene	5	9×10^{-3} – 0.14	0.05	0.05

The results indicate that for all of the compounds assessed, use of the Henry's law constant to predict a soil gas concentration was conservative. This has been confirmed by other authors, using groundwater and soil gas data collected simultaneously (eg United Stated Department of Energy, 1996). This may be partly be due the difficulties of predicting partitioning in a natural, rather than

laboratory, environment, but is also likely linked to the attenuation that takes place across the capillary fringe and biodegradation effects. When collecting soil gas samples to correlate with measured groundwater concentrations, collection of a sample directly over the groundwater can be difficult, typically the sample is taken a minimum of 0.5 m above the groundwater resting level (Hers, *pers comm.*).

It is notable that the halogenated hydrocarbons were present at higher concentrations than benzene. This trend has been observed by other authors such as Hartman (2002) who wrote:

> *"…results of published studies comparing measured soil vapour [gas] concentrations to soil vapour [gas] values calculated from groundwater using Henry's law constants indicate that calculated values are often overestimated by factors of 10 to 100. Contaminant partitioning from soil to soil vapour [gas] is also likely to be far from equilibrium".*

Dr Hartman, a corresponding member of the Project Steering Group, stated that in his personal experience, based on measurements of contaminated soil and soil gas at the same location, the soil gas concentrations for petroleum hydrocarbons are often overestimated using the Henry's law constant by a factor of 10 to 1000. Conversely, for halogenated hydrocarbons, the use of soil data to predict soil gas concentrations can result in an underestimation of the concentration in soil gas (Hartman, 2002). A clear correlation between measured concentrations of halogenated hydrocarbons in soil and soil gas is rarely observed in studies reported in literature, due to the complex source distribution and migration associated with these compounds (often associated with DNAPLs).

The relationship between predicted concentrations of VOCs in soil gas versus measured concentrations where NAPL is present, is still under investigation. A recent presentation of data by representatives for Health Canada (Hers *et al*, 2007, related guidance in preparation) substantiates the findings of other authors when looking at dissolved phase sources of petroleum hydrocarbons in groundwater and predicted concentrations in soil gas. The report quotes three sites where the ratio between measured and predicted concentrations of benzene/toluene/ethylbenzene/xylenes (BTEX) was 2×10^{-3} to 1×10^{-5}. However for four sites with LNAPL present, the ratio of measured to predicted concentrations of BTEX ranged from 0.02 to 1.4. Figure A2.1 is taken from the presentation (Hers *et al*, 2007).

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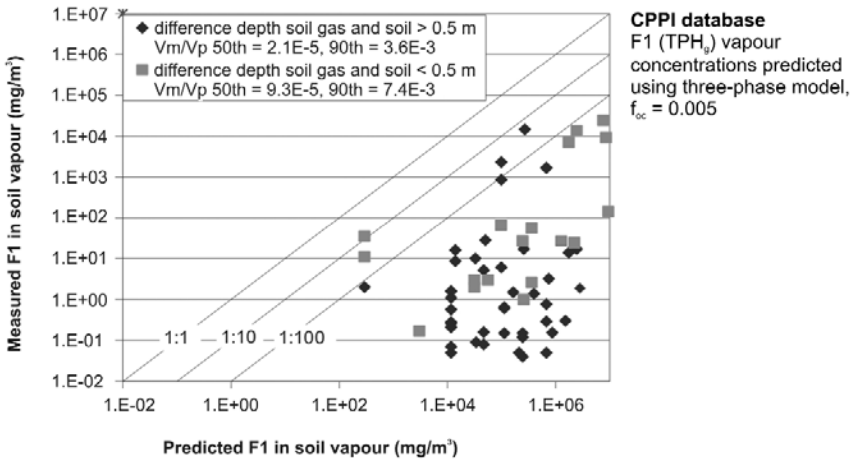

Note:

Taken from the Canadian Petroleum Products Institute (CPPI) database. F1 (TPH_g) soil gas concentrations predicted using a three-phase model, f_{oc} set at 0.005.

Approximate relationship between measured and predicted soil gas ("vapour" in the plot) concentrations. Measured soil gas concentrations are at least 10 times less than predicted.

Figure A2.1 ***Predicted versus measured concentrations of TPH compounds in soil gas (taken from Hers et al, 2007)***

In general, it can be concluded that using the simple partitioning equations results in a conservative estimate of many types of VOC concentration in soil gas. However, the level of conservatism in the predicted concentration is variable, depending on the site setting, the types of VOCs present and the source medium. Predicted concentrations of petroleum hydrocarbons in soil gas (from a source within soil or groundwater) are at least 10 times higher (and often greater) when compared with site measurements, most likely due to a range of factors, such as biodegradation and how the compounds behave as part of a mixture. This can also be the case for halogenated hydrocarbons present in the dissolved phase, although predicted concentrations in soil gas from a groundwater source can be close to that measured in some circumstances (for example, where the capillary fringe is thin in coarse-grained soils (Hers *pers comm.*). However, where halogenated hydrocarbons are present adsorbed to soils (or as a gaseous phase due to a leak of vapours), often no distinct correlation between predicted and measured concentrations is observed. Dissolved phase measurements of halogenated hydrocarbons can typically be a useful indicator of the potential presence of the same compounds in soil gas, but the same cannot be concluded for measurements of halogenated hydrocarbons in soils. Where NAPL is present, the correlation between measured and predicted concentrations of VOCs in soil gas is variable based on studies to date.

Vapour migration through the unsaturated zone

Migration via the unsaturated zone occurs through diffusive and advective processes. The general consensus in literature (for example, Evans *et al*, 2002) is that for most sites, diffusive effects predominate but advective effects should be noted (such as large fluctuations in groundwater or sources present in the shallow ground). During transport through the unsaturated zone, the persistence of the compound, or mixture of compounds, in the environment is vital. As seen for the partitioning of contaminants into soil gas, a distinction between petroleum hydrocarbons and halogenated hydrocarbons (and other more persistent volatiles) can be made. Considerable research has been undertaken, which illustrates that biodegradation of petroleum hydrocarbons in

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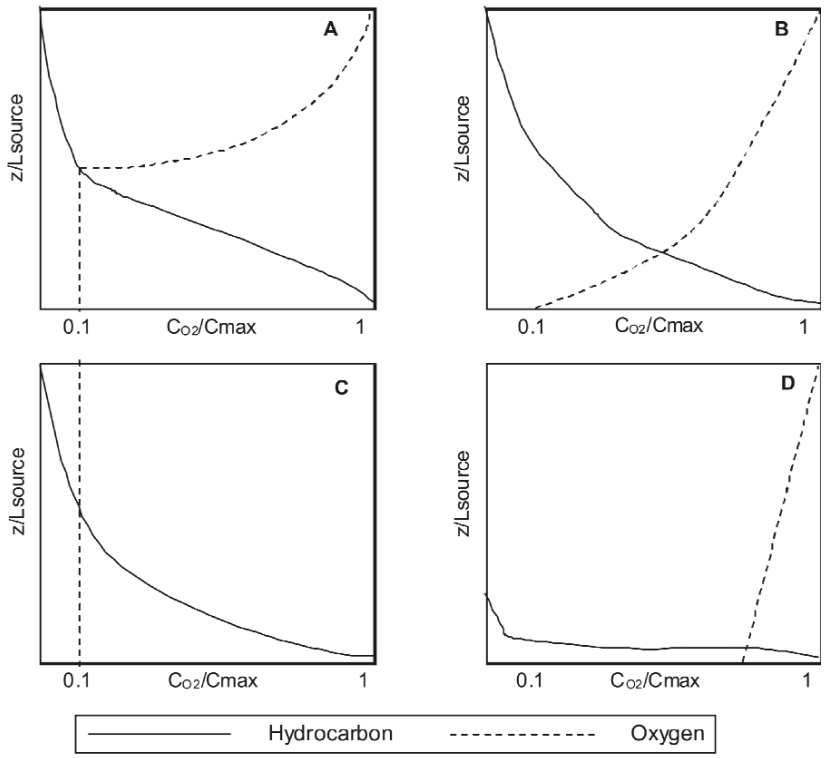
the unsaturated occurs regularly and can significantly affect the potential for vapour intrusion or emission (for example, Fischer *et al*, 1996, Fitzpatrick and Fitzgerald, 2002, Roggemans *et al*, 2001, Lahvis and Baehr, 1999, Golder Associates, 2006 and DeVaull, 2007) to the extent that "there are not many cases of proven vapour intrusion documented in the scientific literature" (Tilman and Weaver, 2005). The transport of petroleum hydrocarbons is extremely sensitive to biodegradation in the unsaturated zone (Johnson, 2002). The sensitivity to the biodegradation may in some cases dwarf the sensitivity of VOC transport to other factors (for example, meteorological factors, building factors, barometric). In particular, there is likely to be limited potential for vapour intrusion to occur at sites with a dissolved phase of petroleum hydrocarbons only where the water table and building foundation are separated by more than 1 m. Vapour intrusion from petroleum hydrocarbons is limited at these sites because the source mass in groundwater is insufficient to significantly limit oxygen availability and biodegradation in the unsaturated zone. Note that some regulatory agencies in the US and Canada have incorporated a "bioattenuation" factor into generic screening levels for sites affected by petroleum hydrocarbon contamination (for example, Health Canada, 2004, NJDEP, 2005, MADEP, 2004 and NHDEP, 2006).

Four different behavioural categories of petroleum hydrocarbons in soil gas as they migrate through the unsaturated zone (adapted from Roggemans *et al*, 2001) are shown on Figure A2.2.



Note:

CO_2/C_{max} = 0.1 corresponds to CO_2 > 2% v/v (usable oxygen)

z is the distance measured down from the upper surface (ground surface or basement foundation)

Lsource is the distance from the upper surface of the VOCs source to the upper boundary

z/Lsource represents the normalised depth profile

Figure A2.2 ***Four typical behavioural categories of petroleum hydrocarbons in soil gas (adapted from Davis et al, 2004 and Roggemans et al, 2001)***

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The research carried out by Roggemans *et al* (2001) supported the hypothesis that aerobic biodegradation was *"an important factor in the development of measured soil gas profiles"*. Fischer *et al*, (1996) illustrated that oxygen is commonly present under building foundations, while field data from several sites across Australia was reported to illustrate that biodegradation of petroleum hydrocarbons occurs (Davis *et al*, 2004). Hartman (2004) summarises studies on the percentage of oxygen required to allow degradation of petroleum hydrocarbons to occur, and analysis of data from sites across the USA by Davis (2006) resulted in guidance that biodegradation was likely to occur if 2 ft of "clean" fine-grained soils (5 ft of coarse-grained soils) and at least five per cent oxygen were present (even beneath buildings). The results of the study of site-specific data by Davis were supported by the work by Abreu and Johnson (2006) who have modelled this process theoretically, although the research was focused on coarse-grained soils. Also, depleted oxygen (for example, concentrations in soil gas of less than two per cent) does not necessarily indicate that no aerobic biodegradation is occurring, rather that the rate of oxygen consumption may exceed the rate of oxygen availability (in other words, aerobic biodegradation is occurring but the rate is limited). For this reason, oxygen concentration gradients may be a more reliable indicator of biodegradation than oxygen concentrations. Further work is being undertaken to assess this, but with limited data available for UK sites. The Davis "rule of thumb" should not be relied on for UK soils, but a site-specific approach that incorporates biodegradation in assessing the vapour intrusion pathway may be more appropriate for application at sites with petroleum hydrocarbons, in particular, sites with lower concentration sources (for example, dissolved phase). Based on their biodegradation in the unsaturated zone in many cases, the potential for significant lateral migration of these compounds in soil gas is usually limited, unless the CSM dictates otherwise (for example, the presence of a significant preferential flow pathway).

Halogenated hydrocarbons (such as trichloroethene) and other VOCs do not show the same behaviour as petroleum hydrocarbons in the unsaturated zone, potentially because they do not degrade easily under aerobic conditions (Davis *et al*, 2004 and ITRC, 2007). Anaerobic degradation of these compounds may occur under some circumstances (Wiedemeier *et al*, 1999), but typically a more limited reduction in soil gas concentrations between the source area and ground surface occurs. There is a higher potential for these compounds to migrate not only vertically from the source but laterally.

In the US, the lateral distance that significant attenuation of VOCs in soil gas between the source and receptor occurs has been discussed within regulatory guidance, based on work undertaken in the field and theoretically by authors such as Lilian Abreu and Paul Johnson. In some states, where VOCs are considered as a single group of compounds, an "exclusion distance" (ie the distance between source and receptor that means the pathway does not need further consideration) of 30 m lateral offset between the source/plume and receptor has been adopted (for example, California, Pennsylvania and Colorado). In other states, where petroleum hydrocarbons are considered separately to halogenated hydrocarbons, an exclusion distance of between 5–10 m has been adopted for the petroleum hydrocarbons compared to 30 m for halogenated hydrocarbons (for example, Utah, New Jersey and Indiana). Limited work has been undertaken in the UK on the appropriateness of adopting such exclusion criteria when assessing sites affected by land contamination in the UK, but such criteria could be developed in the future.

The distinction between the behaviour of petroleum hydrocarbons and other compounds (ie halogenated hydrocarbons) in the unsaturated zone also affects

where soil gas samples should be collected. Collection of soil gas samples within the source zone should represent the worst-case soil gas concentration, but the use of near-slab versus sub-slab sampling points needs consideration. For petroleum hydrocarbons, where the oxygen content beneath a building is likely to be refreshed from ambient air (for example, buildings constructed over a coarse medium), near-slab sampling should provide a good estimate of the concentrations beneath the building (Abreu and Johnson, 2006). Also, for buildings located over low concentration petroleum hydrocarbon sources, near-slab sampling is likely to be representative of sub-slab sampling (Abreu *et al*, 2007). For buildings where the oxygen content is low/air recharge beneath the house is low or the compound(s) of concern do not easily biodegrade aerobically, use of near-slab rather than sub-slab sampling points could underestimate the concentrations in soil gas beneath the building (Davis *et al*, 2004). This has been confirmed through studies undertaken in Flanders (Van Geert *et al*, 2004).

For undeveloped sites, the location where soil gas samples are collected is important. Studies illustrate the effect the building construction can have on flow from soil towards the building (for example, Abreu and Johnson, 2005). Collection of samples purely from shallow locations, where no buildings are present but development is planned, could result in an underestimate of the level of risk via vapour intrusion. This has again been confirmed through studies undertaken by Van Geert *et al* (2004) in Flanders. The measured soil gas concentrations at the source depth were shown to remain relatively consistent, whereas the shallow soil gas concentrations varied widely depending on the presence of a slab, geology and groundwater fluctuations. Note that the effects of introducing a cover system have not been conclusively shown to affect the concentration gradient of VOCs in soil gas (for example, Davis *et al*, 2004 for a house in Australia, and Roggemans *et al*, 2001). Further work is needed in this area of research and for UK buildings.

The presence of a large flux of bulk ground gases such as methane or carbon dioxide (ie in a landfill) could affect the transport of volatile compounds through the unsaturated zone (acting as "carrier gases"), although there is a paucity of peer-reviewed literature studies to support this, and the effect may be limited.

Migration into an indoor air space – J&E model

Many studies relating to the vapour intrusion pathway have focused on the level of attenuation from groundwater/soil gas to the indoor air space, and whether currently used models are appropriate. Much discussion on this subject revolved around the use of the J&E model as a predictive tool, specifically at the Colorado Department of Transportation Materials Testing Laboratory (CDOT-MTL) site in the USA. In 2000, Kurz reviewed indoor air quality testing results from 153 residential homes (Kurz, 2000) for the CDOT-MTL site in comparison to groundwater concentrations. One primary contaminant of concern was 1,1-dichloroethene, as a degradation product of both 1,1,1-trichloroethane and trichloroethene. The predicted concentrations in indoor air (J&E model) were compared to the measured concentrations in indoor air. Three out of five cases had concentrations of 1,1-dichloroethene within an order of magnitude of the predicted concentration. For a proportion of the houses, a "false negative" was identified, where the model used apparently under predicted the indoor air concentration. Kurz concluded that for low or high level concentrations, the J&E model algorithms (as presented by the RBCA methodology) would be:

> *"…an economical method for making mitigation decisions". However, "…the high false-negative rate at moderate concentrations in groundwater indicates*

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testing is needed in homes that are predicted to be below the action level, to minimise the false-negative rate"

This article and the publicity associated with the reporting of the site in the Denver Post effectively led to changes in the way USEPA recommended vapour intrusion was assessed. However, since this article was published, many authors identified potential discrepancies in the method used to assess the data. Hartman (2002) highlighted that there were:

"two very big potential errors that, combined, could introduce errors of two to three orders of magnitude in the soil vapour value used in the model calculation"

Firstly, the soil vapour values were calculated from groundwater concentrations, and secondly, the groundwater concentrations were not measured under the majority of houses but estimated from a groundwater concentration contour plot. Johnson *et al* (2002) undertook a further review of the data, modifying the dataset to account for (a) non-detects and (b) potential contribution from alternative sources. The data were then used to calculate attenuation "alpha" factors (α):

$$\alpha = [C_{indoor}/C_{soil\ gas\ source}] = [C_{indoor}/H*C_{groundwater}]$$

Empirically-derived attenuation factors fell into the 10^{-6} to 10^{-4} range, with an overall average of 3×10^{-5} [(mg/L-indoor air)/(mg/L-soil gas)]. Estimates for the attenuation factor from the J&E vapour intrusion model ranged between 5×10^{-6} to 2×10^{-4} with a best estimate of 9×10^{-5} [(mg/L-indoor air)/(mg/L-soil gas)]. The authors concluded that the model supports the validity of Johnson and Ettinger (1991) for cases where degradation is expected to be insignificant, but not for situations involving easily degradable compounds where it typically over predicts.

Further research was undertaken in the USA to assess whether the continued use of the J&E model was appropriate for the development of screening levels. Hers *et al* (2003) evaluated the 1991 J&E model for prediction of indoor air quality using case study data from 11 petroleum hydrocarbon and "chlorinated solvent" sites. Measured vapour attenuation factors ranged from $\sim 1 \times 10^{-6}$ to 1×10^{-4} [(mg/L-indoor air)/(mg/L-soil gas)] and conservative to reasonable estimates (depending on the VOC under assessment) were achieved using the J&E model. However, they also concluded that some of the "generic" alpha values adopted by some regulatory authorities in the USA may not be conservative for cases, where the contaminant was "nonbiodegradable…shallow to moderate depth [of] contamination, and high advection potential".

USEPA and various states now adopt the use of slab attenuation (α) factors (groundwater and soil gas) at a screening level (Folkes, 2006), which are, in some cases, orders of magnitude more stringent than those originally generated by Hers *et al* (2003) using the J&E model. While in literature there seems to be consensus that the J&E model generates conservative (and in some cases highly conservative) screening levels for petroleum hydrocarbons (groundwater and soil gas), the uncertainty with compounds such as halogenated hydrocarbons has resulted in a move away from the J&E model in the USA. Preference is for the use of (conservative) α factors at a generic level followed by site-specific measurements if the α value is failed. USEPA $\alpha_{groundwater}$ is currently 1×10^{-3}, the $\alpha_{deep\ soil\ gas}$ is 0.01 and the $\alpha_{shallow\ soil\ gas}$ is 0.1 (sub-slab) (Folkes, 2006). USEPA maintains a database of alpha values taken from empirical datasets.

The current situation in the USA is that some states do not accept the use of the J&E model (for example, New York) while other states still accept its use (for example, South Carolina), and have used the model to generate alpha factors. However, recent presentations given in the USA (for example, Army Corps of Engineers, 2007) indicate that USEPA is likely to adopt the methods, if not the whole document, for vapour intrusion measurement and assessment as compiled by the ITRC (2007). The ITRC guidance is more flexible and pragmatic in its recommendation of the use of the J&E model, highlighting circumstances where the model is, and is not, appropriate to use.

Migration into an indoor air space – other vapour intrusion models

The majority of research relating to the subject of vapour intrusion and use of site measurements in place of vapour intrusion models originates from the USA. The use of vapour intrusion sub-models, including J&E, is still accepted as good practice in other European countries, such as The Netherlands, Belgium, Italy, Denmark, Finland, France and the UK (Carlton, 2007) as well as globally (for example, Brazil).

While the review by Evans *et al* (2002) to recommend an appropriate vapour intrusion model for use in the UK (for developing screening levels) identified that the J&E model should be adopted, work has been continuing in the UK and globally since this was published. This work aims to provide a greater selection of vapour intrusion models for use with different building constructions/different site settings (for example, Wilson, *pers comm*, Turczynowicz and Robinson, 2007 and Wijnen and Lijen, 2006). Much of the research has stemmed from the fact that different building constructions are used in each country, as such a single vapour intrusion model is unlikely to be suitable for every country or situation. In The Netherlands, the building construction typically includes a "crawl space", which is accounted for in the vapour intrusion models used (CSOIL and VOLASOIL). The work undertaken by Wijnen and Lijen (2006) to validate VOLASOIL against field data indicated that the model provided a good correlation with site data for estimating indoor air concentrations of tetrachloroethene and trichloroethene (groundwater source), although certain adjustments to the model were recommended to reduce the potential for significantly overestimating the concentration in indoor air. Similar construction is seen for some UK buildings. In Australia, both foundation slab-on-grade and crawl space construction is found, and are being considered in the development of a vapour intrusion model. Chapter 2 of this guide provides an overview of typical UK building constructions, and different modelling tools that can be used to simulate vapour intrusion into each of these constructions are discussed in Appendix A11.

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A3 Case study 1: Redevelopment of a light industrial site for continued light industrial use

The aims of this case study are summarised Table A3.1.

Table A3.1 ***Summary of Case study***

Case study summary	Information
Site location	Southern England
Case study description	Redevelopment of a light industrial site for continued light industrial use To illustrate the phased approach to assessing the vapour emission/intrusion pathways, including: ❑ a preliminary risk assessment ❑ a generic quantitative risk assessment ❑ a detailed quantitative risk assessment ❑ consideration of remediation options.

A3.1 INTRODUCTION

The site comprised a derelict piece of land of about 0.2 ha historically used for light industrial activities. As part of a planning application to redevelop the site with new light industrial units, environmental works were undertaken to assess whether the former use of the site, or surrounding land, had resulted in the presence of contaminants in the subsurface.

A3.2 PRELIMINARY RISK ASSESSMENT (CHAPTER 4)

The first stage in the assessment was the preliminary risk assessment (PRA), submitted as part of the planning application. This included a desk study, site walkover and development of initial CSM (see Chapter 4).

Based on a review of several data sources, including the site redevelopment plan, the desk study was undertaken, which highlighted the following about the site:

Table A3.2 ***Summary of desk study and site walkover findings***

Factor	Findings
SIte elevation	3 m above ordnance datum
Historical use	Developed in the 1950s and used as an engineering works. There were no records of leaks or spills at the site
Use of surrounding land	General light industrial works since the 1900s. No residential properties in the area around the site
Geology	Quaternary brickearth overlying Cretaceous upper chalk (major aquifer)
Hydrogeology	Groundwater anticipated at 3 m below grade, with a southerly flow direction

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The site walkover helped to refine potential areas of concern warranting further investigation, including:

- former locations of above-ground storage tanks (concrete bases still in place)
- flooded underground concrete sumps in the south west of the site.

The above-ground storage tanks had historically contained petroleum hydrocarbon fuels, while the concrete sumps were the location where waste chlorinated aliphatic hydrocarbons had previously been stored. VOCs of particular concern at the site included light end aliphatic and aromatic hydrocarbon fractions alongside halogenated hydrocarbons (including trichloroethene and its potential degradation products). Several vapour intrusion/vapour emission pollutant linkages were considered potentially active based on the results of the desk study and site walkover. Following the PRA, environmental planning conditions were set for the site, and ground investigations and a generic quantitative risk assessment were recommended as a next step.

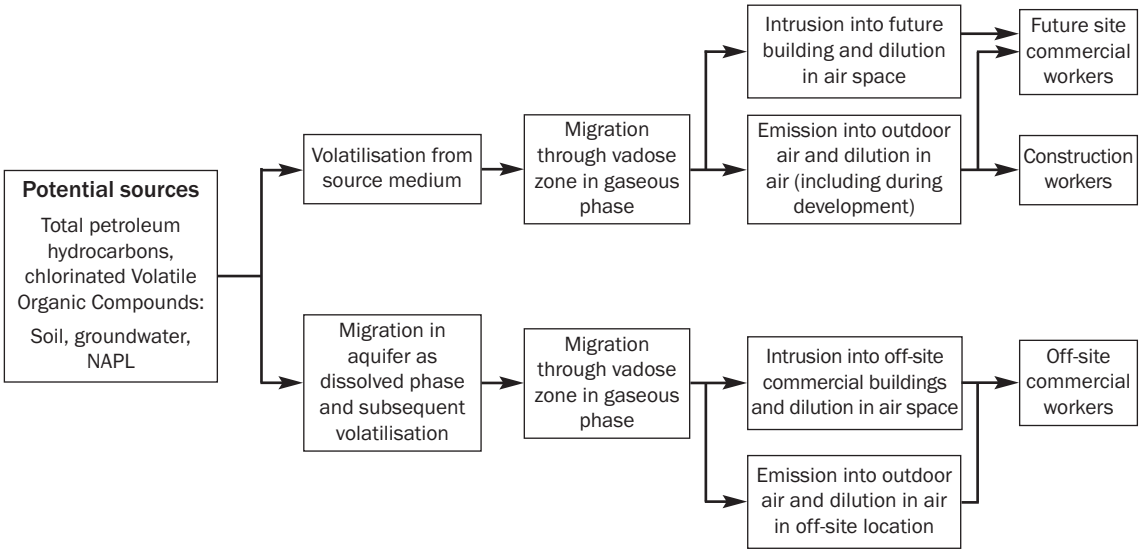

Figure A3.1 ***Initial conceptual site model – vapour intrusion/emission pollutant linkages***

A3.3 GENERIC QUANTITATIVE RISK ASSESSMENT (CHAPTER 7)

The scope for the ground investigations at the site were agreed with the planning authority before works began, and included:

- excavation of several trial pits and sampling of soils from different depths
- progression of several boreholes and installation of nested groundwater monitoring wells
- installation of monitoring wells to allow "bulk" ground gases to be sampled
- three groundwater monitoring visits, six "bulk" ground gas monitoring visits.

The ground investigation had a second aim, which was to collect data regarding geotechnical conditions beneath the site. The scope of works, including selection of investigation techniques, was developed considering the need for different types of data output.

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The results of the ground investigation are summarised as follows:

Table A3.3 ***Summary of site investigation findings***

Factor	Findings
Geology	❑ made ground (about 1 m in thickness) ❑ brickearth deposits (about 1 m to 2 m thickness) ❑ upper chalk (shallowest depth 2 m below grade).
Hydrogeology	❑ the piezometric surface of the chalk was about 2 m below grade ❑ a single groundwater body was identified, flowing towards the south-east with a hydraulic gradient of 0.001 to 0.002 ❑ site data indicated a hydraulic conductivity of 1 m/day in the chalk, which matched data from other sites in the area.
Contaminant distribution	❑ concentrations of total petroleum hydrocarbons (aliphatic and aromatic fractions in the range C5->C35 range) above MDL were measured in soil and groundwater, with a small thickness of LNAPL identified in one monitoring well in the north of the site, close to where an SET containing petroleum hydrocarbons used to sit ❑ concentrations of chlorinated hydrocarbons (trichloroethene, cis-1,2 dichloroethene and vinyl chloride) above MDL were measured in groundwater in the south-west of the site. No DNAPL was encountered. The impacts were encountered close to small underground concrete sumps, historically believed to have been used for waste solvent storage.

A3.3.1 Refinement of CSM

The results of the investigation demonstrated the presence of VOCs beneath an area of the site where a building was planned to be constructed. The pollutant linkages considered potentially active because of the v-PRA were still considered so, based on the site data. No further qualitative/semi-quantitative screening (see Section 7.3) was undertaken on the basis of the results of the site investigation.

A3.3.2 Use of SGVs/GAC

The use of GAC as a screening tool was considered (see Section 7.4). Generic assessment criteria had been developed for commercial end use for both soils and groundwater, and the assumptions used to derive the GAC were considered appropriate, or reasonably conservative, for the site. Also, the made ground was relatively homogeneous, the contamination was likely to underlie a reasonable proportion of one of the future industrial units, and no significant preferential pathways were identified. GAC for commercial end-use were used to assess whether the measured concentrations of the contaminants could present a risk to human health via inhalation exposure. The results highlighted that the vapour intrusion pathway could present a significant risk to future building users from the chlorinated hydrocarbons in groundwater. Also, the potential risk to water resource receptors underwent further assessment.

A3.4 DETAILED QUANTITATIVE RISK ASSESSMENT (CHAPTER 8)

Further investigation was undertaken to delineate the area contaminated by the chlorinated VOCs, further boreholes were drilled and groundwater monitoring wells were installed. For this site, the collection of further groundwater data and

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assessment of the vapour intrusion using the model RISC v4 (incorporating the J&E model) were selected in place of measurement of soil gas for VOCs because of the need to consider multiple pollutant linkages.

The model was set up using site data where possible, and site-specific assessment criteria (SSAC) were developed based on the proposed site development plan. It was assumed that remediation could be required following the results of the v-DQRA, so the vapour emission pathway was also considered within the v-DQRA to provide site-specific remediation criteria if needed.

Comparing the measured concentrations of the contaminants to the SSAC indicated that one contaminant of concern, vinyl chloride, was present in groundwater at concentrations that were slightly higher than the SSAC (64μg/l), ranging from around 50 to 100μg/l. The pollutant linkage concerned was the on-site vapour intrusion pathway, and the CSM was refined for the vapour intrusion/emission pathways:

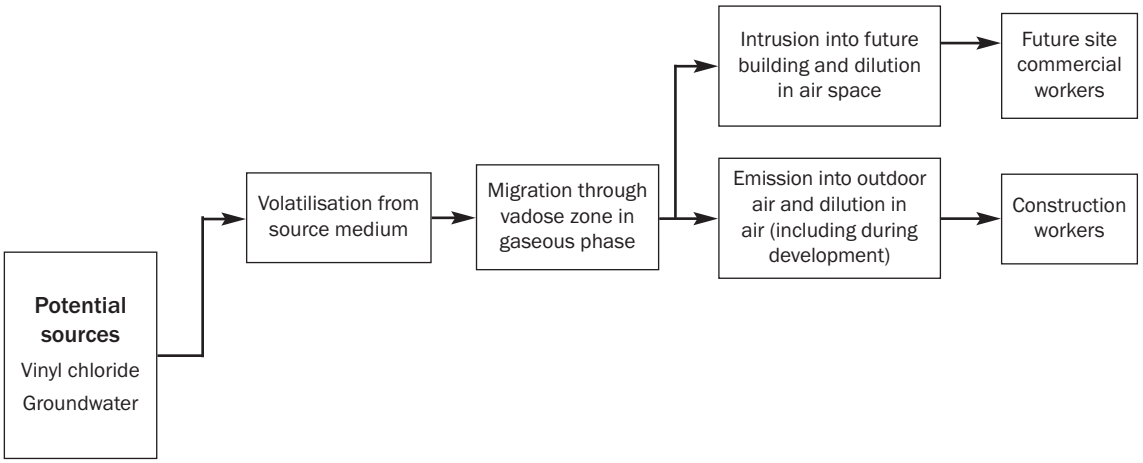

Figure A3.2 ***Refined conceptual site model – vapour intrusion/emission pollutant linkages***

A3.5 REMEDIATION OPTIONS (CHAPTER 9)

The viable options for the site were:

- to treat/remove the source
- to break the pollutant linkage.

The primary contaminant of concern, vinyl chloride, was not used on the site historically, and was believed to be present because of the reductive dechlorination of trichloroethene. The microbial degradation of trichloroethene had resulted in the formation of cis-1,2 dichloroethene, which then degraded under anaerobic conditions to form vinyl chloride. A review of the measured concentrations of trichloroethen, cis-1,2 dichloroethene and vinyl chloride was undertaken to assess whether continued degradation of trichloroethene could lead to an increase in the concentration of vinyl chloride in groundwater.

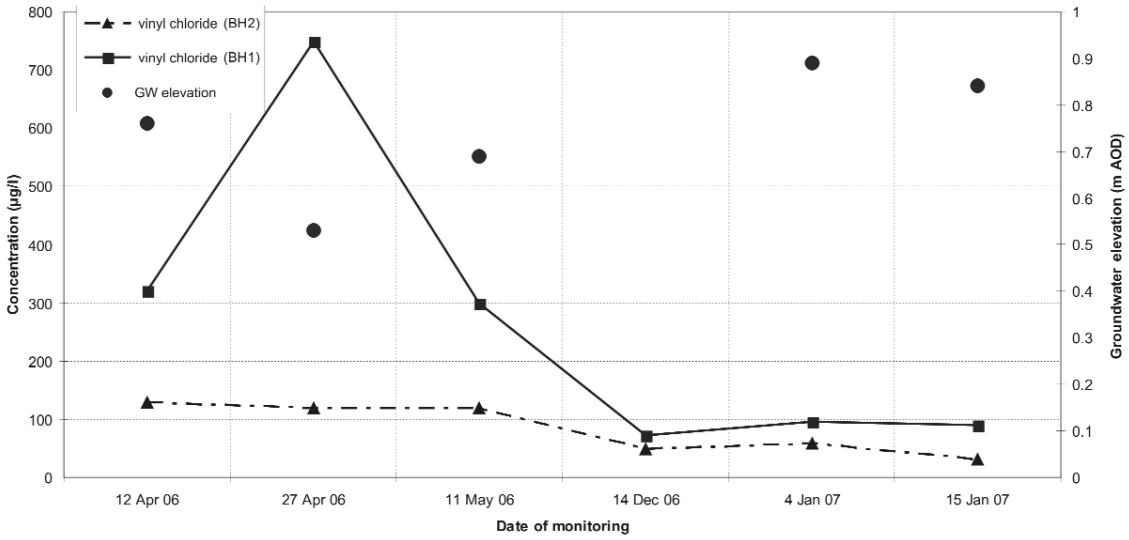

Figure A3.3 ***Measured concentrations of vinyl chloride in groundwater from the two monitoring wells with the highest recorded concentrations (µg/l)***

The results indicated a general downward trend in measured concentrations of vinyl chloride. A similar trend was observed for the parent products trichloroethene and cis-1,2 dichloroethene.

Based on discussions with the planning authority and the relatively low level of the magnitude of the contamination in comparison to the SSAC, the selected remediation option was to break the pollutant linkage. A passive solution was employed, taking the form of an engineered gas membrane, designed to resist decay by VOCs, and fitted during the construction process. The underground concrete sumps, considered to form the source of the contamination by chlorinated VOCs, were removed from site.



Figure A3.4 ***One of the underground concrete sumps removed during construction works***

Environmental planning conditions were discharged for the site following three groundwater monitoring visits undertaken once construction was complete. The monitoring demonstrated that the construction works had not resulted in the further mobilisation of contaminants into the groundwater, and that the risks to the identified receptors (including controlled waters) had been adequately assessed and managed.

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A4 Conceptual site model checklist

This checklist has been adapted from ITRC (2007). It is noted that the information presented in the checklist should not be considered comprehensive. However, the checklist should be a useful tool to aid collation of suitable desk study/site reconnaissance information with which to assess the vapour migration/intrusion pathway through development of a conceptual site model.

Where an element of the desk study/site reconnaissance information is not known, or cannot be confirmed, further data sources or investigation may be required before a robust conceptual site model can be developed. However, for some of the items on the checklist, it may not be appropriate or possible to collect site specific data, and conservative or reasonable assumptions may need to be made (for example, building construction for an off-site property).

Geology/hydrogeology		**Considered**
Underlying soils/geology:	For example, from geology maps, borehole logs ■ different soil types/geologic units ■ heterogeneity/homogeneity of geology ■ depth and lateral extent of units that may affect migration of soil gases.	☐
Hydrogeology:	For example, from hydrogeology maps, pre-existing site data ■ depth to groundwater ■ number of groundwater bodies and interaction (for example, perched or leaky aquifer) ■ groundwater flow direction ■ groundwater flow regime (for example, tidally influenced, seasonal fluctuations).	☐
Land-use		
Change in end use:	For example, from redevelopment plans ■ end use change planned ■ redevelopment plans available.	☐
Site and surrounding land-use	For example, interviews with site staff, condition of site ■ current and future site users ■ occupational exposure ■ occupiers of surrounding land.	☐
Site cover	For example, from site reconnaissance or development plans ■ buildings on site (current and/or planned) ■ buildings on surrouding land ■ nature and condition of cover for open areas (current and/or planned).	☐
Utilities (public, domestic or industrial)	For example, utility service traces ■ presence of utilities ■ on-site route for utilities, including likely entry into buildings ■ route off-site for utilities ■ depth of utilities and construction.	☐
Buildings		
Building type	For example, from site reconnaissance ■ dimensions of existing/future buildings ■ dimensions of off-site buildings ■ use of site buildings (users, frequency) ■ use of off-site buildings (users, frequency).	☐
Building construction (on-/off-site)	For example, from site reconnaissance, local authority planning office ■ above ground construction ■ nature of ventilation (for example, air conditioning) ■ foundation construction (type, depth, basement, above ground) ■ preferential ingress pathways (for example, utilities leading into basement).	☐
Sources		
Presence of VOCs	For example, current and historical site use ■ historical site use ■ current site use ■ surrounding land-use (current and historical) ■ historical/current reports of odours (may need immediate risk-management action).	☐
Types of VOCs/ source media	For example, DOE profiles ■ types of VOCs (or other volatile compounds) that could be present ■ presence and type of non aqueous phase liquid ■ VOCs in soils ■ VOCs in groundwater ■ VOCs in other media.	☐
Location of sources	For example, from site use ■ location of current/historical sources ■ potential for off-site source ■ depth to source(s) ■ lateral and vertical extent of source(s) ■ characteristics of sources (for example, contaminant characteristics) ■ location of likely sources compared to site/off-site buildings or open areas.	☐

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A5 Example building survey

EXAMPLE BUILDING SURVEY

This example survey form has been developed to aid the assessor in considering the vapour intrusion pathway. The survey would be completed for each building under assessment, if needed, and parts of the survey can be undertaken without access to the building interior. Sketches are an additional useful tool for recording site data.

Information gathered during the building survey may help to highlight areas of concern within the building, potential vapour entry points (eg utility entry points into a buildling), and which vapour intrusion model may best simulate the characteristics of the building under assessment.

This survey should not be considered comprehensive. Those questions marked with an * indicate where desk study information or a site walkover (without entry to the building) may allow an answer to be given.

Prepared By: _____ **Date / Time Prepared:** _____

Site Name: _____

Site Address: _____

Building Reference _____ On-Site Y/N Off-Site Y/N

Part I Building Characteristics

*Building Type:

☐ Residential house ☐ Residential flats ☐ Industrial premises ☐ Not known
☐ Bungalow ☐ Commercial premises ☐ Mixed use ☐ Attached by a party wall
☐ Other: _____

If the property is commercial, industrial or mixed use:

*Business Type: _____
*Does it include residences (i.e. multi - use)? ☐ Yes ☐ No ☐ Not known
*If yes, are these located on the ground floor or below? ☐ Yes ☐ No ☐ Not known

*Property Location/Neighborhood:

☐ Primarily residential ☐ Primarily commercial ☐ Primarily industrial
☐ Other: _____

*Approximate building age (if known): _____

*Number of floors above ground, including ground floor and uses (if known): _____

*Number of floors below ground and uses (if known): _____

Building perimeter length (m) ☐ ☐ Measured ☐ Approximated

Building height (m) ☐ ☐ Measured ☐ Approximated

Sketch of building layout presented on page 3 ☐ Yes ☐ No

Part II Building Construction Details

General description of above ground building construction ☐ wood frame ☐ concrete ☐ stone ☐ brick ☐ Steel frame

Basement type: ☐ full ☐ crawlspace ☐ no basement ☐ other/unknown _____

Basement/crawl space floor (if present): ☐ concrete ☐ dirt ☐ stone ☐ other/unknown _____

Lowest floor space in property: ☐ uncovered ☐ covered with (e.g. carpet): _____ ☐ Not known

If lowest floor is concrete: ☐ unsealed ☐ sealed with: _____ ☐ Not known

Foundation/basement walls: ☐ poured ☐ block ☐ stone ☐ other/unknown _____

Foundation/basement walls: ☐ unsealed ☐ sealed with: _____ ☐ Not known

The basement, if present, is: ☐ wet ☐ damp ☐ dry ☐ mouldy ☐ Not known

The basement, if present, is: ☐ finished ☐ unfinished ☐ partially finished ☐ Not known

Drainage sump present? ☐ Yes ☐ No ☐ Not known

Water in sump? ☐ Yes ☐ No ☐ not applicable/unknown

General condition of the basement (e.g., cracks, utility ports, drains etc.) _____

*General desciption of building (e.g.construction materials, general houskeeping): _____

Part III Potential Preferential Pathways

Service entry point locations ☐ Assumed ☐ Observed ☐ Not known
Locations indicated on attached plan? ☐ Yes ☐ No ☐ None observed
Any vents on or near to building? ☐ Yes ☐ No
If yes, is the use known? (e.g. gas mitigation measures) _____
Does the building have a lift(s)? ☐ Yes ☐ No ☐ Not known
If yes, how many (if known)?:
Is location(s) indicated on attached plan? ☐ Yes ☐ No

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Part IV Heating, Venting and Air Conditioning

Types of mechanical ventilation systems present and/or currently operating in the building:

☐ Air Conditioning ☐ Mechanical Fans ☐ Heat Exchanger(s) ☐ Other (Please, specify) ☐ None ☐ Not known

Source of return air:

☐ inside air ☐ not applicable ☐ outside air ☐ Other (Please, specify) ☐ combination ☐ Not known

Part V Mitigation Measures

Is there a gas mitigation system for the building / structure?

☐ Yes ☐ No ☐ Not known

Why was it installed? E.g. radon, brownfield development

Date of Installation (If Yes): _____

Is the system active or passive

☐ Active ☐ Passive ☐ Not known

Details if known _____

Are the basement walls or basement/ground floor sealed with waterproof paint or epoxy coatings?

☐ Yes ☐ No ☐ Not known

Sub-slab moisture barrier in place?

☐ Yes ☐ No ☐ Not known

Type of barrier (If Yes): _____

Part VI Additional Information

Were any indoor or outdoor odours noted during the building survey?

☐ Yes ☐ No ☐ No access

If yes, description of odours: _____

Were there any reports of indoor or outdoor odours noted in or around the building in recent years?

☐ Yes ☐ No ☐ Not known

If yes, any details?: _____

Type of the ground cover outside of the building:

☐ grass ☐ Other (Please specify) ☐ concrete ☐ asphalt _____

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A6 Case study 2: Electric socket manufacturing plant near to gas works

The aims of this case study are summarised Table A6.1.

Table A6.1 ***Summary of Case study 2***

Case study summary	Information
Site location	Southern England
Case study description	Electric socket manufacturing plant near to gas works
Aim of case study	To illustrate how multiple investigation techniques and lines of evidence can be used to assess the vapour intrusion/emission pathways where the geology and contaminant distribution is relatively complex.

A6.1 INTRODUCTION

The site comprised electric plug and socket manufacturing plant, present on the site since the 1960s. A former gas works was identified in the preliminary risk assessment as being near to the site, which had reportedly undergone remediation in the 1990s before use as a public open space.

The work was initially for acquisition for redevelopment and later development.

A6.2 PRELIMINARY RISK ASSESSMENT (CHAPTER 4)

The first stage in the assessment was the PRA. This included a desk study, site walkover and development of initial CSM.

A summary of the desk study information highlighted the following about the site (Table A6.2):

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Table A6.2 ***Summary of desk study findings***

Factor	Findings
Historical use	■ the site was previously occupied by agricultural land until the early 1900s, when a nursery was developed ■ by 1938, the southern most part of the site was occupied by a "Bakelite works" and the central part of the site was occupied by an "electroplating works" ■ the site expanded and by 1961 the current site layout was present. The site manufactured electrical sockets, plugs and switches. Activities include metal stamping, forming, coating, degreasing and assembly.
Use of surrounding land	■ a gas works was located near to the south east corner of the site and had occupied this land for some 100 years ■ some remediation works to part of the gas works land was undertaken in the early 1990s before the land was handed for use as public open space.
Geology	■ drift deposits (Kempton Park Gravels), alluvium 250 m east of the site overlying the gravels (minor aquifers) ■ London Clay (non aquifer) ■ Reading Beds (mottled clays with sand and pebble beds) (minor aquifer) ■ Thanet Sands (minor aquifer) ■ chalk (major aquifer).
Hydrogeology	■ likely to be complex, because of the presence of culverted watercourses in the area of the site. ■ groundwater vulnerability unclear from the desk study, but either a minor or non aquifer depending on the presence of drift deposits overlying the London Clay.

A local borehole log (100 m south east of the site) provided the following information about the geological sequence:

- made ground and fluvial sands and gravels (9 m thickness)
- London Clay (2.3 m thickness)
- Reading Beds (10.1 m thickness)
- Thanet Sands (12.2 m thickness)
- chalk, at about 32.5 m below grade.

The site walkover helped to refine potential areas of concern warranting further investigation, including several storage tanks, process areas and the former use of the adjacent site as a gas works.

The site layout and potential areas of concern are shown on Figure A6.1:

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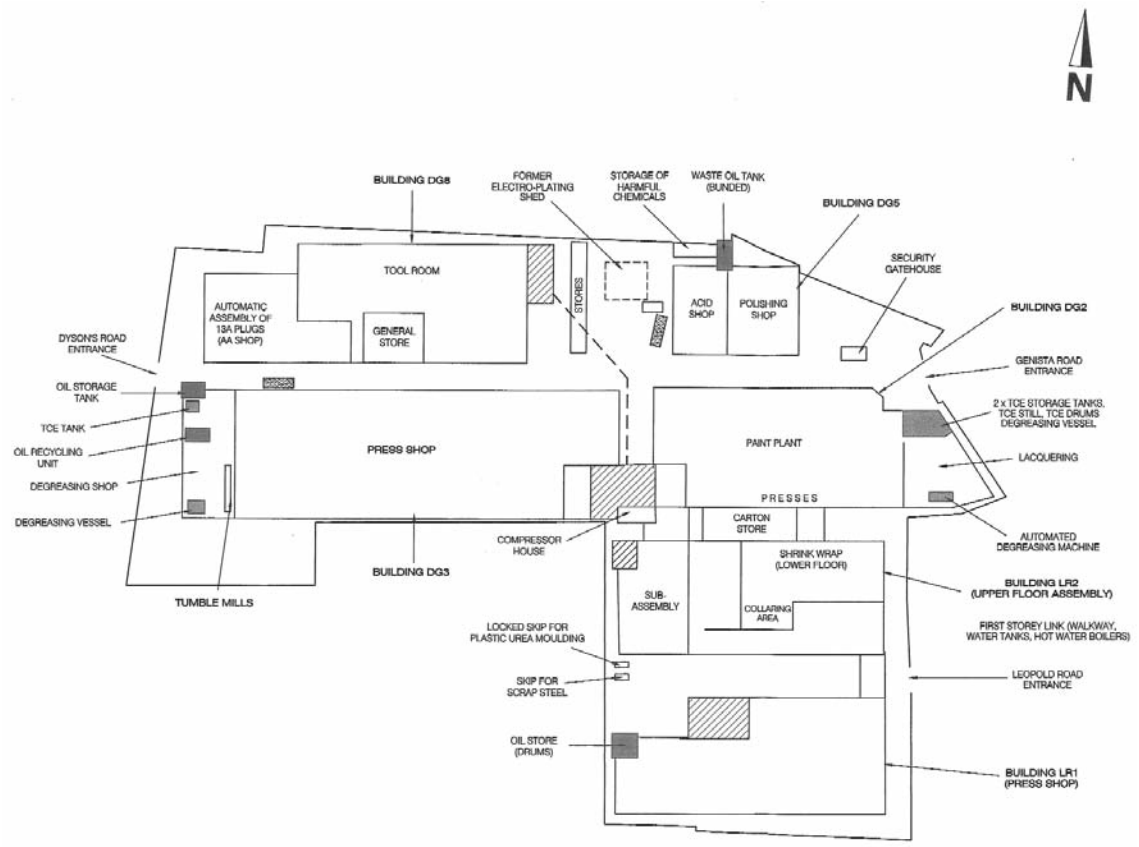

Figure A6.1 ***Site layout plan and potential areas of concern***

Several vapour intrusion/vapour emission pollutant linkages were considered potentially active based on the results of the desk study and site walkover. There was the potential for a range of different contaminants to be present beneath the site, associated with on- and off-site sources, including contaminants associated with both DNAPLs and LNAPLs. Following the PRA, a ground investigation was recommended as a next step, using a range of exploratory tools given the potential range in contaminants.

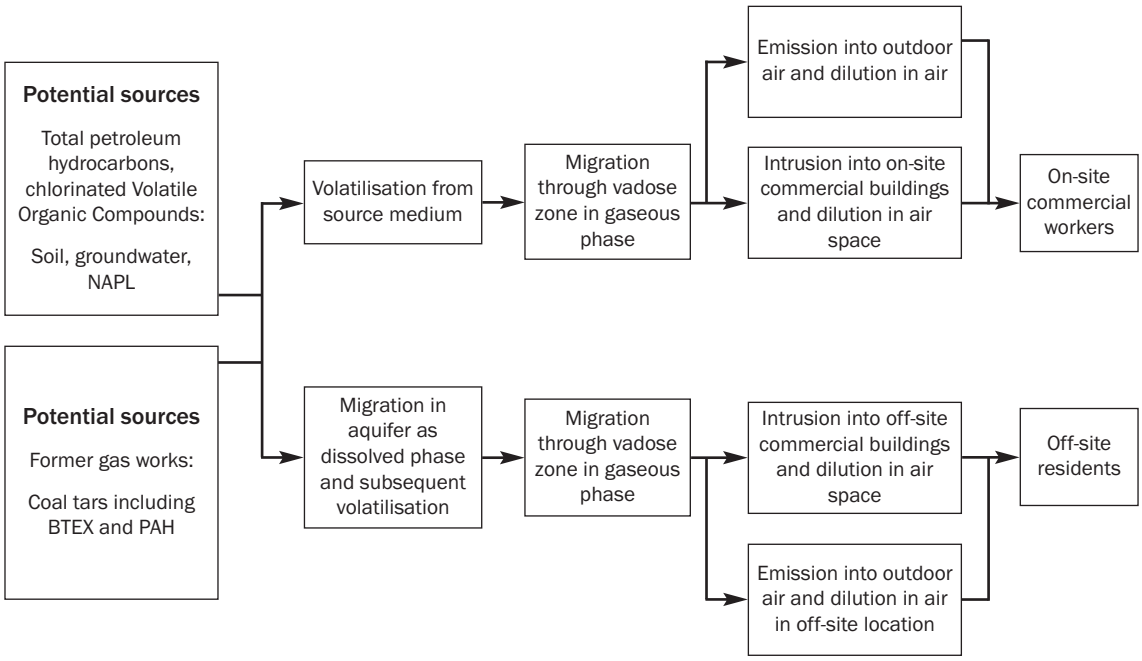

Figure A6.2 ***Initial conceptual site model – vapour intrusion/emission pollutant linkages***

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A6.3 GROUND INVESTIGATIONS (CHAPTERS 5 AND 6)

A range of exploratory techniques were used in an integrated ground investigation, to help assess a range of potential pollutant linkages, because of the potential complexity of the underlying geology and contaminant distribution:

- *in situ* probing, collecting real time data on the subsurface conditions, to a maximum depth of 12 m below ground level using:
  - a membrane interface probe (MIP)
  - a laser induced fluorescence (LIF) probe
- progression of 13 boreholes to a maximum depth of 15 m below ground level, and installation of monitoring wells primarily for groundwater monitoring although gas taps were also installed. The wells were installed using the knowledge gained from LIF and MIP probing on the likely changes in geology as well as the contamination profile
- progression of 19 window sample boreholes to a maximum depth of 3 m below ground level and installation of soil gas monitoring wells, both on- and off-site. The gas and groundwater installation were installed over several phases
- further trial pitting and window sampling was also carried out.

The MIP contains an electrical conductivity sensor combined with measurement of the rate of penetration that can be used to identify changes in strata. Chemical sensors are used to analyse soil gases, which pass through the teflon membrane on the probe. These sensors comprise:

- a PID (used to identify compounds that ionise by ultraviolet light), which is particularly sensitive to aromatics and chlorinated hydrocarbons
- an FID (used to identify compounds that ionise in a hydrogen flame), which is particularly sensitive to combustible hydrocarbons although it will respond to a range of compounds including chlorinated hydrocarbons
- a dry electrolytic conductivity detector (DELCD), which is a halogen specific detector and will respond to chlorinated and brominated hydrocarbons.

In particular the DELCD allowed potential contamination by chlorinated hydrocarbons to be distinguished from contamination by coal tars, which were also detected using the LIF. The conductivity measurements also helped distinguish clay and gravel.

The LIF system uses a friction cone penetrometer to identify the strata encountered. A laser induced florescence is used as the chemical sensor. This measures and characterises aromatic hydrocarbons present in the soil, and was used to investigate the presence of coal tars.

The results of the *in situ* probing were used to identify appropriate locations and depths for boreholes/monitoring wells. Soil gas samples were collected both on- and off-site using a gas syringe and a sorbent tube (Tenax™), followed by laboratory analysis.

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A6.4 FINDINGS OF THE INVESTIGATION (CHAPTERS 5 AND 6)

The geological cross-section in Figure A6.3 combines the data from a range of different exploratory techniques to provide a good understanding of the subsurface geology and contaminant distribution.

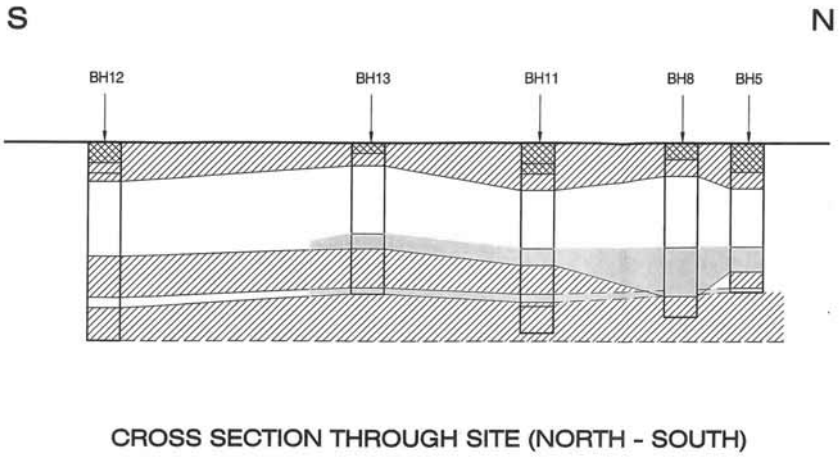

Figure A6.3 ***Interpretation of site cross-section (north – south)***

The investigations identified the presence of site-derived chlorinated hydrocarbons (solvents) as DNAPL present within the Kempton Park Gravels as well as a localised area of hydrocarbon fuel from a nearby oil tank (where free product was later detected). Where the London Clay was absent, the DNAPL had infiltrated deeper, as shown on Figure A6.3 as deeper shading in boreholes BH13, BH11, BH8 and BH5.

Impact by coal tars, originating from the Gas Works was also identified, present in the deeper strata. Soil gas measurements identified the presence of BTEX, and trichloroethene in soil gas.

A6.5 GENERIC QUANTITATIVE RISK ASSESSMENT (CHAPTER 7)

A generic quantitative assessment of the potential risk to human health from the measured concentrations of VOCs in soil gas was undertaken. The use of SGVs (or GAC developed using the same assumptions as for the SGVs) was not considered appropriate because:

- the contaminant distribution was complex, with a mixture of contaminants present
- the underlying geology was relatively heterogeneous, with interbedding of different lithologies (such as sands and clays)
- soil gas data had been collected for which no GAC had been developed.

The measured concentrations of VOCs in soil gas were compared directly to acceptable indoor and outdoor air concentrations, assuming no attenuation was occurring during transport to the surface. This conservative, screening assessment demonstrated that there was not an unacceptable level of risk from

the vapour intrusion or vapour emission pathways with the exception of one location near the degreasing area, where chlorinated solvent vapour were at the ambient air screening values.

Remediation was still required to address other pathways of concern. The remediation strategy was agreed with the regulators. This included delineation and removal of the shallow areas of chlorinated solvent and the localised oil contamination. A pump and treat system was installed for treatment of the free product locally present on the site. A vapour membrane with ventilated sub-floor void and sealed service entries was installed in buildings as a precautionary measure. The foundations were also designed to avoid creating preferential pathways either down through the London Clay to the aquifer below or up into the buildings.

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A7 Descriptions of common soil gas exploratory techniques

A7.1 SHALLOW/DRIVEN PROBE (HOLLOW ROD)

A hollow metal spike or rod is inserted into the ground and a soil gas sample is taken from the top of the rod. The typical construction of a rod is steel, with a diameter of 1 to 5 cm (ITRC, 2007). Replaceable tubing runs down the centre of the rod, and the sampling equipment is attached to the above-ground section of the tubing. A surface seal is applied to limit the dilution of the sample with atmospheric air.

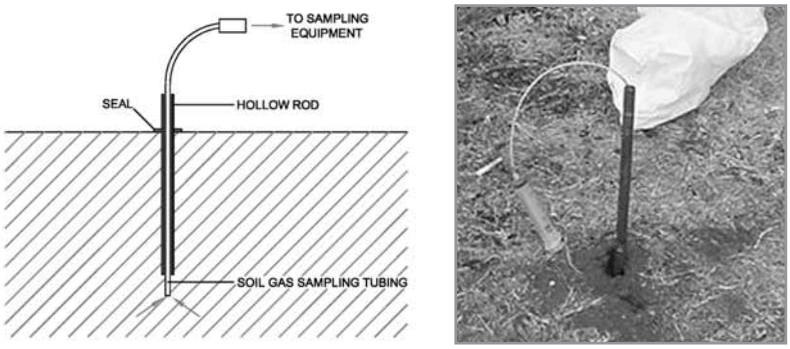

Figure A7.1 ***Use of shallow/driven probe (hollow rod)***

A7.2 DRIVEN BURIED SOIL GAS MONITORING TUBE/PIPE

A narrow diameter tube or pipe is driven into the ground, often within a borehole, with a pointed tip (see Figure A7.2). The pipe is usually less than 2 cm in diameter, and is made from a relatively inert material such as stainless steel. Other constructions include HDPE and polyetheretherketone (ITRC, 2007). The pointed tip, commonly referred to as a soil gas implant probe or anchor, can be used to collect the soil gas sample, or just to aid the installation process. Where the soil gas implant is not used to collect the sample, a perforated section (usually in the form of a mesh), analogous to a perforated section within a groundwater monitoring well is present just above the implant. A granular material (such as sand) is applied as a backfill around the implant, with the remainder of the monitoring borehole sealed to surface with a compound such as bentonite.

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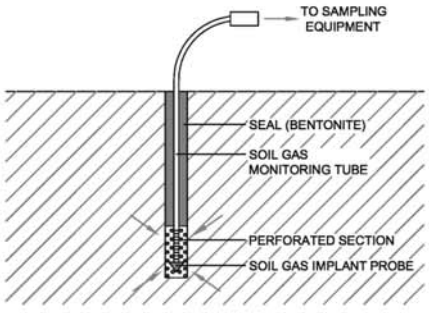


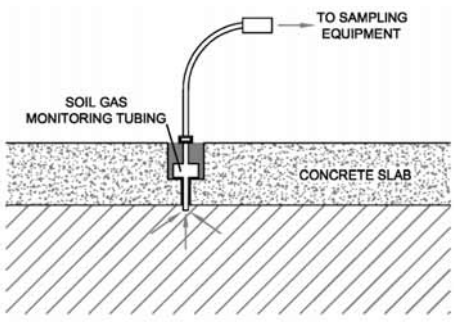


Figure A7.2

Use of buried soil gas monitoring pipe

A7.3 BURIED SOIL GAS MONITORING TUBE/PIPE (SUB-SLAB OR NEAR-SLAB)

A drill is used to create a narrow void through the slab. The sampling tube is inserted into the void, and sealed in place, either resting flush with the base of the slab or just below it (see Figure A7.3). The tube is typically made from stainless steel with stainless steel compression fittings (ITRC, 2007) usually with a diameter of less than 1 cm.



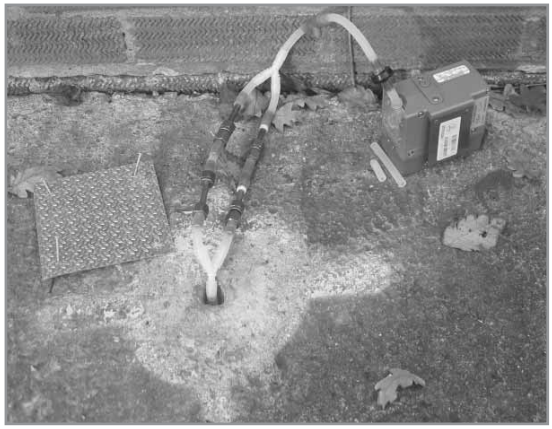


Figure A7.3

Sub-slab/near-slab sampling

A7.4 SURFACE EMISSION – FLUX CHAMBER

For measurement of VOCs, the flux chamber is typically constructed from an inert, non-absorbing material. Examples include stainless steel (Hartman, 2004). A typical flux chamber set up (dynamic chamber) is shown on Figure A7.4.

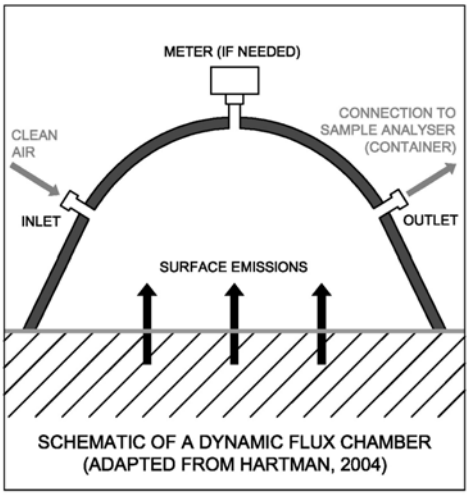




Figure A7.4 ***Surface emission sampling***

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A8 Case study 3: Vapour intrusion assessment

The aims of this case study are summarised Table A8.1.

Table A8.1 ***Summary of Case study 3***

Case study summary	Information
Site location	Northwest England
Case study description	Vapour intrusion assessment of 145 properties surrounding a closed and covered waste disposal area, where a comprehensive, multi-year investigation demonstrated that vapour intrusion was strongly dependent on the properties of geologic and backfill materials beneath the buildings.
Aim of case study	■ to highlight the importance of a robust CSM at the appropriate scale when assessing the vapour intrusion pathway, especially where the subsurface geology includes low-permeability layers ■ to illustrate different exploratory/analytical techniques used to assess the vapour intrusion pathway when buildings are present at a site, including measurement of indoor air quality in multiple properties.

A8.1 INTRODUCTION AND INITIAL CSM

The site comprises two former sandstone quarries that were later used for disposal of wastes from a chemical manufacturing plant from around 1930 until the 1950s/1970s (Crump *et al*, 2002, McAlary *et al*, 2002). The bedrock is the Permo-Triassic Sandstone with interbeds of mudstone, dipping about three to five degrees south east.

The south end of one quarry was primarily filled with lime slurry, comprising low percentage concentrations of VOCs, including dissolved chlorobutadienes, dissolved chlorinated ethenes and fine particles in water. Initially the supernatant water exfiltrated from the lagoon into the surrounding bedrock, and the resultant settled solids were dredged and relocated to the northern part of the quarry. In contrast, a mixture of wastes including drummed wastes was disposed of in the second quarry. Around 6000 tonnes of VOCs were reportedly disposed of in total (McAlary *et al*, 2002). Although both quarries have been covered for more than a decade, the potential for vapour intrusion into properties built near to the former quarries has led to an extensive programme of ground investigations, indoor air monitoring and remediation works since the late 1990s.



Figure A8.1 *Historical photograph of one quarry (courtesy Derrick Crump, BRE)*

A8.2 INITIAL GROUND INVESTIGATIONS

Ground investigations were initially undertaken to characterise the geological and hydrogeological setting near to the quarries. Investigation techniques included (McAlary *et al*, 2002):

- drilling of four deep (>70 m) continuously-cored boreholes (two vertical and two angled under the base of the quarries)
- drilling of 48 soil gas monitoring boreholes (seven to depths of between 30–40 m below ground level)
- outcrop mapping and fracture mapping in tunnels
- ground-level reconnaissance
- geophysical testing including cross-hole resistivity.

A8.3 FINDINGS OF THE INITIAL GROUND INVESTIGATIONS

The data from the vapour intrusion assessment indicated that the bedrock imposes a significant resistance to vertical vapour transport compared to the quarry spoil materials. This is attributable to the presence of finer-grained layers (upward fining cycles in the sandstone and mudstone layers) in the bedrock, which impede the infiltration of percolating rainwater. Perched water was sometimes found above the mudstone and fine grained layers. By contrast, the poorly consolidated heterogeneous and freely-draining quarry spoil materials (sand and rock fragments) provide a preferential pathway for subsurface vapour migration. The simple conceptualisation of the first quarry is shown in Figure A8.2.

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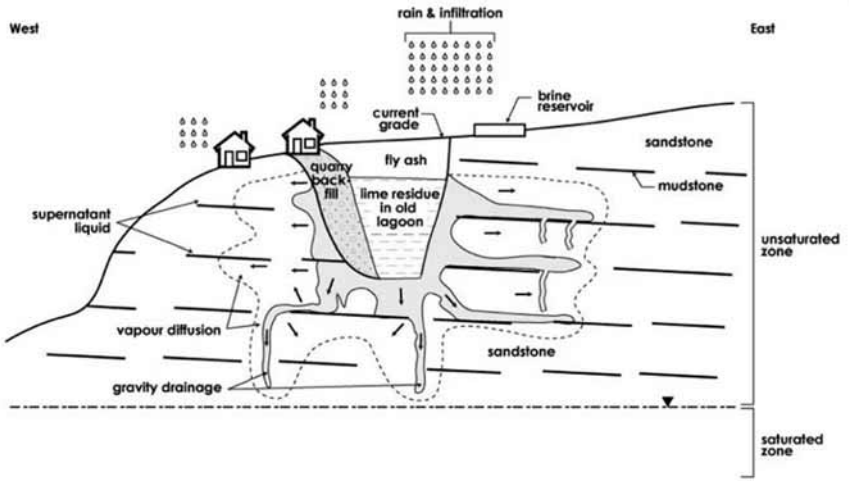

Figure A8.2 ***Schematic conceptualisation of the first quarry (reproduced from McAlary et al, 2002)***

In situ and laboratory testing for permeability and porosity identified the following:

Table A8.2 ***Results of in situ and laboratory testing of geological conditions***

Data	Findings
Sandstone soil gas permeability tests (>1000 sandston be core samples Pneumatic tests to assess large-scale soil gas permeability in subsurface	Ranged from 10^{-11} to 10^{-16} m² ~ 10^{-11} m² (vertical, sandstone) >2 × 10^{-10} m² (quarry fill)
Total porosity (>1000 sandstone core samples)	15 to 30 %

A8.4 POTENTIAL POLLUTANT LINKAGES

The presence of >100 properties immediately adjacent to the quarries, and in some cases built on rubble filled areas of the quarry, combined with VOCs in the subsurface, most notably hexachlorobutadiene (HCBD), meant there was the potential for the vapour intrusion pathway to cause unacceptable inhalation exposures for properties near the former quarries.

A detailed programme of soil gas monitoring and indoor air sampling was undertaken, due to the complexities of the CSM, namely:

- physical properties of the geologic materials under field conditions such as porosity, effective permeability, field moisture content
- the presence of heterogeneous, very coarse-grained and poorly consolidated, quarry spoil backfill under some properties
- building characteristics such as building ventilation, construction and occupant lifestyle.

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A8.5 ASSESSING THE VAPOUR INTRUSION PATHWAY IN DETAIL

Following a public announcement in 2000, a programme of further investigations was undertaken, including indoor air monitoring measuring for the presence of volatile compounds that could be attributed to the quarry fill material. A phased approach to the investigations was undertaken, summarised in Table A8.3 (Crump *et al*, 2002). Indoor air sampling was performed using a method developed specifically for the project to attain very low reporting limits (0.003 ppbv/v) for the chlorinated butadienes against a threshold value of 0.6ppv/v.

Table A8.3 ***Summary of investigation chronology***

Chronology	Investigation
Phase 1: January to March 2000	■ sampling indoor air quality in 240 properties ■ collection of duplicate pumped indoor air samples using stainless steel adsorbent tubes (Tenax™), single eight hour sampling event in living/occupied rooms of each building ■ samples analysed by laboratories for the presence of HCBD ■ detectable concentrations in 21 properties close to the first quarry ■ concurrently, highly sensitive method of sampling and analysis developed for compounds including HCBD, with a quantifiable range of 0.003 ppb to 10 ppb (pumped adsorbent tubes and 24 hour sampling).
June 2000	The UK Department of Health Committee on Toxicity advised that continuous exposure to HCBD in air at concentrations less than 0.6 ppbv/v would not result in appreciable adverse health effects.
Phase 2: June 2000 to October 2001	■ sampling indoor air quality in 145 properties, including groups of properties in other locations in England ■ monitored on four occasions, plus a sub-set of buildings monitored more frequently to assess daily, weekly, monthly and seasonal changes ■ all sampling undertaken in main living area using pumped sampling technique over 24 hour period, plus an outdoor air sample and measurement of local weather conditions ■ many QA/QC protocols, including duplicate sampling and use of a second laboratory to undertake the analysis.

Full details on the methodologies used to undertake the soil gas sampling and air quality testing is presented in Crump *et al* (2002) and Wilkinson *et al* (2002). Further testing included multiple rounds of soil vapour monitoring from several dozen nested vapour monitoring wells for VOCs via Tedlar bag and chlorinated butadienes via ATD tubes, building pressure/ventilation studies, pneumatic testing (McAlary *et al*, 2002), geophysical logging, trial pits to verify the limits of quarry spoil backfill and hundreds of outdoor air samples. A comprehensive statistical analysis of the data was performed to identify the subsurface to indoor air attenuation factor, which showed a notable difference between quarry backfill and undisturbed layered bedrock areas.

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Figure A8.3 ***Sampling air quality at the site (courtesy Derrick Crump, BRE)***

The importance of good QA/QC and peer review procedures was a vital outcome of the programme of works, as highlighted by Wilkinson *et al* (2002). For this site, it provided valuable evidence that the analysis process was under control.

The compound HCBD was encountered at concentrations in indoor air that exceeded the Department of Health exposure guideline of 0.6 ppbv/v in 22 properties, all but one of which were built on areas of backfill with highly permeable quarry spoil materials. For one house located near the first quarry, measurements of indoor air quality on an almost weekly basis provided a range of concentrations from 0.068 ppbv/v to 0.387 ppbv/v, all of which are easily resolved against the average outdoor air concentration of 0.007 ppbv/v. All readings in the control properties had measured concentrations of HCBD of less than 0.003 ppbv/v, with the exception of a single measurement of 0.005 ppbv/v (Crump *et al*, 2002).

The findings of the long-term programme of indoor air monitoring in several residential properties at the site indicated that there was the potential for significant risk from the measured concentrations of HCBD in indoor air in 29 properties. As a result of the works, many properties were acquired and demolished at the site in 2002.

A8.6 RISK COMMUNICATION

A risk communication strategy was critical to the works at the site, to provide the residents with:

- information in an accessible and understandable format
- a forum for raising concerns and asking questions
- regular update reports
- confirmation that everything possible was being done to address the situation quickly and efficiently, while minimising the disruption to resident's lives
- assurance that the strategy for dealing with the situation had been developed taking the resident's views into consideration.

A8.8 FURTHER INFORMATION

For further information regarding the investigations undertaken at the site, refer to the following:

CRUMP, D R and WILKINSON, G (2000)
"The assessment of land contaminated with hexachlorobutadiene and the role of measurement in assessing the indoor air quality in properties in the immediate vicinity"
Proc Competing precisely with the environment, Runcorn, 21 November 2000

CRUMP, D R, BROWN, V, ROWLEY, J, LLEWELLYN, J, WILKINSON, G and MOSS, R (2002)
"Sampling of hexachlorobutadiene in the air of homes at a site contaminated by industrial waste in England"
Proc Indoor Air 1, Monterey, California, 30 June to 5 July 2002, pp 944–949

McALARY, T, DOLLAR, P, DEHAVEN, P, WILKINSON, G, MOSS, R, LLEWELLYN, J and CRUMP, D (2002)
"Assessment of subsurface vapour transport through Triassic sandstone and quarry fill into indoor air in Weston Village, Runcorn, UK"
Proc Indoor air, Monterey, California, 30 June to 5 July 2002, pp 902–907

WEALTHALL, G P, STEELE, A, BLOOMFIELD, J P, MOSS, R, and LERNER, D N (2001)
"Sediment filled fractures in the Permo-Triassic sandstones of the Cheshire Basin: Observations and implications for pollutant transport"
Journal of Contaminant Hydrogeology, 50, Elsevier BV, pp 41–51

WILKINSON, G, MOSS, R, CRUMP, D, BROWN, V, ROWLEY, J, HAFKENSCHEID, T, KEARN, R, CARP, A, and KRISTENSON, J (2002)
"Quality control and quality assurance procedures used during the indoor air monitoring in Weston Village, Runcorn"
Proc Indoor air, Monterey, California, 30 June to 5 July 2002 pp 950–955

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A9 Volatility and toxicity screening methodology

A9.1 INTRODUCTION

USEPA developed a screening mechanism to identify compounds that were likely to have sufficient volatility and toxicity to present a risk through the vapour intrusion pathway. The methodology was documented within the draft OSWER guidance (USEPA, 2002). A similar, modified methodology is included in this guidance as a tool to help the assessor select which compounds of concern require further consideration for the vapour intrusion/emission pathways.

The methodology takes into account the likely volatility of a compound, using the Henry's law constant, and the likely toxicity of a compound, using a modified health criteria value based on inhalation exposure compared to the saturated vapour (soil gas) phase concentration of the pure component. This screening should be used with care. For compounds with an extremely low toxicological threshold for the inhalation pathway or where the compound is close to failing the screening, professional judgement and multiple lines of evidence may be required before a decision can be made regarding the potential risk associated with the vapour emission or intrusion pathways.

A9.2 VOLATILITY SCREENING

The first stage of the screening using Henry's law constant was originally proposed by Lyman *et al* (1982) where the following definitions were made (converted from $atm.m^3mol^{-1}$):

$K_H < 0.01$ $Pa.m^3mol^{-1}$ (low volatility)

$K_H > 0.01$ and < 1 $Pa.m^3mol^{-1}$ (volatilise slowly)

$K_H > 1$ and < 100 $Pa.m^3mol^{-1}$ (volatilisation is an important transfer mechanism)

$K_H > 100$ $Pa.m^3mol^{-1}$ (volatilisation will proceed rapidly)

Note:

1 atmosphere is equivalent to 101325 Pa.

Within existing guidance documents (for example, SNIFFER, 2003 and USEPA, 2002), if a compound has a Henry's law constant of less than 1 $Pa.m^3mol^{-1}$ (about 1×10^{-5} $atm.m^3mol^{-1}$) then it is considered unlikely to present a risk through vapour intrusion/emission pathways. This screening methodology adopts the same principle. It is acknowledged that this form of screening will typically only be of use where lower volatility compounds (for example, semi-volatile organic compounds) are present in addition to VOCs.

UK guidance recommends the use of chemical properties appropriate for 10°C (EA, 2009b and EA, 2008). The same assumption is made within the volatility screening methodology where possible.

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EA guidance (2008) gives information on calculating chemical properties (for example, Henry's law constant) at a particular reference temperature, alongside guidance on converting between different measurement units, which should also be referred to. The dimensionless form of the Henry's law constant is referred to as the air-water partition coefficient (K_{aw}).

A9.3 TOXICITY SCREENING

The second stage of the screening uses knowledge about the toxicity of the compound through inhalation exposure, and was included within the draft OSWER guidance (USEPA, 2002).

The screening involves calculation of the theoretical saturated soil gas (vapour) concentration of the pure component, and comparison to a modified health criteria value based on inhalation exposure. This process is described in more detail in the following sections, and an example is provided Section A9.5.

A9.3.1 Calculating the saturated vapour phase concentration

The following equation (taken from EA, 2009b) can be used to calculate the theoretical saturated soil gas (vapour) concentration of the pure component:

$$C_{sat\ vap} = P_v \times (M/(R \times T_{amb})) \times 1000\ mg\ g^{-1} \times 1000\ \mu g\ mg^{-1}$$

$C_{sat\ vap}$	saturated vapour concentration above the pure chemical at ambient temperature and pressure (μgm^{-3})
Pv	saturated vapour pressure at ambient temperature and pressure (Pa)
M	molecular weight (g mol^{-1})
R	molar gas constant (Pa m^3 mol^{-1} K^{-1}), 8.314472
T_{amb}	ambient temperature (K)

The calculation can either be undertaken for 10°C (283K), or for a system at a higher temperature (for example, 25°C (298K)), as a conservative assumption.

A9.3.2 Calculating a modified health criteria value

To undertake the toxicity screening, an appropriate health criteria value (HCV) needs to be defined. In the UK, the HCV for the inhalation exposure pathway takes the form of either a tolerable daily soil intake (TDSI) for threshold compounds, or an index dose (ID) for non-threshold compounds (EA, 2009a). Both the TDSI and ID, in units of $\mu g_{compound} kg_{bodyweight}^{-1} day^{-1}$, need to be modified into an acceptable air concentration (μgm^{-3}) to allow comparison with the calculated vapour phase concentration. The following simple modification can be undertaken, assuming a child receptor, following guidance presented by USEPA (2002):

$$C_{air} = (TDSI_{inhalation} \times 13.3)/11.85$$

or

$$(ID_{inhalation} \times 13.3)/11.85$$

C_{air}	modified HCV (μgm^{-3})
TDSI	tolerable daily soil intake (μgm^{-3})
ID	index dose ($\mu gkg^{-1}day^{-1}$)

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An inhalation rate of 11.85 m^3day^{-1} and a body weight of 13.3 kg were adopted in this modification, based on a 0–6 year old female child (time-averaged) for translating between a daily dose and an associated acceptable air concentration. Data pertinent specific receptor age ranges in the UK could be also used (EA, 2009b and Jeffries, 2009). In some cases, the original toxicological study which was used to derive the HCV may be based on an acceptable air concentration, which can be used, thereby removing the need for this conversion.

A9.3.3 Undertaking the toxicity screening

Comparison between the saturated vapour phase concentration and the modified HCV allows the assessor to complete the toxicity screening. If the calculated saturated vapour phase concentration is less than the modified HCV, it is likely that the toxicity of the compound relating to the vapour intrusion and exposure pathway will not present a significant risk to human health. However, as noted before, this screening should be used with care. For compounds with an extremely low toxicological threshold for the inhalation pathway or where the compound is close to failing the screening, professional judgement and multiple lines of evidence may be required before a decision can be made regarding the potential risk associated with the vapour intrusion or emission pathways.

A9.4 RESULTS OF THE SCREENING

The results of the screening can help the assessor decide which compounds of concern need further consideration. If a compound is found to pass either the volatility screening or toxicity screening (ie considered to be of relatively low volatility and/or relatively low toxicity to human health via inhalation in gaseous phase), and care is taken with the interpretation of the results (for example, where the compound is close to failing the screening) then no further assessment of the compound is required for the vapour intrusion/emission pathway, for the majority of sites.

A9.5 EXAMPLE CALCULATION

Three example compounds, X, Y and Z, have been identified in soils beneath a site. Screening for volatility and toxicity has been undertaken to assess whether either compound warrants further consideration for the vapour intrusion/emission pathways. A large flux of potential carrier gases has not been identified, and the most sensitive receptor was identified as a child.

Screening for volatility

The Henry's law constant for the compounds was identified as:

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Table A9.1 ***Adopted Henry's law constant, saturated vapour pressure and molecular weight***

Compound	Henry's law constant at 10 ˚C, Pa m^3mol^{-1} (H)	Saturated vapour pressure at 10 ˚C Pa (P_v)	Molecule weight g mol^{-1} (M)
Compound X	1×10^{-2}	0.003	220
Compound Y	4.5	2.4	150
Compound Z	3×10^{-3}	70	90

Compound Y is the only one of the three compounds with a Henry's law constant greater than 1 $Pa.m^3mol^{-1}$.

Screening for toxicity

Health criteria values (HCVs) based on inhalation exposure were identified as:

Table A9.2 ***Adopted health criteria values***

Compound	HCV	Units	Modified HCV	Units
Compound X	800	$\mu gkg^{-1}day^{-1}$	898	μgm^{-3}
Compound Y	1×10^{-5}	$\mu gkg^{-1}day^{-1}$	1.12×10^{-5}	μgm^{-3}
Compound Z	90	$\mu gkg^{-1}day^{-1}$	101	μgm^{-3}

Note:

Modified HCV = HCV × (13.3/11.85) for the purpose of this example.

Calculating the saturated vapour phase concentration for each compound:

Compound X

$C_{max,vp}$ = (0.003 × 220)/(8.314 × 283) × 103 × 103

= 281 μgm^{-3} (less than modified HCV)

Compound Y

$C_{max,vp}$ = (2.4 × 150)/(8.314 × 283) × 103 × 103

= 1.53 × 105 μgm^{-3} (considerably greater than modified HCV)

Compound Z

$C_{max,vp}$ = (70 × 90)/(8.314 × 283) × 103 × 103

= 2.7 × 106 μgm^{-3} (considerably greater than modified HCV)

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Results of the screening

The results are documented in Table A9.3:

Table A9.3 ***Results of screening***

Compound	Is compound sufficiently volatile?	Is compound sufficiently toxic?	Assess further for vapour intrusion/emission?
Compound X	No	No	No
Compound Y	Yes	Yes	Yes
Compound Z	No	Yes	Potentially

For compound Z, although it is not considered sufficiently volatile, the saturated vapour phase concentration is orders of magnitude greater than the modified HCV. So further consideration would need to be given as to the likely fate and transport of the compound in the environment before screening out from further assessment for the vapour pathways.

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A10 Development of generic assessment criteria (v-GAC)

A10.1 INTRODUCTION

As part of the CLEA methodology, the EA has provided guidance on the development of GAC (for example, EA, 2009a and 2009b) to offer protection to human health (primarily from chronic health effects, due to long-term exposure), with a focus on contaminants present in soil.

Soil Guideline Values (SGVs) are a form of GAC, which have been developed using the input parameters and algorithms included in the EA guidance. When assessing exposure from soil by a human health receptor it is generally accepted that SGVs will be used where available and appropriate. Where no SGV is developed, extra pollutant linkages need considering or the compounds of concern (such as halogenated hydrocarbons) cannot be reliably assessed through the use of soil data alone, assessors may wish to develop GAC using the same (or similarly appropriate) assumptions used to develop the SGVs. This appendix provides guidance on how to develop GAC for the vapour intrusion and emission pathways, for both a soil and groundwater source. However, note that the GAC may include further source media and pathways. The following stages need consideration when developing GAC for the vapour intrusion and emission pathways:

- potentially active vapour inhalation pollutant linkages
- choice of modelling tool
- toxicity/chemic-physical data
- physical input parameters
- building input parameters
- exposure parameters
- development of the v-GAC.

When developing v-GAC, the assessor should, where necessary, take into account degradation products that may not be present in the source medium but may be generated through degradation during transport in the unsaturated zone. In some cases the degradation daughter compound can represent a higher risk to human health than the parent compound (such as tetrachloroethene and the degradation products trichloroethene, 1,2-dichloroethene and vinyl chloride, as discussed in Chapter 4).

A10.2 POTENTIALLY ACTIVE VAPOUR INHALATION POLLUTANT LINKAGES

There are several potentially active vapour inhalation pollutant linkages that may need consideration when developing the GAC. Based on the CSM used to develop SGVs, the following pathways would be considered for an on-site human health receptor from a soil source:

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- inhalation of vapours, originating from a soil source, in an indoor air space
- inhalation of vapours, originating from a soil source, in an outdoor air space.

Note that although these are described as two separate pathways, in practice the receptor is often exposed to the pathways combined. However, for many sites, there will be a need to consider other significant vapour inhalation pathways, both for human health receptors on a site, and human health receptors located at an off-site location. There is no specific guidance in the UK now as to how to develop GAC for exposure to groundwater, either on or off-site. However, several assumptions within the CLEA methodology regarding exposure to contaminants in soils can also be applied to exposure to a dissolved phase groundwater source. Within this appendix, the vapour inhalation pathways shown in Table A10.1 are considered within development of the GAC.

For some sites, there is further potential risk to off-site human health receptors via the vapour intrusion/emission pathways from transport in the unsaturated zone, in gaseous form. The likelihood of transport off-site via the unsaturated zone may depend on the presence of significant preferential pathways (for example, large-scale drainage routes), a considerable driving force and/or the nature of the compound. Research, both theoretically and using empirical data, indicate that for compounds that undergo relative rapid microbial degradation in the unsaturated zone, such as petroleum hydrocarbons, the potential for off-site transport is limited (see Appendix A2). For such complex situations or where significant preferential pathways are present or suspected, a GAC should not be derived. Instead, a site by site assessment is likely to be required, which may include the development of SSAC where appropriate. Consideration should still be given at a generic level to the likelihood for off-site transport via the unsaturated zone in gaseous form when assessing a site, which may be qualitatively or for some sites through collection of site data.

Table A10.1 ***Vapour inhalation pathways typically considered in development of GAC***

Source media	User of site	Occupier of off-site land
Soil	Inhalation of vapours in an indoor air space	Leaching of contamination from soil, transport off-site in groundwater and later volatilisation and inhalation in an off-site indoor air space.
	Inhalation of vapours in an outdoor air space	Leaching of contamination from soil, transport off-site in groundwater and later volatilisation and inhalation in an off-site outdoor air space.
Groundwater	Inhalation of vapours in an indoor air space	Transport off-site in groundwater and later volatilisation and inhalation in an off-site indoor air space.
	Inhalation of vapours in an outdoor air space	Transport off-site in groundwater and later volatilisation and inhalation in an off-site outdoor air space.

A10.3 CHOICE OF MODELLING TOOL

There are many software packages that can adopt the guidance within the CLEA methodology, and be used to develop GAC for a soil or groundwater source. Examples of different software packages that incorporate the J&E model and outdoor air CLEA model are provided in Table A10.2, with some of the potential advantages and disadvantages of each package when considering the

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vapour intrusion/emission pathways (see also Gardner *et al*, 2004 and Swartjes, 2002). During the consultation phase of developing this guidance, the three software packages in the table were the most widely cited as being used to undertake quantitative risk assessments.

Table A10.2 ***Commonly used software packages for developing GAC***

Software Package	Advantages (for GAC development)	Disadvantages (for GAC development)
CLEA 1.06	Released by the Environment Agency as part of the CLEA methodology	Limited to on-site exposure to soil source
	Freely available and relatively user friendly, implements additivity across pathways	Cannot model a groundwater source
RBCA Toolkit v2.5	Flexible and user friendly. In-built database can be easily modified to include UK specific data	Not freely available
	The J&E model for exposure to soils is the same as recommended by CLEA	Additivity not undertaken across all pathways
	Extra pathways (for example, off-site migration in groundwater)	Modifications required to in-built chemical/toxicological database required
RISC v4.05	The J&E model for exposure to soils is the same as recommended by CLEA	Not freely available
	Flexible and user friendly. In-built database can be easily modified to include UK specific data	Modifications required to in-built chemical/toxicological database required
	Extra pathways (for example, off-site migration in groundwater)	Additivity not undertaken across all pathways
	Many algorithms in software are similar/same as for CLEA	Does not include the dust inhalation pathway

The table illustrates that there is no single software package that models all pathways of concern, each has advantages and disadvantages.

A10.4 TOXICITY AND CHEMICAL PROPERTIES DATA

Health criteria value (toxicity) guidelines for the inhalation of vapours from contaminants present in the subsurface have been provided for several VOCs by Defra and the EA, alongside guidance on how to derive HCVs where no toxicity report is provided (EA, 2009a). The HCVs are derived to enable the assessment of chronic health effects from long-term exposure. Assessors will also need to consider potential health effects from other exposure duration, such as acute health effects from short term exposure.

Chemical properties for a range of compounds is provided within EA (2008), with a wide selection of data sources cited that can be reviewed in the absence of a UK recommended dataset of chemical properties for a compound. For petroleum (non-halogenated) hydrocarbons, the conservatism inherent in use of the Henry's law constant to predict the concentration in soil gas from a soil or groundwater source should be considered when developing screening levels for these compounds (see Appendix A2), and can be accounted for within CLEA 1.06 (see Appendix A11, the sub-surface soil to indoor air attenuation factor).

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A10.5 PHYSICAL INPUT PARAMETERS

Physical input data (such as soil porosity and bulk density) can be found in EA guidance (2009b). The GAC will typically be developed for a sandy loam soil type, as for the SGVs, but the calculation of GAC for extra soil types could be undertaken if required and appropriate.

When considering vapour inhalation pathways associated with a groundwater source or off-site migration via an aquifer, certain assumptions external to those presented in the CLR documents would have to be made about the physical input parameters for the modelling. These include the following:

- depth to groundwater
- capillary fringe properties (if present)
- aquifer properties (such as hydraulic conductivity and effective porosity)
- distance to off-site property/outdoor air space.

The physical input parameters, where not present in the CLEA methodology, will need to be taken from alternative literature sources. The selected parameter values should be taken from UK data sources where possible, and mirror the conceptualisation of the unsaturated zone for the purposes of developing a GAC. These could include the EA and British Geological Survey aquifer properties manuals (Jones *et al*, 2000 and Allen *et al*, 1997) or values derived from the software model CONSIM2 (developed on behalf of the EA). Sensitivity testing may need to be undertaken to justify the selected parameter values.

A10.6 BUILDING INPUT PARAMETERS

For the vapour intrusion pathway, the building type needs to be selected before developing the GAC. Following the method used for SGV development, for a residential site the building type is typically a small terraced house (without basement) while for a commercial/industrial site, the building type adopted is typically an office (without basement – pre-1970s). Generic UK building input parameters are provided in EA (2009b).

A10.7 EXPOSURE PARAMETERS

Exposure input parameters for the vapour intrusion and emission pathways are provided in the CLR documentation (EA, 2009b and Jeffries, 2009). Designed for exposure to a soil source, similar parameters can be adopted for the vapour intrusion and emission pathways for a groundwater source.

A10.8 DEVELOPMENT OF THE GAC FOR VAPOUR INTRUSION/EMISSION PATHWAYS

The defined input parameters are used to develop screening levels, or GAC, for the pathways of concern. During development of the GAC, consideration will need to be given to multiple potential pollutant linkages, as for the SGVs. The CLEA methodology requires that the hazard index for each pathway for an environmental source medium is added to provide an indication of overall risk. A total hazard index of greater than unity indicates a potentially significant risk. If using a software package where additivity across pathways cannot be computed, an external calculation may need to be performed, following the guidance presented within the CLEA documentation.

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There is no specific guidance in the UK now for considering additivity from exposure from different sources present at sites affected by contamination (such as a soil and groundwater source). For the vapour intrusion and emission pathways, the modelling is effectively considering the potential risk from compounds in soil gas phase. The compounds in soil gas may originate from soil, groundwater or an alternative source, or in many cases, a combination of more than one source. Considering the effects of additivity across source media would be difficult to employ based on available guidance. When developing GAC for source media other than soils, the potential contribution may need to be considered qualitatively (or semi-quantitatively) on a site by site basis, but no formal method for including additivity across source media is proposed in this guidance. The assessor should note the type of VOC present (for example, petroleum hydrocarbons versus halogenated hydrocarbons) and any levels of conservatism incorporated into the assessment when undertaking the risk evaluation and the need to consider contributions to the overall risk from different sources present at a site. Also, multiple sources, for example, one source beneath a building and a second source close to the building, will need consideration.

A10.9 DEVELOPING GAC FOR OTHER MEDIA

More experienced assessors may choose to develop GAC for other media, for example, soil gas. However, in many cases this would form part of a v-DQRA, through the development of SSAC for different source media, as discussed in Chapter 8. Assessors should note the need to consider the contribution from the different modelled exposure pathways (for example, ingestion of soil) to the overall risk level, if generating a GAC for a range of source media. In some cases, use of a more simple screening method can take the place of development of a GAC. For example, measured concentrations of VOCs in soil gas can be compared directly against target indoor air concentrations (such as a modified HCV, see Appendix A9), or even background levels in ambient air, to demonstrate the likelihood of the vapour intrusion pathway presenting a risk to human health.

A10.10 ASSESSING DEGRADATION PRODUCTS

For some VOCs, degradation daughter compounds may need to be considered in the assessment, and a GAC developed for the daughter compounds even if not identified at a site. For example, the microbial degradation of tetrachloroethene already discussed in Chapter 4. At a generic stage of assessment, the following methodology could be used to quantify whether the daughter products of tetrachloroethene (if produced) could present a risk through the vapour intrusion pathway. The values quoted below are for indicative purposes and do not represent screening levels.

Example scenario

Tetrachloroethene, trichloroethene and cis 1,2-dichloroethene have been identified at a site during a single groundwater monitoring visit, at representative concentrations of 1 mgL^{-1}, 0.8 mgL^{-1} and 0.1 mgL^{-1} respectively in groundwater. Vinyl chloride has not been measured in groundwater above the laboratory method detection limit of 0.001 mgL^{-1}. Vinyl chloride has the lowest HCV based on inhalation exposure.

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GAC are developed for the three compounds detected, as well as for vinyl chloride:

Compound	GAC (mgL^{-1})	Representative concentration (mgL^{-1})	Failure of GAC?
Tetrachloroethene	5	1	No
Trichloroethene	0.9	0.7	No
cis 1,2-dichloroethene	0.3	0.08	No
Vinyl chloride	0.07	Not detected	Not for current conditions

The relative molecular mass of each compound is used to (conservatively) assess the potential for degradation compound concentrations, and the risk via vapour intrusion, which could increase in the future. This assumes that each compound degrades to form the daughter compound with the lowest inhalation-HCV (in this case, vinyl chloride).

Compound	Relative molecular mass (RMM)	Representative concentration, C_R (mgL^{-1})	Modified concentration (C_M) assuming degrades to form vinyl chloride (mgL^{-1})
Tetrachloroethene	166	1	0.38
Trichloroethene	131.5	0.7	0.33
cis 1,2-dichloroethene	97	0.08	0.052
Vinyl chloride	62.5	Not detected	Not applicable

Where the modified concentration is:

$$CM = C_R \times (RMM_{\text{vinyl chloride}}/RMM_{\text{compound of concern}})$$

By comparing the modified concentrations (CM) to the GAC for vinyl chloride, this simple approach can be used to assess risk from the potential degradation product, even though not encountered at the site.

Compound	Modified concentration (mgL^{-1})	Vinyl chloride GAC mgL^{-1})	Failure of GAC?
Tetrachloroethene	0.38	0.07	Yes
Trichloroethene	0.33	0.07	Yes
cis 1,2-dichloroethene	0.052	0.07	No

Note that this approach does not account for the potential for all three compounds to degrade to produce vinyl chloride concurrently. So a further step could be to sum the modified concentrations before comparison to the vinyl chloride GAC.

The results would suggest that further investigation and assessment is required, such as longer-term monitoring or detailed assessment to establish the likelihood of vinyl chloride forming in the future, or sampling of soil gas for the presence of each of the compounds above the groundwater table.

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A11 Commonly used modelling tools/ software packages

This table provides an overview of commonly used modelling tools that include some capability to model the vapour intrusion and emission pathways. The review undertaken by Turczynowicz and Robinson (2007) provides further examples of vapour intrusion models, such as VAPEX3, Unocal and the Australian CSIRO model.

A11.1 CLEA V1.06

Developed by	Environment Agency, in conjunction with the Scottish Environment Protection Agency, the Northern Ireland Environment Agency and Defra
Freely available?	Yes
Relevant pathways:	❑ inhalation of vapour indoors, originating from a soil source ❑ inhalation of vapours outdoors, originating from a soil source.
Methodology	Uses guidance within the CLEA methodology
Vapour intrusion model?	J&E model (with or without source depletion, no degradation in vadose zone). Includes sub-surface soil to indoor air attenuation factor which is chemical-specific.
How appropriate to UK building types?	❑ use of J&E model: originally designed to model a building with a basement, which forms part of the living space ❑ can be used to model most UK building constructions, although likely to over predict the rate of intrusion into suspended slab (concrete beam and block/cast *in situ*, timber with vented void) construction, and not the most appropriate vapour intrusion model for permeable basement floors.
Vapour emission model?	Calculation of volatilisation factor described in EA (2009b)
Risk evaluation?	❑ generation of hazard indices ❑ generation of generic assessment criteria (GAC) for soil ❑ generation of site-specific assessment criteria (SSAC) for soil.
Advantages	❑ designed specifically for the CLEA methodology ❑ additivity across pathways included automatically ❑ includes a range of other exposure pathways ❑ considers likelihood of residual or free phase product being present ❑ includes sub-surface soil to indoor air attenuation factor to reduce conservatism in modelling vapour intrusion where appropriate ❑ models direct emission from surface soils ❑ freely available.
Limitations	❑ only soil source term can be modelled ❑ no degradation option.

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A11.2 RISC V4.05

Developed by	Lyn Spence (originally in conjunction with BP)
Freely available?	No
Relevant pathways:	❑ inhalation of vapour indoors, originating from a range of source media ❑ inhalation of vapours outdoors, originating from a range of source media.
Methodology	RBCA ASTM
Vapour intrusion model?	J&E model (no source depletion), with additions
How appropriate to UK building types?	❑ use of J&E model originally designed to model a building with a basement, which forms part of the living space ❑ can be used to model most UK building constructions, although likely to over predict the rate of intrusion into suspended slab (concrete beam and block/cast *in situ* and timber with vented void) construction, and not the most appropriate vapour intrusion model for permeable basement floors.
Vapour emission model?	Box model similar but not identical to the CLEA methodology
Risk evaluation?	❑ generation of hazard indices ❑ can be used to generate GAC ❑ generation of SSAC.
Advantages	❑ can model a range of source media (soil, groundwater, soil gas, indoor air and outdoor air) ❑ includes a range of other exposure pathways ❑ can model risk to off-site receptors, via groundwater migration, from vapour emission and intrusion ❑ considers likelihood of residual or free phase product ❑ includes two forms of model to assess degradation in vadose zone ❑ for a soil source soil, the overlying unsaturated soils can be modelled as a different soil type to the source ❑ a lower permeability lens can be modelled within the vadose zone overlying the source ❑ in-built database can be easily modified.
Limitations	❑ not freely available ❑ not designed to model emissions from surface soils ❑ additivity across vapour emission/intrusion pathways not undertaken.

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A11.3 RBCA TOOLKIT FOR CHEMICAL RELEASES V2.5

Developed by	Groundwater Services Inc
Freely available?	No
Relevant pathways:	❑ inhalation of vapour indoors, originating from a range of source media ❑ inhalation of vapours outdoors, originating from a range of source media.
Methodology	RBCA ASTM
Vapour intrusion model?	J&E model (with or without source depletion)
How appropriate to UK building types?	❑ use of J&E model originally designed to model a building with a basement, which forms part of the living space ❑ can be used to model most UK building constructions, although likely to over predict the rate of intrusion into suspended slab (concrete beam and block/cast *in situ* and timber with vented void) construction, and not the most appropriate vapour intrusion model for permeable basement floors.
Vapour emission model?	Similar but not identical to CLEA methodology
Risk evaluation?	❑ generation of hazard indices ❑ can be used to generate GAC ❑ generation of SSAC.
Advantages	❑ Includes a range of other exposure pathways ❑ can model a soil or groundwater source ❑ can model risk to off-site receptors, via groundwater migration, from vapour intrusion ❑ can model risk to off-site receptors, via simple air dispersion modelling, from inhalation of outdoor air ❑ considers likelihood of residual or free phase product ❑ can model direct emission from a surface soil source ❑ in-built database can be easily modified.
Limitations	❑ not freely available ❑ additivity across vapour emission/intrusion pathways not undertaken ❑ cannot model degradation in vadose zone ❑ adjustments needed to either toxicity data or exposure data, as requires tolerable concentration in air ($\mu g m^{-3}$), as opposed health criteria value ($\mu g_{contaminant} kg_{bodyweight}^{-1} day^{-1}$)

A11.4 SNIFFER (2003)

Developed by	Scotland and Northern Ireland Forum for Environmental Research
Freely available?	Yes
Relevant pathways:	❑ inhalation of vapour indoors, originating from a soil source ❑ inhalation of vapours outdoors, originating from a soil source.
Methodology	Based primarily on older CLR documents (pre-2009)
Vapour intrusion model?	Percentage of soil gas entering indoor air defined by user (dilution factor)
How appropriate to UK building types?	Relies on a setting a factor of dilution between soil gas and indoor air space, so not of great use for predicting vapour intrusion
Vapour emission model?	Percentage of soil gas entering outdoor air defined by user (dilution factor)
Risk evaluation?	❑ can be used to generate GAC ❑ generation of SSAC.
Advantages	Relatively user friendly and freely available
Limitations	❑ does not use the J&E or CLEA vapour intrusion model ❑ cannot model degradation in vadose zone ❑ limited to the assessment of soils on-site.

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A11.5 USEPA JOHNSON AND ETTINGER SPREADSHEET

Developed by	USEPA
Freely available?	Yes (currently in revision)
Relevant pathways:	❑ inhalation of vapour indoors, originating from a soil source ❑ inhalation of vapour indoors, originating from a groundwater source ❑ inhalation of vapour indoors, originating from a soil gas source.
Methodology	Based on the J&E model
Vapour intrusion model?	See above
How appropriate to UK building types?	❑ use of J&E model originally designed to model a building with a basement, which forms part of the living space ❑ can be used to model most UK building constructions, although likely to over predict the rate of intrusion into suspended slab (concrete beam and block/cast *in situ* and timber with vented void) construction, and not the most appropriate vapour intrusion model for permeable basement floors.
Vapour emission model?	Not included
Risk evaluation?	❑ generation of risk levels ❑ can be used to generate GAC ❑ generation of SSAC.
Advantages	Relatively user friendly and freely available
Limitations	❑ inbuilt database does not use UK input parameters, difficult to alter ❑ cannot model degradation in vadose zone ❑ limited to the assessment of the vapour intrusion pathway for on-site users

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A11.6 RISC-HUMAN V3.2

Developed by	Van Hall Institute (The Netherlands)
Freely available?	No
Relevant pathways:	❑ inhalation of vapour indoors, originating from a range of source media ❑ inhalation of vapours outdoors, originating from a range of source media.
Methodology	CSOIL (indoor and outdoor air) and VOLASOIL (indoor air)
Vapour intrusion model?	❑ CSOIL (intrusion through concrete pores or emission from open basement floor) ❑ VOLASOIL (intrusion through cracks in foundation slab).
How appropriate to UK building types?	❑ use of CSOIL and VOLASOIL: designed to model a building with a crawl space, or basement that does not form part of living space ❑ can be used to model suspended slab (concrete beam and block/cast *in situ* and timber with vented void) construction with a vented void, or buildings with basement living space present, although not strictly the scenarios the models were designed for.
Vapour emission model?	CSOIL emission and dilution algorithms, taking surface roughness into account
Risk evaluation?	Generation of hazard indices
Advantages	❑ includes a range of other exposure pathways ❑ can model a soil or groundwater source, including for more unusual building scenarios than within other models ❑ can modify database relatively easily.
Limitations	❑ not freely available ❑ does not use the same vapour emission/intrusion algorithms as within CLR documentation ❑ cannot model degradation in vadose zone ❑ limited to the assessment of risks to on-site users.