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CONTAMINATED LAND MANAGEMENT ACT 1997

Notice of Guidelines

‘Assessment and management of hazardous ground gases: Contaminated Land Guidelines’

Notice is hereby given, under section 105 (1) of the *Contaminated Land Management Act 1997*, that the ‘Assessment and management of hazardous ground gases: Contaminated Land Guidelines’ are made. This guideline takes effect under section 105 (2)(c) of the *Contaminated Land Management Act 1997* upon publication in the *Government Gazette*.

18 December 2019

ARMINDA RYAN
Director Contaminated Land Management
Environment Protection Authority

Assessment and management of hazardous ground gases

Contaminated Land Guidelines



www.epa.nsw.gov.au

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1. Introduction

1.1 Ground gas issues in contaminated land management

Ground gases are frequently encountered during the assessment and remediation processes that occur before redeveloping potentially contaminated sites. They may also be encountered on land adjacent to such sites. As awareness of the issue has grown, so has the number of sites found to be impacted and requiring management.

Failing to recognise and appropriately manage risks associated with ground gases while assessing and remediating potentially contaminated land, or when developing land adjacent to sites impacted by ground gases, may have significant consequences. These may include construction delays and additional costs; large legal liabilities for neighbouring landholders; adverse long-term health impacts from exposure; and structural damage, injury and death due to gas explosions. These are not hypothetical consequences – all have occurred either in Australia or overseas.

1.2 Why these guidelines were created

These guidelines were first issued in November 2012. At that time, although there had been a number of incidents involving ground gases in NSW, other Australian states and territories, and internationally, both public and professional awareness and understanding of the problem was limited. There was no comprehensive guidance for assessing and managing ground gases on contaminated land in NSW, and very little formal guidance in other Australian jurisdictions. The first edition noted that:

Comprehensive guidance is available from overseas sources, particularly the United Kingdom (UK), but much of this is not readily accessible in Australia and cannot be applied without adaptation to reflect local geological, meteorological and regulatory regimes.

Whilst some sites have been successfully managed over a number of years, there are well-founded concerns that the lack of formal guidance within the NSW regulatory process has resulted in inconsistency in the approaches adopted for management of land impacted by ground gases. Such inconsistency has led to both over-conservative and under-conservative design of mitigation measures, and in some cases to significant ground gas issues being identified late in the development process when management is much more difficult and expensive, or not being identified at all.

1.3 This edition

This is the second edition of these guidelines. In the seven years since the original edition was published, practitioners in NSW have gained substantial experience working with the guidelines and with assessing and managing hazardous ground gases more generally. Furthermore, over that period there have been significant changes to other relevant guidance documents, most notably:

- the National Environment Protection (Assessment of Site Contamination) Measure 1999 (the ASC NEPM), which was revised in May 2013
- British Standard (BS) 8576:2013, *Guidance on Investigations for Ground Gas – Permanent Gases and Volatile Organic Compounds (VOCs)*, which was first published in 2013
- BS 8485:2015+A1:2019, *Code of Practice for the Design of Protective Measures for Methane and Carbon Dioxide Ground Gases for New Buildings*, fully revised in 2015, further amended in 2019
- CIRIA C748, *Guidance on the Use of Plastic Membranes as VOC Vapour Barriers*, first published in 2014.

A revised edition of these guidelines is therefore timely.

1.4 Definitions

The term 'hazardous ground gas' is applied to both gases and vapours¹ that are present within the pore space of soils and rocks and adversely impact human health and safety or the integrity of structures, and may consequently affect activities such as constructing and managing buildings. Such gases or vapours may have natural or anthropogenic origins.

These guidelines are part of a series of guidelines made by the NSW Environment Protection Authority (EPA) dealing with various aspects of managing contaminated land. Accordingly, they focus on ground gases in the context of redeveloping potentially contaminated land or development adjacent to such land.

The ground gases that are generally of concern in this context are:

- methane
- carbon dioxide
- carbon monoxide
- hydrogen
- hydrogen sulfide
- petroleum vapours
- radon
- volatile organic compounds (VOCs)
- mercury vapour.

A distinction is made between radon, VOCs and mercury vapour and the other six ground gases. Radon, VOCs and mercury vapour are generally encountered at trace (parts per billion to parts per million) concentrations, when they become carcinogens or chronic toxicants. The other six ground gases may be encountered at percentage concentrations, when they become potentially explosive, asphyxiating or acute toxicants. They are referred to as 'bulk ground gases' in these guidelines, although the terms 'general gases' and 'permanent gases' may be used in other publications.

The physical, chemical and toxicological properties of common ground gases are tabulated in Appendix 2 and summarised below.

1.4.1 Bulk ground gases

Methane (CH₄) is a flammable gas that is explosive in the concentration range 5–15% volume to volume (v/v) in air. Somewhat different ranges may apply in atmospheres with enhanced or reduced oxygen concentrations, and ranges are also influenced by physical conditions.² It is also potentially an asphyxiant if its presence results in a low oxygen concentration. It is less dense than air.

Carbon dioxide (CO₂) is an asphyxiant and toxic gas that is significantly denser than air. Toxic effects may become noticeable at 2% v/v and severe at 5% v/v.

Carbon monoxide (CO) is an acutely toxic gas that is also flammable and potentially explosive. Toxic effects may become apparent at a concentration of 100 ppm and the explosive limits in air are 12.5–74.2% v/v. It has neutral buoyancy in air.

Hydrogen (H) is a flammable, potentially explosive gas that is much less dense than air. Explosive limits are 4–74% v/v.

Hydrogen sulfide (H₂S) is a flammable and acutely toxic gas that is denser than air. It has a very low odour threshold; the unpleasant odour is a nuisance at low concentrations. Symptoms of toxicity may become noticeable at 20 ppm and lethal at 400–500 ppm. The explosive limits in air are 4.5–45.5% v/v.

¹ Vapours may exist in equilibrium with the liquid or solid phases of the same material at ambient temperature. Gases may only exist in the gas phase under ambient conditions.

² See Appendix 2 for details.

Petroleum vapours at percentage concentrations are flammable, potentially explosive and acutely toxic; lower explosive limits (LELs) for many volatile hydrocarbons are in the low percentage range. Petroleum vapours are denser than air. Some components of petroleum vapour are also chronically toxic at trace concentrations and as such are also considered with VOCs in Section 1.4.2.

1.4.2 Trace ground gases

Radon (Rn) is a radioactive gas that is much denser than air. Two isotopes, radon 222 and radon 220, are of interest as ground gases.

Radon 222 has a half-life of 3.82 days, but is generated by the radioactive decay of longer-lived radioisotopes (such as uranium 238 and its daughter products), meaning the mass present may be constantly replenished. Radon 222 and its short-lived daughter products release alpha and beta radiation as they decay to lead. The alpha particles are particularly damaging if decay occurs when radon has been inhaled into the lungs, and the hazard is compounded because the radioactive daughter products are solid and not readily exhaled. Radon exposure can cause lung cancer.

Radon 220 has a half-life of less than one minute.

VOCs include a very wide range of compounds that may partition into soil gas following soil or groundwater contamination by volatile liquids. VOCs may also be present as trace contaminants in other ground gases, such as landfill gas. In terms of frequency of impact and toxicity, monocyclic aromatic hydrocarbons and the chlorinated aliphatic compounds are the most significant VOC contaminants. Monocyclic aromatic compounds include benzene, toluene, the xylenes and trimethyl benzenes, and ethylbenzene. Chlorinated aliphatic compounds include tetrachloroethene (PCE), trichloroethene (TCE), the dichloroethene isomers (DCE), chloroethene or vinyl chloride (CE), 1,1,1-trichloroethane (TCA), 1,2-dichloroethane (EDC), chloroethane (CA), tetrachloromethane or carbon tetrachloride (CT), and chloroform (CF).

Some organic compounds that are regarded as semi-volatile (SVOCs) may cause vapour issues in some circumstances. Examples are naphthalene, chlorinated benzenes and chlorinated butadienes.

Mercury (Hg) is unique among metallic elements in that it becomes a liquid at 25°C. It also has a significant vapour pressure; the vapour is colourless, odourless and highly toxic. Mercury has been used in a number of industrial processes, but is now being phased out. The unusual physical properties of mercury allow spillages to penetrate deeply into the soil sub-surface. Although the number of sites impacted is relatively small, mercury vapour may be a significant and persistent hazard in the soil at these sites.

1.5 Format and purpose of these guidelines

Section 2 of these guidelines describes the issues relating to ground gases as they have been encountered in Australia and overseas.

Section 3 sets out recommended approaches and procedures for assessing and characterising sites that may be impacted by ground gases.

Section 4 focuses on assessing the risks associated with ground gases, while Section 5 – which is closely linked to Section 4 – outlines options for managing and mitigating those risks.

Section 6 describes the planning and regulatory process relating to ground gases in NSW.

The guidelines are not intended to be a comprehensive manual of field investigation procedures or mitigation design. References to appropriate sources of such information are provided.

The guidelines as a whole focus on bulk ground gases (ground gases that occur at percentage concentrations), particularly methane. This is because these are not dealt with in other guidelines made or approved in NSW (including the ASC NEPM), and because they are commonly encountered at potentially hazardous concentrations in a wide range of land uses and geological settings. However, the guidelines also address trace ground gases, providing cross-references to other guidelines where appropriate.

These guidelines are not intended to address on-site issues associated with active landfills that are currently managed through the landfill licensing process, that is, under an Environment Protection

Licence (EPL) issued pursuant to the *Protection of the Environment Operations Act 1997* (POEO Act). However, they will be useful when considering off-site issues associated with such landfills and during landfill closure and post-closure stabilisation.

These guidelines draw heavily on ground gas assessment and management procedures, and associated guideline documents, developed in the UK. In particular, approaches have been adapted from BS 8485:2015+A1:2019 and various CIRIA publications to suit local conditions.

1.6 Legal framework, policy and relationship to other guidelines

These guidelines form part of a set of guideline documents made by the EPA to support the administration of the *Contaminated Land Management Act 1997* (CLM Act) and are intended to assist consultants, site auditors, landholders, developers and members of the public dealing with land that is impacted, or potentially impacted, by hazardous ground gases.

These guidelines complement other guidelines made by the EPA, and also a number of national guideline documents the EPA has approved, particularly the ASC NEPM. Those guideline documents are listed in the bibliography and, where appropriate, specifically referenced in the text. A list of the other guidelines in this series is provided in the bibliography under 'Relevant NSW legislation, regulations and guidelines'. In 2010, the then NSW Department of Environment, Climate Change and Water issued the *Vapour Intrusion: Technical Practice Note*, which deals specifically with the migration of trace ground gases into buildings, and the consequent risks. There is inevitably some overlap with these broader guidelines, but the two documents should be seen as complementary, with different emphases.

In these guidelines, the term **qualified and experienced professional** is used to describe persons who may undertake specific activities related to the assessment and management of hazardous ground gases. As used here, it is consistent with (and a special case of) its usage in Schedule B2 of the ASC NEPM. The term is also consistent with the description of appropriate qualifications and experience provided in Schedule B9 of the ASC NEPM: in these guidelines, consistent with s4.2 of Schedule B9, 'qualified and experienced professional' implies possession of qualifications that are relevant to, and appropriate experience in, the assessment and management of hazardous ground gases.

In accordance with its Contaminated Land Consultant Certification Policy, the EPA requires that all reports submitted to the EPA to comply with the requirements of the CLM Act be prepared, or reviewed and approved, by a **certified consultant**. This requirement applies to reports dealing with hazardous ground gases. At the time of finalisation of these guidelines, 'certified consultant' means an Environment Institute of Australia and New Zealand *Certified Environmental Practitioner - Site Contamination* (CEnvP SC) or a Soil Science Australia *Certified Professional Soil Scientist - Contaminated Site Assessment and Management* (CPSS CSAM). However, at present neither qualification specifically requires experience with ground gases. The EPA administers operational and recently closed landfill sites under the POEO Act. Other guideline documents – for example, the NSW EPA's *Environmental Guidelines: Solid Waste Landfills* (2016) – apply to licensed landfill sites and also to operational landfill sites that are exempt from licensing under Schedule 1 of the POEO Act.

The NSW Department of Planning, Industry and Environment has published a series of guidelines that address risk assessment for planning and development of hazardous industries. While there is a clear distinction between planning issues relating to new developments and managing legacy sites, there is overlap in the area of risk concepts and risk assessment. Those guidelines are referenced in the text where appropriate and are listed in the bibliography.

2. Origin and migration of hazardous ground gases

2.1 Sources of ground gases

As indicated in Section 1 of these guidelines, ground gases are diverse. Their sources are similarly diverse. While some sources have been predominant in the issues experienced in relation to ground gases in Australia and elsewhere, it is important to recognise the wide range of potential sources, both anthropogenic and natural, that exist. Consultants and other users of these guidelines need to be aware of these sources, so that they can anticipate problems. Tables 1 and 2 list the sources and origins of relevant ground gases in NSW: these sources are discussed in the following sub-sections.

Table 1 Anthropogenic sources and origins of hazardous ground gases

Source	Origin	Methane	Carbon dioxide	Other gases
		Typical concentration range (v/v)		
Putrescible waste landfill	Anaerobic microbial decay of putrescible waste	20–65%	15–57%	Several hundred non-methane organic gases (typically <1% of total volume), some toxic; hydrogen sulfide; potentially mercury vapour
Non-putrescible (inert) waste landfill	Decay of timber, green waste, etc. co-disposed with inert waste (see Section 2.1.2)	20–65%	15–40%	
Coal washery reject (chitter) used as fill	Aerobic and anaerobic microbial decay, spontaneous combustion	0–40%	0–20%	Carbon monoxide if spontaneous combustion occurs
Soils subject to long-term stockpiling	Aerobic and anaerobic microbial decay	0–40%	0–20%	–
General uncontrolled fill	Aerobic and anaerobic microbial decay of materials, such as timber and organic soil, some organic shales	0–20%	0–10%	–
Reclaimed wetlands and mangroves	Anaerobic microbial decay of organic material	10–90%	0–5%	Hydrogen sulfide
Agricultural wastes		60–75%	18–40%	Trace organic gases (generally <1%), some odorous; hydrogen sulfide
Sewers – direct source		60–75%	18–40%	
Sewage leakage into ground		60–75%	18–40%	
Sewage sludge, cess pits		60–75%	18–40%	
Burial grounds, including cemeteries		20–65%	10–40%	–
Chemical and other industrial sites	Tank, pipe and process leaks and spills	30–100%	2–8%	Trace organic gases (VOCs) (generally <1%), some odorous; mercury
Petroleum fuel sites	Tank and pipe leaks and spills	0–20%	0–10%	Hydrocarbon vapours, BTEX (benzene, toluene, ethylbenzene and xylenes)

Source	Origin	Methane	Carbon dioxide	Other gases
Dry-cleaning, electronics sites	Solvent spills and leaks	0–20%	0–10%	Chlorinated hydrocarbon vapours
Foundry sands	Anaerobic microbial decay of waste materials, such as binders and fillers	Up to 50%	15–40%	Trace organic gases (VOCs) (generally <1%), some odorous
Natural gas pipes	Pipe leaks	90–95%	0–9.5% from CH ₄ methane oxidation	Carbon monoxide (0–5%)
Abandoned coal mine workings	Coal seam gas	<1–90%	0–6%	Carbon monoxide (0–10%)
Stress relief following longwall goafing in active mines		<1–90%	0–6%	Carbon monoxide (0–10%)
Coal seam gas exploration and production		90–95%	0–6%	Carbon monoxide (0–10%)
Abandoned wells and oilfield infrastructure	Leaking casing and annular cement seals	90–95%	2–8%	–

Table 2 Natural sources and origins of hazardous ground gases

Source	Origin	Methane	Carbon dioxide	Other gases
		Typical concentration range (v/v)		
Soil	Physical, chemical and biological weathering	<2 ppm	350 ppm	–
Soil	Oxidation of organic matter		0–10%	–
Swamps and wetlands, waterlogged soils	Anaerobic microbial decay of organic material	10–90%	0–5%	Phosphine (PH ₃)
Coal measures strata	Coal seam gas	<1–90%	0–6%	–
Organic shales	Tightly held gas originating from both biogenic and thermogenic processes	60–90%	0–5%	Ethane, H ₂ S
Carbonate strata, including shelly sands	Dissolution of carbonates by acidic groundwater (e.g. due to oxidation of acid sulfate soils)		1–20%	–
Natural gas traps	Leakage	90–95%	2–8%	–
Granite	Radioactive decay of uranium	N/A	N/A	Radon typically <200 Bq/m ³

2.1.1 Putrescible waste landfill sites

The anaerobic biodegradation of putrescible waste in landfill produces methane and carbon dioxide through the fermentation of intermediate products, such as carboxylic acids. Landfill gas varies in composition due to a multitude of variables, including the composition of the waste, the age of the landfill, the moisture content and the temperature. Typically, the gas contains up to 65% methane and 25–35% carbon dioxide.

Other gases associated with landfill gas include hydrogen, nitrogen, hydrogen sulfide and a range of organic compounds, sometimes referred to as non-methane organics, or simply as VOCs. More than 500 substances have been reported in landfill gas (UK Environment Agency 2002). These include:

- higher alkanes and alkenes
- ketones
- cycloalkanes and cycloalkenes
- esters
- monocyclic and polycyclic aromatic hydrocarbons and derivatives
- organosulfur compounds
- organohalogens
- oxygenated compounds
- alcohols
- aldehydes.

While many of these substances are benign or occur at very low concentrations, some have significant toxicity at the concentration range commonly present, and others are odorous. The former include toxic gases, such as chloroethene (vinyl chloride), which may be derived from chlorinated solvents but may also be generated by anaerobic microbial action on polychloroethenes, such as polyvinyl chloride (PVC), in the waste (Smith and Dragun 1984).

Concentration ranges for some of the more significant VOCs and other minor components in landfill gas are listed in Appendix 3.

Used in conjunction with the conceptual site model (CSM) and site history, analytical data for trace gases may assist with identifying the sources of ground gases, as some indicate specific types of landfill and industrial processes. It should be appreciated that imported fill may not have been screened for volatile chemicals, or may have received only basic screening.

An active or recently closed landfill site can produce gas that is under significant pressure – typically 0.3–3 kPa). When a landfill is capped, lateral migration is likely to occur unless the pressure is controlled by gas extraction for power generation or flaring, or venting by some other means. Phased landfilling, compartmentalisation and variable saturation may make it difficult to effectively and uniformly control gas pressures. Landfill gas is a powerful greenhouse gas, as well as being odorous and flammable, so uncontrolled venting to the atmosphere has been discouraged by carbon emissions pricing, the *Environmental Guidelines: Solid Waste Landfills* and, usually, by conditions attached to landfill EPLs.

Many literature sources indicate that a typical putrescible waste landfill passes through a number of well-defined maturation stages, as shown in Figure 1, followed by an exponential decay in the methane generation rate, with little gas generation after periods of around 30 years, as shown in Figure 2. However, this assumes that favourable conditions exist for rapid anaerobic decay. In unfavourable conditions (for example, dry fill, fully saturated fill and putrescible pockets in hard fill), degradation may be slow and the methane generation time greatly extended, albeit at lower rates.

The Australian Government (2008) estimated that 23% of degradable waste remains after 30 years and 11% after 50 years. Therefore, it should not be assumed that a landfill will not produce significant methane just because it is old.

Modelling (using codes such as GasSim) often predicts longer generation times. Logically, under adverse conditions, degradation times become geological. The predicted lives of some UK landfills are greater than 1000 years, and this is also likely to be the case with some NSW landfills.

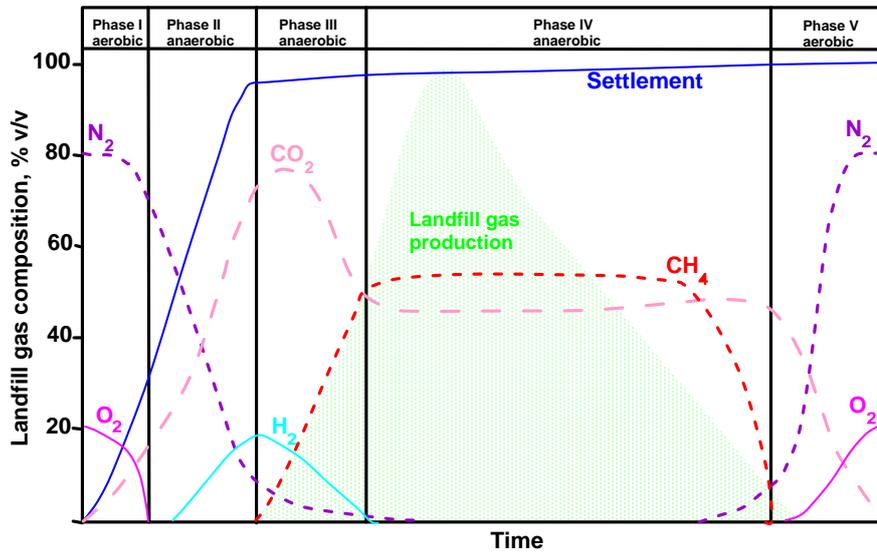


Figure 1 Theoretical stages in landfill maturation

Source: Pohland et al. 1986

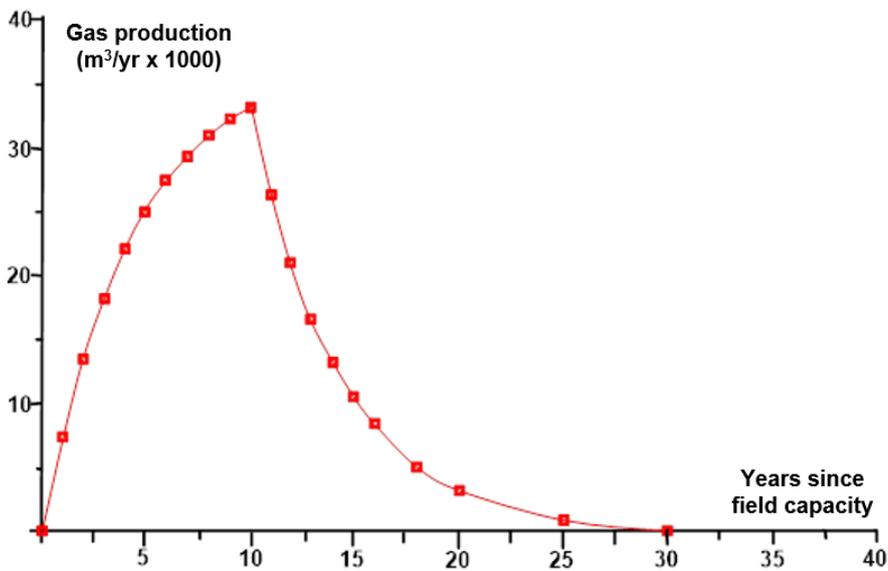


Figure 2 Variation in gas production rate with time

Source: CM Jewell and Associates Pty Ltd

2.1.2 'Inert' waste landfill sites

Most towns and cities in NSW have closed landfill sites that contain so-called 'inert' waste. In Western Sydney, these are commonly located in former shale quarries or brick pits, although valley fills were also used. Inert waste may consist predominantly of building and demolition rubble, excavation spoil and hard wastes, but it almost always contains some timber, paper, green waste and other biodegradable materials. Sometimes inert waste landfills were used for casual or occasional disposal of putrescible wastes, or illegal disposal of industrial waste.

Therefore, inert waste landfills also produce landfill gas, but at a lower rate than putrescible waste landfills. However, because conditions for gas generation are not ideal, it may persist for extended periods. Where waste is deposited below the watertable and there is little groundwater throughflow, as in former brick pits, degradation may be very slow, again extending the gas generation period.

Building and demolition waste frequently contains plasterboard (gyprock) waste, which may generate hydrogen sulfide under anaerobic conditions. Hydrogen may be generated when acidic groundwater reacts with galvanised iron roofing, guttering and pipe waste. A wide range of trace gases may also be present.

2.1.3 General uncontrolled fill

Typically, uncontrolled fill also contains a certain amount of timber, green vegetation and, sometimes, organic soils. Chitter (coal washery reject) has been widely used as fill material in the coalfield areas of NSW, particularly in the Hunter and Illawarra regions. It contains both coal fines and organic shale, and is relatively reactive due to its fine particle size. Occasionally, where conditions permit sufficient oxygen access, spontaneous combustion can occur in the ground, producing carbon monoxide and carbon dioxide. Carbonaceous shale derived from the Triassic and Permian shales of the Sydney Basin is also a common component of fill, including virgin excavated natural material (VENM) fill. It has an organic carbon content of up to 7%, though typically less than 4%. Biotic and abiotic degradation of all of these materials may generate carbon dioxide under aerobic conditions, and both methane and carbon dioxide under anaerobic conditions, but the rate of gas production is generally low. In recently placed fill, the reaction rate may be faster due to the presence of a higher proportion of fresh surfaces. Where the fill is thick or the upper part is well compacted, high gas concentrations can be encountered. These conditions are not usually associated with high gas pressure or sustained flow rates, but flow forced by barometric pumping or groundwater level fluctuations may occur.

2.1.4 Reclaimed wetlands and mangroves

In many coastal and some inland areas of NSW, wetlands and mangrove swamps have been reclaimed by filling. The highly organic swamp peats and mangrove muds remain below the fill and may decay slowly over many years, generating methane and carbon dioxide. Marine and estuarine deposits often contain sulfides, and may release hydrogen sulfide.

2.1.5 Organic waste disposal

Pits used for disposing of any type of organic waste – including agricultural wastes, animal carcasses, shed litter and sewage sludge – can be very effective biogas generators.

2.1.6 Abandoned coal mine workings

Coal seams contain methane within cleats in the coal, and this methane is adsorbed onto the coal. Any type of coal working is likely to release methane, which may oxidise within mines to produce carbon monoxide and carbon dioxide.

Abandoned, shallow, bord and pillar workings lie beneath many areas around Newcastle. Shafts, adits and zones of fractured rock may allow methane to migrate from such old workings. Methane migration may be enhanced following atmospheric pressure changes or rises in water level within partially flooded workings.

Gas migration may also occur as a result of stress relief following goafing in active longwall mines, and has been reported in connection with coal seam gas extraction operations in other parts of the world.

2.1.7 Other anthropogenic sources of methane and carbon dioxide

Other anthropogenic sources listed in Table 1 include gas pipes, sewers, burial grounds, and petroleum and coal seam gas exploration and production operations.

2.1.8 Natural sources of methane and carbon dioxide

Potential natural sources of methane and carbon dioxide include natural swamps and wetlands, organic soils, natural release from the Permian coal measures within the main sedimentary basins of eastern NSW, and natural release of carbon dioxide from carbonate rocks along the Great Dividing Range. Shelly sands with a high calcium carbonate content are common along the NSW coast, but the carbonate dissolution equilibrium is controlled by the atmospheric partial pressure of carbon dioxide in the shallow, unconfined aquifers generally formed by these sands, such that there is no net release of this gas. This is not the case where a strong acid is present as a product of other geochemical processes, such as the oxidation of acid sulfate soils. Section 2.2.4 discusses the solution and exsolution of ground gases from groundwater.

2.1.9 Sources of hydrogen sulfide

Hydrogen sulfide is likely to be formed whenever sulfur compounds are subject to reducing conditions. In addition to the natural sources mentioned in Section 2.1.4, sewers, stormwater drains and pits, and landfilled plasterboard may be sources of hydrogen sulfide.

2.1.10 Sources of VOC vapours

VOC vapours may be an issue on and adjacent to former industrial or commercial land where soil or groundwater contamination has occurred as a result of chemical release to the sub-surface. Most known occurrences involve volatile petroleum fuels released at service stations and fuel depots, or chlorinated solvents, which are used in numerous industries, most notably dry-cleaning. Odorous organosulfur compounds and hydrocarbon vapours may be associated with former gasworks sites.

2.1.11 Sources of mercury vapour

Historically, the largest industrial use of mercury was as an electrode in the Castner–Kellner chloralkali electrolytic process for chlorine production. Former chloralkali plants can be significantly contaminated by mercury and mercury vapour. The formerly widespread use of mercury in laboratory and medical instruments, switches, rectifiers and gold mining has resulted in localised contamination on many former industrial and commercial sites.

2.1.12 Sources of radon

Naturally occurring radon 222 is a significant health hazard in some parts of the world. However, this does not appear to be the case in NSW. Survey work by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) (1990, 2011) did not identify average indoor air concentrations of radon above the action level of 200 becquerels per cubic metre (Bq/m³) in any area in NSW, and nationally fewer than 0.1% of homes exceeded the action level. The highest measured concentrations in NSW and Victoria were in areas along the Great Dividing Range. Rocks of the Lachlan Fold Belt, including numerous granitic plutons, underlie these areas.

In the context of redeveloping contaminated land, radon 220 may be formed during the decay of thorium 232 in some areas along the NSW coast where tailings generated during mineral sand dredge-mining operations have been deposited. However, the half-life of this radon isotope is so short (less than a minute) that there is little point in considering it separately from its thorium parent.

2.2 Migration and behaviour of hazardous ground gases

2.2.1 Migration mechanisms

Ground gases may migrate from a source to a potential receptor either in the gas phase or dissolved in groundwater. In the gas phase, the two mechanisms of migration are advection and diffusion.

2.2.2 Advection

Advection is pressure-driven flow. It requires a pressure differential (pressure gradient) that may arise from generation of gas at the source (as with landfill gas), release under pressure (in the case of a pipe leak) or barometric pressure fluctuations (known as barometric pumping). The rate at which flow can occur is controlled by:

- the gas permeability of the soil or rock
- the thickness of the available flow path (often the depth to the groundwater or a low permeability stratum)
- the water saturation of the soil (because water reduces the pore space available for gas migration)
- the pressure gradient.

Barometric pumping can significantly affect the migration of ground gas into buildings. When barometric pressure drops rapidly, particularly for large drops of around 20 hPa, it may be several hours before pressure in the ground responds to the changed condition. This causes a significantly enhanced pressure gradient between the ground and surface, and between the ground and indoor air spaces.

Fluctuations in groundwater level and, in coastal environments, tidal fluctuations may also initiate pressure-driven flow.

Mechanical ventilation systems, thermal convection (known as the stack effect) and wind flow around buildings may result in reduced air pressure within basements and ground floors, and therefore generate an inward pressure gradient.

2.2.3 Diffusion

Diffusion is flow along a concentration gradient, from areas of high concentration to areas of low concentration. The rate at which diffusion can occur is controlled by:

- the diffusion coefficient of ground gas
- temperature
- the thickness of the available flow path
- the water saturation of the soil
- the concentration gradient.

Diffusive flux is usually much lower than advective flux, but in some situations, diffusion can be the dominant migration mechanism. Diffusion is a particularly significant mechanism for VOC, mercury vapour and radon gas intrusion to buildings.

2.2.4 Dissolved phase transport

Many ground gases are soluble in groundwater and can migrate with flowing groundwater. The solubility of all gases in water increases with rising pressure, and decreases with rising temperature, as shown in Figures 3 and 4. For example, as shown in Figure 3, methane has a solubility of about:

- 23 mg/L at a temperature of 25°C and a partial pressure of 101 kPa, or 1 atmosphere (atm)
- 15 mg/L when the partial pressure is 66 kPa, as may be the case in landfill
- 4.22×10^{-5} mg/L in equilibrium with the current atmospheric partial pressure of methane, which is 1.22×10^{-4} kPa (1.87 ppm).

Therefore, almost complete exsolution may occur.

It is possible for this mechanism to generate high concentrations in soil gas above the watertable (partitioning is reversible, so the equilibrium soil gas concentration is the same as the partial pressure in the source). However, mass transport rates are a function of groundwater flow rates and are likely to be low in most aquifers.

This mechanism may become more significant when considering geological sources at great depths and high pressures because, as shown in Figure 3, gases are much more soluble under these conditions.

Many gases dissolve in water, and the exsolution behaviour of gas mixtures is more complex. If the methane concentration exceeds 5% by volume of the gases dissolved in groundwater, and the sum of these gas partial pressures is greater than the atmospheric pressure, there is potential for methane to outgas and reach or exceed the LEL in a confined space when in contact with groundwater. In terms of concentration, a minimum partial pressure in excess of 5 kPa would be required, equivalent to a dissolved-phase concentration of approximately 1600 µg/L (Goody and Darling 2005, Hooker and Bannon 1993).

In a NSW context, concentrations in excess of this value have been measured in investigations associated with tunnelling projects in areas where there has been a history of landfill.

Dissolved-phase transport in groundwater may also be a significant factor in the lateral migration of VOCs.

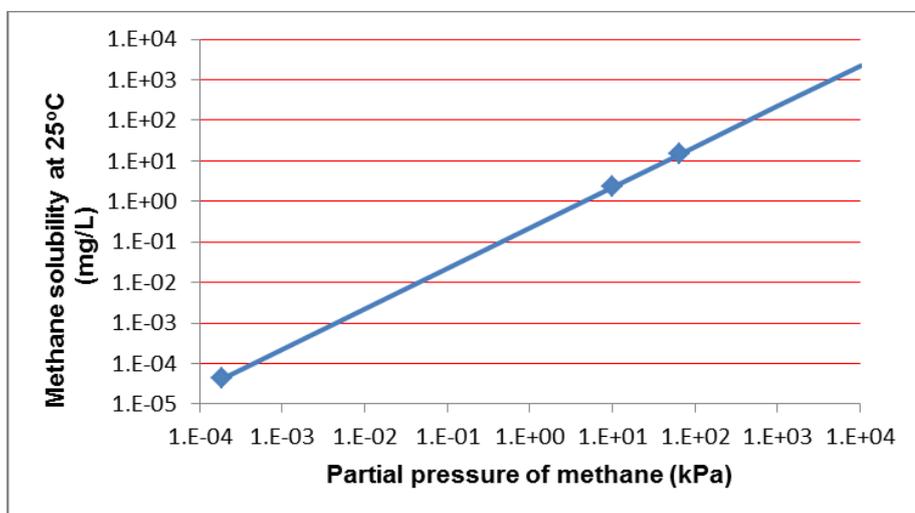


Figure 3 Variation in methane solubility in water with pressure

Source: CM Jewell and Associates Pty Ltd, based on a Henry's law coefficient of $1.4 \times 10^{-5} \text{ mol.m}^{-3}.\text{Pa}^{-1}$

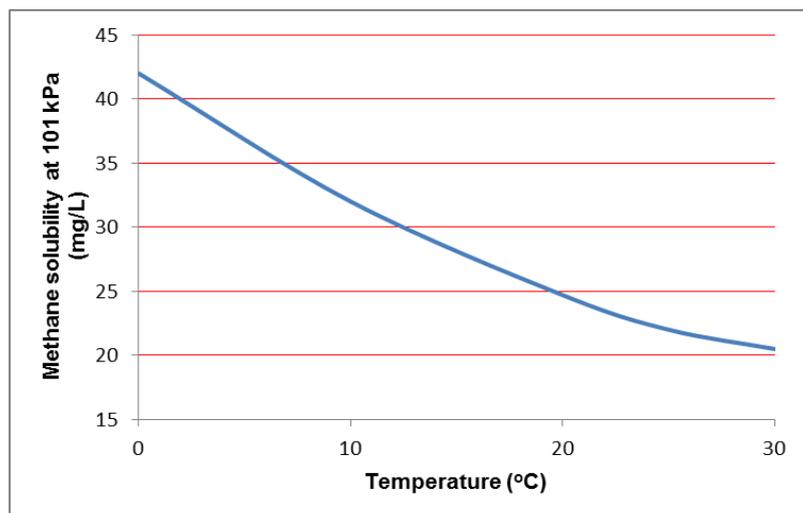


Figure 4 Variation in methane solubility in water with temperature

Source: CM Jewell and Associates Pty Ltd, based on data from Yamamoto et al. (1976)

2.2.5 Other meteorological factors

Migration of ground gases may be influenced by meteorological conditions other than atmospheric pressure.

Rainfall

Rainfall may temporarily saturate the ground surface or the upper part of the soil profile, reducing its capacity to vertically release ground gas into the atmosphere, and encouraging lateral migration. Where the rainfall is sufficient to generate groundwater recharge and cause a rise in the watertable, ground gas may be pressurised by the piston effect, enhancing its rate of migration.

Wind

Pressure gradients may also be formed by the action of the wind on the ground surface, particularly around small topographic features, and around buildings and structures. Wind generates differential pressure between the upwind (high-pressure) and downwind (low-pressure) sides of an obstruction, and complex eddy effects may also occur. These differential pressures may result in ground gas migration, but they may also be harnessed to vent ground gases from buildings.

Temperature

Diurnal temperature variations generally penetrate to only a shallow depth below the ground surface. They may affect the pressure/volume and relative buoyancy of ground gases.

2.2.6 On-site generation and attenuation

Methane, carbon dioxide and other ground gases may also be generated by the decay of organic matter in groundwater contaminated by, for example, landfill leachate or sewage that flows beneath the site.

Methane, carbon monoxide, petroleum vapours and many VOCs, including BTEX (benzene, toluene, ethylbenzene and xylenes) compounds and vinyl chloride, may be chemically or biologically attenuated by oxidation in the soil profile, provided that atmospheric oxygen can gain access to the soil profile at a rate comparable to the inward or upward migration of the ground gas. Some other VOCs, however, are not readily oxidised. See Davis et al. (2009a) and CRC CARE (2013) for a comprehensive description of these processes.

2.2.7 Intrusion into buildings

Ground gases become most hazardous when they intrude into buildings and structures, such as utility access pits and inspection chambers, where they can accumulate at explosive or toxic concentrations, or form an asphyxiating atmosphere. Confined spaces, small rooms and service cupboards are of particular concern. A 'parcel' of gas that has a lower or higher density than air and intrudes into a building may, if circumstances permit, maintain its integrity and accumulate preferentially in higher or lower parts of the building, respectively. However, it is important to recognise that once an intruded gas mixes with the ambient air in a building, it cannot re-segregate.

Where an active source is present, migration and intrusion of bulk ground gases into buildings is generally advective (pressure-driven). In the absence of a nearby source, diffusion may be the dominant process. Conversely, while diffusion is often the primary mechanism for trace ground gas intrusion into buildings, pressure-driven flow may occur due to stack effects, wind-driven pressure gradients and the operation of lifts in shafts.

Ground gas intrusion pathways into buildings are highly dependent on building design and condition. For slab-on-ground construction, cracks, service penetrations and poorly filled construction joints provide the most likely pathways. Cavity wall vents may also allow ingress, particularly where convective currents occur due to a stack effect. Preferential pathways formed by piles, service ducts and trenches, lift shafts, sumps and drains are frequently present.

There is a wealth of literature dealing with trace ground gas (vapour) intrusion into buildings. For more comprehensive guidance, see Interstate Technology and Regulatory Council (2007) (cited in 'Suggested

further reading' in these guidelines); NSW Department of Environment, Climate Change and Water (2010) (cited in 'Relevant NSW legislation, regulation and guidelines'); CRC CARE (2013); Wilson and Mortimer (2018); and Oregon Department of Environmental Quality (2010).

2.2.8 Comparative ground gas hazards

There are significant differences in the hazards posed by toxic trace ground gases, such as VOCs and mercury vapour, and those posed by bulk ground gases, such as methane and carbon dioxide. Table 3 summarises these differences. They determine the priorities for site assessment and characterisation discussed in Section 3.

Table 3 VOC hazards compared to methane and carbon dioxide hazards

VOCs	Methane and carbon dioxide
Fixed source mass	No fixed source mass; continuous generation
Transport via diffusion is main concern, with convective effects important near buildings	Transport via advection is main concern, but other mechanisms (including diffusion) may also be important
Chronic toxicity risk	Acute explosion or asphyxiation risk, and acute toxicity in some cases
Risk assessment focused on modelled long-term average concentrations	Risk assessment focused on measured short-term maximum concentrations and flow rate. Flow rate is as important as concentration

Later sections of these guidelines refer to 'source strength', which is a qualitative measure that considers the concentration of ground gas present, flammability, toxicity, pressure and the likelihood of generation continuing.

3. Site assessment and characterisation

Any consideration of the risks associated with ground gases, however preliminary, needs to be based on an understanding of site conditions. The depth of understanding required will depend on the level of risk assessment being carried out.

As with any land contamination assessment, a staged approach is recommended to maximise the effectiveness of the work and minimise its costs. As is also the case for other types of contaminated land assessment in NSW, the Data Quality Objectives (DQOs) process should be applied from the outset to identify objectives, plan site investigations, and ensure the assessment obtains data of an adequate quality to satisfy objectives. A weight-of-evidence approach, using multiple lines of evidence, is recommended. Early development of a CSM and progressive refinement of that model through compiling the results of a range of investigations are essential components of the site assessment process.

The approach outlined in this section is consistent with that described in sections 2 to 6 and 9 of Schedule B2 of the ASC NEPM and with the reporting process set out in the latest version of the guidelines for consultants reporting on contaminated sites on the NSW EPA website: www.epa.nsw.gov.au/your-environment/contaminated-land/statutory-guidelines.

Sections 3.1 to 3.5 of these guidelines (i.e. on hazardous gases) are relevant to both bulk and trace ground gases. When dealing specifically with trace ground gases, these sections should be read in conjunction with Sections 9.2 to 9.5 of Schedule B2 of the ASC NEPM.

Section 3.6 of these guidelines deals with bulk ground gases and trace ground gases in separate sub-sections.

As is evident from the information provided in Section 2, with the exception of mercury vapour and vapours derived from petroleum hydrocarbons and other VOCs, hazardous ground gases may be of natural as well as anthropogenic origin. While anthropogenic sources may predominate within the context of contaminated land management, these guidelines focus on managing risk, meaning natural sources cannot be excluded from assessment and management requirements. As is the case with naturally occurring asbestos and acid sulfate soils, the hazard becomes a risk largely as a result of human intervention. Effective risk management requires an understanding of the sources of hazardous ground gases, and that understanding is often not possible until an investigation has been carried out. The risk must be managed regardless of the source if a development is to proceed safely. While there may be some distinction in this respect between the objectives of these guidelines and those of the *Environmental Guidelines: Solid Waste Landfills*, these guidelines are consistent with the objects of the CLM Act.

3.1 Desk study

Typically, a desk study involves compiling available information about the historical development and current use of a site and its surrounding area, together with existing data concerning the site's geology and hydrogeology.

The usual sources of this information are historical aerial photography and site photography, site plans, architectural and construction plans, utility service drawings, Google Earth or SIX Maps (public domain) or Nearmap (commercial) imagery, local council records, mine working plans, geological and topographical mapping, and the results of previous site investigations.

In ground gas assessment, historical information for adjacent off-site areas – focusing on extractive industries and waste disposal practices, as well as the storage and use of fuels and solvents – is particularly important and worth any extra effort required to identify and obtain it.

It is important to consider the overall geological setting of the site, including the deep geology; this normally involves reviewing geological mapping and any data that may be available from previous environmental or geotechnical investigations of the site or adjacent properties. In mining areas, historical mine plans (available through DIGS at <https://search.geoscience.nsw.gov.au>) should be consulted.

Meteorological data are required for planning and interpreting ground gas site investigations, and should be accessed at an early stage. As discussed in Section 2.2, pressure, temperature, wind and rainfall data are relevant. The Bureau of Meteorology website (www.bom.gov.au) provides easy access to most of the data likely to be required; other data can be obtained on request.

An initial CSM – including a plan, cross-section and written notes about potential sources, pathways and receptors – should be prepared, based on the desk study.

3.2 Reconnaissance

A site reconnaissance or walkover is essential, and is likely to be most valuable if carried out once basic information about the site has been collated. In addition to allowing the current site conditions and management practices to be observed, it provides an opportunity to view the surroundings, and to discuss past practices with site employees.

The condition of buildings and pavements can usually be readily established during a site reconnaissance, and the presence of stressed vegetation may indicate gas emissions.

3.3 Initial conceptual site model

The initial CSM should be developed before undertaking a ground gas investigation to ensure the sampling plan considers the factors influencing the vapour intrusion pathway and potential exposures. The initial CSM should include a site-specific explanation of the potential gas sources (on-site and off-site), gas migration and intrusion pathways, and attenuation processes. The CSM should take the form of a concise text description and must be supported by figures, including both plans and cross-sections.

The CSM must include information about:

- geology, soil stratigraphy and hydrogeology, particularly noting the presence of fill materials and layers in the stratigraphy with high and low permeability (including fracture permeability), the depth to groundwater and the height of the groundwater capillary fringe
- outcrops of potentially transmissive horizons
- contact between potentially transmissive horizons and tidal water bodies
- physical characteristics of the soils (including moisture content, bulk density, grain size, total porosity and the fraction of organic carbon)
- potential sources of hazardous ground gas on and near the site, including the:
 - type of ground gas anticipated
 - distance to the source
 - depth to the source
 - source age
 - physical and chemical properties of each ground gas
- current or proposed buildings on the site and their use, including the:
 - size and type of construction (slab-on-grade, crawl spaces and basements)
 - condition of buildings and pavements
 - presence of ventilation or heating and cooling systems and other relevant information that may affect the air exchange rate
 - rate of exchange between indoor and outdoor air (that is, the tightness of the construction), including room connectivity and any through-slab piping
 - location and structure of utilities and other potential preferential migration pathways for ground gas (such as lift wells, and sewer and stormwater lines)
 - characteristics of any confined spaces
- potential receptors
- likely transport mechanisms operating between the source and receptors
- likely attenuation mechanisms along lateral and vertical transport pathways
- environmental conditions (including rainfall, barometric pressure, wind speed and direction, and temperature).

Where necessary, initial estimates can be made and refined later by adding site-specific data.

The initial CSM is a critical step in understanding site conditions and potential pathways and links. It helps identify data gaps and uncertainties, and assists in planning an investigation to address these gaps.

3.4 Site investigation

A ground gas site investigation should be planned, and its DQOs established, based on the understanding of the site derived from the CSM. The broad objective of an investigation is to provide the data required to establish the risk that ground gas poses to the existing or proposed future use of the site. Depending on the robustness of the original CSM, a Level 1 (qualitative) risk assessment may have already been completed, so that the data are required to support a Level 2 risk assessment.

As with other types of environmental investigation, the planning and DQO processes should be documented in a sampling, analysis and quality plan. The ground gas investigation may be a standalone project, or may be carried out as part of a broader Phase 2 environmental site assessment or geotechnical investigation.

More detailed guidance is provided in Davis et al. (2009b).

3.4.1 Specific objectives

The specific objectives of a ground gas investigation may include:

- confirming geological and hydrogeological conditions using intrusive sampling and testing, emphasising aspects (such as lithology, structure and permeability) likely to influence gas generation and migration
- establishing whether gas is migrating onto the site by monitoring potential off-site sources of ground gas identified in the CSM
- confirming, where possible, the sources of ground gas encountered on the site
- establishing the lateral and vertical extent of the ground gas sources, and the extent of ground gas migration
- measuring gas composition and concentration in the sources
- assessing whether gas is present in indoor and confined spaces (such as sumps, drains, culverts and service trenches) and, if so, its concentration
- assessing the continuity (or otherwise) and permeability of potential migration pathways
- providing any other data necessary to resolve gaps in the CSM
- constructing an adequate number of permanent gas monitoring points to cover the site and potential pathways
- constructing and sampling groundwater monitoring wells, if required
- providing the gas concentration and gas flow data required to calculate a gas screening value and complete a Level 2 risk assessment, as described in Section 4 of these guidelines
- assessing the influence of a full range of weather conditions on gas concentrations and flow rate
- refining the CSM.

3.4.2 Investigation methodology

While an investigation may include surface flux measurements and active or passive sampling of indoor and confined spaces, it is likely that boreholes will be the mainstay of an intrusive investigation. Boreholes are used both for geological investigation and to construct gas and groundwater monitoring wells. For most purposes, the term 'borehole' may be taken to include relatively shallow drilling through concrete slabs to enable the installation of sub-slab gas monitoring points. The location of boreholes will be influenced by access constraints, and is a matter of professional judgement, based on interpretation of the CSM. However, the following points should be considered.

- Where the source is accessible, boreholes should be drilled in central locations to assess the worst-case conditions, and peripheral locations to confirm the extent of the source.
- Boreholes should be drilled on site boundaries, or off-site if necessary, to assess potential migration pathways, and at least some of them should extend to the full known depth of the source³ (excluding mines and deep geological sources). Where site development or redevelopment is proposed, the depth of investigation should also take into account the actual or proposed construction methods, such as piling.
- Shallow boreholes, drilled close to occupied buildings that cannot be accessed directly, may be used to estimate potential exposure-point concentrations. However, it must be recognised that concentrations beneath large slabs may be higher than those beneath open areas, and individual exterior soil gas samples cannot generally be expected to accurately estimate sub-slab or indoor air concentrations (US Environmental Protection Agency 2015a, Patterson and Davis 2009). This issue is discussed in more detail in Section 4.4.3 of these guidelines.
- When buildings are accessible (for example, on an industrial site) boreholes may be drilled within them.

The number and density of boreholes required on a particular site will also be a matter for professional judgement. It should take into account the sensitivity of the actual or planned site use, the nature of the gas source, the heterogeneity of ground conditions and the robustness of the CSM.

Depending on the ground conditions at a particular site, a range of drilling techniques may be used in ground gas assessments. Conventional and hollow-stem auger drilling may be used, but sonic and direct-push techniques can deliver higher productivity and much better sample recovery when conditions are favourable. Membrane interface probes (MIPs) on direct-push equipment allow rapid initial estimates of the variation of ionisable gas concentrations with depth. This information can be used to guide screen placement for gas monitoring wells and to assess multiple lines of evidence.

Ground gas investigations must extend to the base of potential source zones³, or migration pathways identified in the CSM or by MIPs.

Detailed borehole logs should be prepared; on-site soil materials should be described using the Unified Soil Classification System (USCS); and rock should be described on the basis of lithology, any apparent structure and stratigraphic provenance.

See Davis et al. (2009b), CRC CARE (2013) and BS 8576:2013 for further guidance concerning site investigation methods.

3.4.3 Groundwater and gas monitoring wells

Although other materials may be used where circumstances require it, both groundwater and gas monitoring wells will generally be constructed of screw-jointed unplasticised PVC pressure pipe. This material is suitable for most installations, is readily available from several suppliers in NSW and is widely used for constructing groundwater monitoring wells. Standard screen sections have 0.4-mm factory-cut slots, although other dimensions are available. Most outdoor installations can use a standard pipe diameter of 50 mm. It may be necessary or advantageous to use a pipe with a smaller diameter for some purposes, such as to install an effective seal in shallow wells with limited space. Stainless-steel implants on 6-mm polyethylene or Teflon tubing are often used for sub-slab gas concentration monitoring. (Note that these are not suitable for borehole flow-rate measurements).

Screens should be placed thoughtfully across the permeable horizons of interest, and be appropriately gravel-packed. Where MIPs have identified vertical stratification of gas concentrations or multiple pathways, or where these are otherwise deemed likely, multiple wells screened at different depths or multi-port wells should be installed. Multiple wells should also be installed to avoid connecting potential gas sources (such as thick layers of fill material) with high-permeability horizons that may be subject to pressure fluctuations due to barometric or tidal effects. It may not be necessary to install multiple wells at all locations, but the proportion should be sufficient to allow unambiguous interpretation of all site data.

³ In this context, 'source' refers to the source of bulk or trace gases in the vadose zone and not to an ultimate source as dissolved or NAPL in the saturated zone.

For both gas and groundwater monitoring wells, it is extremely important to place sound bentonite pellet or grout seals in the annulus between the standpipe and the borehole wall. If pellets are used, they should be adequately hydrated by pouring water into the annulus above the pellets. Without effective seals, gas monitoring wells are useless, so leak testing is recommended. A review of the performance of different types of seals, which supports the use of bentonite pellets over alternative grout systems, is available (Olafsen-Lackey et al. 2009).

Gas monitoring wells should be fitted with a cap tapped to take a quick-connect nipple (or a manual valve and nipple) that seals the well and allows easy connection to a measuring instrument.

Generally, and preferably, the primary function of a well will be either gas or groundwater monitoring, and the well will be designed accordingly. Although not preferable, dual-purpose wells are possible, provided that neither function is compromised (as it will be in many situations). In particular, screen placement must allow both water and gas to enter the well over the full range of water levels. Partitioning effects and the potential effects of groundwater fluctuations on gas pressure and flow must also be considered.

3.4.4 Surface emission measurements

Gas emissions may be measured at the ground surface using a walkover approach and portable measuring equipment (NSW Environment Protection Authority 2016a).⁴ This typically, but not necessarily, involves using a flame ionisation detector and GPS units linked to a dual-channel data logger. This method is frequently used to assess the integrity of capping on both active and disused landfills, but may be adapted to other gas sources if required. The measurements may be affected by meteorological conditions (particularly fluctuations in barometric pressure and temperature), soil moisture and gas oxidation within the soil profile. This method is not routinely used for ground gas investigations but may be appropriate in some circumstances (for example, when investigating vegetation dieback or VOC emissions on former landfill sites that have been redeveloped for recreational use, to assess the integrity of a compacted soil barrier and as part of a weight-of-evidence approach on complex sites).

Surface emissions may also be measured using a flux chamber (flux box). Static or dynamic chambers may be used, and each has advantages and disadvantages. Flux chamber measurements are most useful when applied as part of a weight-of-evidence approach, and in conjunction with borehole methods to assess ground gas discharge to open ground (where the surface will remain open following development) or through paved surfaces that are in poor condition. Flux chamber measurements may be affected by meteorological conditions, particularly:

- antecedent rainfall, which may reduce the air-filled porosity and therefore both the gas permeability and diffusivity of surface soils
- barometric pressure fluctuations, which may increase or decrease the advective component of gas flux.

More detailed information is provided in Davis et al. (2009b) and in Appendix 4.

Large flux chambers may be used to assess the flux of bulk ground gases, as described by CIRIA (2007)⁵ and the UK Environment Agency (2010). The latter reference provides guidance on how to construct or improvise such flux boxes, take measurements and calculate gas flux.

3.4.5 Gas sampling and measurement techniques

Detailed guidance on gas monitoring and sampling, including field measurement and sampling equipment and appropriate quality assurance and quality control (QA/QC) requirements, is provided in Appendix 4.

⁴ Section 5.4, pp. 33–4.

⁵ Section 5.4, pp. 57–8.

Depending on the gases being assessed, concentration measurements may be taken using field instruments, or samples may be obtained using sorbent tubes or SUMMA canisters and submitted for laboratory analysis. Standard QA/QC protocols should be applied and data quality indicators assessed.

Field instruments are usually used to measure bulk ground gas concentrations, pressure and flow rates in boreholes, and gas concentrations in flux chambers and during surface surveys. Initial, maximum and steady gas concentrations – and, for borehole measurements, pressure (internal and external) and flow rate – are recorded. Alternatively, equipment recording to a data logger at specified intervals may be used. The essential field measurements for calculating and assessing borehole flow rates for bulk ground gases are the:

- static gas pressure in the borehole
- dynamic gas pressure at the sampling flow rate
- atmospheric pressure
- differential pressure
- combined gas flow rate
- concentration (as %v/v) of each hazardous ground gas.

These measurements are equally important for evaluating site conditions and assessing risk.

Sampling and laboratory analysis, rather than field measurements, are generally used for trace ground gases, and may be used to ensure bulk gases meet specific requirements, such as assessing time-averaged indoor air concentrations.

Dissolved-phase VOC concentrations in groundwater may be used for risk assessments of trace ground gases, as described in Section 4.4.4.

3.4.6 Duration of gas monitoring

Determining a gas screening value and characteristic situation (as described in Section 4.3.4) requires, at a minimum, assessing borehole flow rates and hazardous gas concentrations from an appropriate number of monitoring locations over an appropriate number of monitoring rounds. These should include measurements taken during falling atmospheric pressure. The number of monitoring locations and duration of monitoring should be selected based on the site, depending on the sensitivity of the site use, the ground gases of concern and the source's gas-generation potential. These guidelines are not intended to be prescriptive in this respect; professional judgement is required, based on a sound CSM, the DQOs, and an understanding of monitoring methods and their limitations. Such decisions must be fully justified in the relevant reports.

For bulk ground gases and moderate-sensitivity development (equivalent to the 'residential use with minimal access to soil' exposure setting), CIRIA (2007) recommends between six and 12 monitoring events extending over two to 24 months (unless the source's gas-generation potential is very high). However, CIRIA indicates that the key requirement should be to capture the worst-case meteorological scenario. Because NSW has relatively infrequent, slow-moving weather systems compared with the UK, a longer period of monitoring for each risk setting is likely to be required to capture the worst-case scenario.

Continuous monitoring equipment is available to measure gas concentrations and pressure in boreholes, concentrations in ambient air and atmospheric pressure (Appendix 4). Using this type of equipment may reduce the number of monitoring events and the overall length of the monitoring period required, compared with an event-based monitoring program. It may also capture transient barometric pressure events that would otherwise be missed. However, specific knowledge and experience are often required to validate the data. The equipment is also expensive, meaning site security may be an issue.

For Australian conditions, a worst-case meteorological scenario can be estimated from the fifth-percentile three-hour pressure decrease rate for the site, based on a two-year dataset for the nearest Bureau of Meteorology site with continuous pressure recording.

BS 8576:2013^{6,7} adopts a somewhat different approach, stating that:

Gas monitoring does not necessarily need to be carried out under worst case conditions. It does not necessarily need to be at low or falling atmospheric pressure, but rather should be continued until it is unlikely that additional data will change the interpretation of the data, the outcome of the risk assessment and proposed remedial actions. This requires continued assessment of data as the monitoring progresses. One of the main considerations is to assess whether gas flow rates or concentrations could possibly increase and thereby affect the risk assessment and hence the choice of protective measures.

BS 8576:2013⁸ also provides a framework for assessing the sufficient duration for gas monitoring.

A shorter period of monitoring may suffice for trace ground gases that are assessed for risk using chronic toxicity and reasonable maximum long-term exposure (RME) estimates, provided that these capture a range of meteorological and any other relevant conditions sufficient to estimate the RME. CRC CARE (2013) provides specific guidance on the number of sampling events required for petroleum vapour intrusion monitoring based on the margin of safety between the highest measured concentration and the screening-level guideline.

These guidelines are not intended to be prescriptive in this respect. Consistent with the general approach to contaminated land assessment adopted in NSW and nationally, professional judgement is required, based on a sound CSM and the sensitivity of the proposed site use. Such decisions must be fully justified in the relevant reports.

3.4.7 Other monitoring

Existing or newly constructed structures on a site may provide an opportunity for additional ground gas monitoring that will add to the information available about a site. This may prove useful in a weight-of-evidence approach. Such structures may include trenches, drains, sumps and inspection pits. At least in the first instance, such monitoring would be carried out using field instruments, such as a flame ionisation detector, or both a landfill gas meter and a photoionisation detector. A written and photographic record of monitoring locations should be made at the time of monitoring. From a site assessment perspective, a single round of monitoring supplemented by a follow-up to check anomalies will likely suffice. Ideally, this work should be carried out in conditions where barometric pressure is falling, and early in the day.

Additional monitoring to comply with the requirements of the Work Health and Safety Regulation 2017, as described in Section 5.2.3, may be required.

3.5 Refined conceptual site model

Following site investigation, the CSM should be refined to incorporate the results of the investigation. It is possible, indeed likely, that some initial assumptions may need to be changed based on the data acquired. As with the initial CSM, the refined model should be reviewed, and any outstanding data gaps identified. Additional investigation should be planned to fill these gaps as part of an iterative process of data acquisition and review.

3.6 Site characterisation

3.6.1 Preferred approach

Site characterisation to determine the impact of hazardous ground gases should be based on progressive refinement of the CSM, consideration and evaluation of all the available lines of evidence,

⁶ It is understood that, at the date these guidelines were issued, BS 8576:2013 was under review.

⁷ Section 8.6 and Annex F.

⁸ Annex F, Table F1.

and application of the multi-level risk assessment approach outlined in Section 4. This approach is preferable to simple comparison with assessment criteria.

However, these criteria are listed in the following sections for a number of reasons:

- some mandatory criteria apply for sites regulated under the POEO Act, and these criteria may be regarded as notification criteria (from a public safety perspective) in other circumstances
- there are established vapour intrusion screening criteria for VOCS – ASC NEPM health investigation levels (HILs)
- there are indoor air criteria for radon.

3.6.2 Bulk ground gas assessment criteria – sites subject to an EPL

The NSW EPA (2016a) *Environmental Guidelines: Solid Waste Landfills* apply to landfill sites regulated under the POEO Act. The *Environmental Guidelines: Solid Waste Landfills* specify minimum standards for the design, construction, operation, reporting and post-closure management of landfill sites. Gas management is regulated within that context.

Most active landfills are regulated by a NSW EPA EPL issued under the POEO Act. When landfills close, the NSW EPA usually continues to regulate them under the POEO Act until stabilisation criteria and other criteria (such as for leachate management) are met.

The following criteria for gas management are provided within *Environmental Guidelines: Solid Waste Landfills*:

Sub-surface monitoring criterion (off-site migration)

The threshold levels for further investigation and corrective action are detection of methane at concentrations above 1% (v/v) and carbon dioxide at concentrations of 1.5% (v/v) above established natural background levels.⁹ ... If methane is detected at concentrations above the threshold level, the occupier must notify the EPA promptly.

Surface emission criterion

The threshold level for further investigation and corrective action is 500 ppm v/v methane at any point on the landfill surface for intermediate and finally-capped areas.

Gas accumulation criterion – enclosed structures (Section 5.4)

The threshold level for further investigation and corrective action is detection of methane at concentrations above 1% (v/v). ... If methane is detected at concentrations above the threshold level, the occupier must notify the EPA within 24 hours.

Criteria to show that the landfill is stable and non-polluting post-closure, demonstrated in a certified statement of completion (Section 10.2)

- *Gas concentration levels in all perimeter gas wells are less than 1% v/v methane and less than 1.5% v/v carbon dioxide above the established natural background for a period of 24 months.*
- *The methane concentration at the surface of the final capping should not exceed 500 ppm.*

Section 148 of the POEO Act also imposes a general obligation to immediately report to the NSW EPA and other relevant authorities any pollution incidents causing or threatening material harm to the environment. Further details are provided in Section 6.2 of these guidelines.

⁹ NSW EPA (2016a) has not adopted the approach recommended in the UK industry guidance document, *Perimeter soil gas emissions criteria and associated management* (C&P Environmental Ltd 2011), that no compliance limits should be set for carbon dioxide because 'carbon dioxide is a poor choice of gas to regulate emissions from landfills because there are alternative sources in the sub-surface environment'.

Requirements for development on closed landfills (Section 10.3)

- *The landfill should meet the EPA's stabilisation criteria for reduction in leachate strength, stormwater contamination and gas levels ... The gas criteria are particularly important for developments that create enclosed spaces where gas can accumulate or migrate (e.g. buildings, basements, manholes, tunnels, service ducts, stormwater and sewer pipes). These criteria may be less critical in the case of open developments: sporting fields, golf courses and car parks are sometimes created over recently closed landfills.*
- *The development should not compromise the functioning of the environmental controls at the site. Any proposed encroachment into the landfill (e.g. footings, piling or utilities) should not compromise the integrity of the landfill capping, lining and gas collection systems. The development should not impede drainage of rainfall off the cap. Constructed water features such as ornamental ponds should be avoided on landfill caps ...*
- *The risk of gas accumulation in any enclosed spaces within the development should be appropriately managed through design measures such as venting systems, sub-floor systems, gas barrier systems and other measures for managing sub-surface gas migration.*
- *The former landfill must be structurally and geotechnically sound for the proposed development. Settlement and slope stability analyses should be conducted by a suitably qualified and experienced person. Buildings and utilities should be designed and constructed to withstand the effects of differential settlement.*
- *Periodic methane monitoring should be conducted in all buildings and underground utilities. Automatic methane sensors should be installed in buildings directly above landfilled areas.*

3.6.3 Volatile organic compounds

Table 1A(2) of Schedule B1 of the ASC NEPM provides interim soil vapour HILs for a limited number of chlorinated VOCs, specifically the chlorinated ethenes PCE, TCE, cis 1,2-DCE and CE, and the chlorinated ethane 1,1,1-TCA. Tables 1A(3) to 1A(5) provide soil, groundwater and soil vapour health screening levels (HSLs) for benzene, toluene, ethylbenzene, xylenes and naphthalene (BTEXN) and the total recoverable hydrocarbon F1 and F2 fractions.

3.6.4 Other criteria

The action level for radon 222 in indoor air in residential buildings is 200 Bq/m³. In workplaces, the action level is 1000 Bq/m³. ARPANSA (2002a and 2002b) indicates that intervention is required if radiation levels are consistently above these values.

Appendix 2 includes toxicity reference values for both bulk and trace ground gases, including some chlorinated methanes and ethanes. These data are consistent with the ASC NEPM, or use data from sources listed in the ASC NEPM that were current when these guidelines were prepared. The currency of toxicological data should be checked before they are used: Appendix 2 provides references to toxicological data sources.

Toxicological data should be used within the risk assessment framework described in Section 4 of these guidelines.

The NSW EPA's air quality impact assessment criteria are set out in Section 7.2 of the *Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales* (NSW Environment Protection Authority 2016b).

The one-hour impact assessment criterion for inorganic mercury vapour is 0.0018 mg/m³.

4. Risk assessment framework

Risk assessment is a fundamental part of evaluating contaminated land, developing engineering designs and delivering public utilities, such as water and power. It is, therefore, rational that risk assessment – and subsequent risk management – must underlie any process for assessing and managing sites impacted by hazardous ground gases.

The purpose of risk assessment is to aid professional judgement and enable decisions that are legal, justified, transparent and understandable.

4.1 Fundamentals

Risk has two components: hazard (or potential consequence) and probability (or likelihood of the potential consequence becoming a reality). Hazard and consequence may vary independently, and it is, therefore, common to use a matrix to assess risk as the product of these two variables. This may be carried out in either a qualitative or a quantitative manner.

A qualitative approach matrix is commonly used to assess workplace risks, for example.

A quantitative human health risk assessment process is commonly used to assess chronic toxicity risks associated with chemical contaminants in land. In this process, the risk matrix is simplified in one of two ways. The matrix may be reduced to a single dimension by specifying a single value for hazard and then focusing on calculating the probability of that consequence occurring (for example, in the case of non-threshold cancer risk, the development of one extra cancer per lifetime in a population). In the case of threshold risk, the process is further simplified by specifying a threshold value of exposure to a particular chemical, below which adverse effects are unlikely, and comparing calculated exposure to this threshold.

Figure 5 illustrates the components of the risk analysis and assessment process. The process incorporates a feedback loop. The first pass through the risk analysis process is a 'maximal' risk assessment. Subsequent passes assess the 'residual' risk after implementing mitigation or management measures.

While the fundamentals of the risk assessment process are the same for all types of ground gases, the procedures used for the bulk ground gases differ from those used for trace gases. In both cases, however, risk assessment should first be carried out in a qualitative manner and subsequently, if warranted, refined by a semi-quantitative or fully quantitative assessment.

Whether dealing with bulk or trace ground gases, a weight-of-evidence approach involving progressive refinement of a CSM is likely to provide the most reliable outcome.

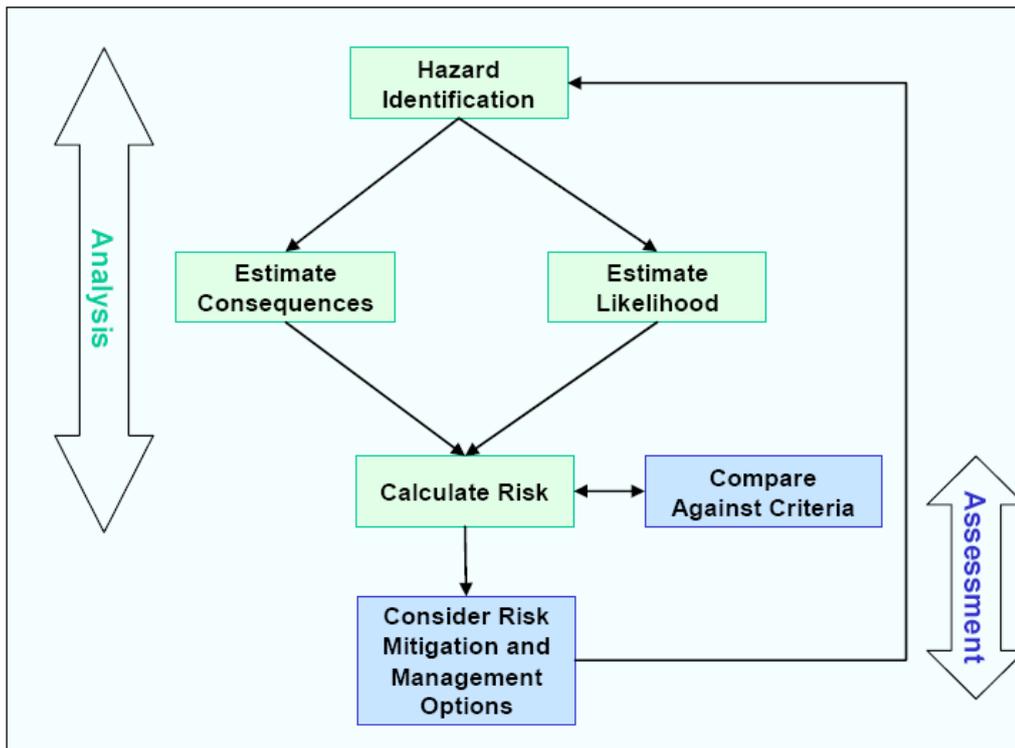


Figure 5 Risk analysis and assessment process

Source: NSW Department of Planning (2011a)

4.2 Guidance documents

The following Australian- and overseas-sourced guidance documents provide a framework for assessing risks associated with ground gases.

AS/NZS ISO 31000:2018 Risk Management – Principles and Guidelines describes a general process of risk assessment that may be applied to a wide range of circumstances where it is necessary to assess the potential outcomes of uncertain processes. This document provides a sound and accepted basis for developing a site-specific risk assessment approach.

The NSW Department of Planning and Infrastructure released guidelines for hazardous development that are relevant to risk assessment and risk management on sites impacted by bulk gases.

The **Assessment Guideline: Multi-Level Risk Assessment** (NSW Department of Planning and Infrastructure 2011), **Hazardous Industry Planning Advisory Paper No 3: Risk Assessment** (HIPAP 3) (NSW Department of Planning 2011a) and **Hazardous Industry Planning Advisory Paper No 6: Hazard Analysis** (HIPAP 6) (NSW Department of Planning 2011b) are particularly relevant.

It is worth noting that, while those guidelines are intended to be applied during the planning process and specifically to assess off-site risks, the methodology outlined can also be used to assess on-site risks associated with ground gases. This is due to the longstanding NSW Government policy of using community risk assessment procedures in contaminated land risk assessments, unless exceptional circumstances apply.

The most comprehensive and relevant guidance for risk assessment in the specific context of ground gases can be found within CIRIA document C665 – **Assessing Risks Posed by Hazardous Ground Gases to Buildings** (2007). This document sets out detailed, practical procedures for assessing risks associated with bulk ground gases, and was used extensively in preparing these guidelines. Section 6 of **BS 8485:2015+A1:2019** outlines a process for ground gas characterisation and hazard assessment that is substantially derived from CIRIA C665. While there are differences in emphasis (for example, with respect to using DQOs and the centrality of a risk-based approach) these guidelines and BS 8485:2015+A1:2019 are consistent in all significant areas.

enHealth (2012a) has published **Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risks from Environmental Hazards**, which provides an Australian guidance framework

for assessing health risks associated with chemical toxicants. This document includes default values for exposure assessments and guidance on evaluating sources of toxicological information. It is specifically relevant to the quantitative assessment of chronic health risks associated with trace ground gases.

enHealth's **Australian Exposure Factor Guidance** (2012b) is a companion to *Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risks from Environmental Hazards*. This handbook provides risk assessors with tabulated data on human factors that may be used as inputs to the exposure assessment component of an environmental health risk assessment. These factors are relevant to quantitative assessments of risks associated with trace and bulk ground gases.

Schedule B4 of the **ASC NEPM** (revised 2013) complements *Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risks from Environmental Hazards* and provides detailed guidance on both qualitative and quantitative assessment of human health risks associated with chronic exposure to chemical toxicants.

4.3 Multi-level risk assessment – bulk ground gases

The *Assessment Guideline: Multi-Level Risk Assessment* recommends a three-stage risk assessment approach involving:

- preliminary screening
- risk classification and prioritisation
- risk analysis and assessment.

The guideline states that this approach should be built around a consequence-based screening method and a rapid risk-classification technique. The level of risk assessment undertaken should be limited to that necessary to support an appropriate remedial solution or to justify a decision that no action is required.

The *Assessment Guideline: Multi-Level Risk Assessment* states that the results of the screening step are used to assess whether it is necessary to proceed to a risk assessment, while the output of the classification and prioritisation step is used to determine which of three levels of assessment is appropriate:

- Level 1 is an essentially qualitative approach based on comprehensive hazard identification and a subjective professional assessment of probability.
- Level 2, a partially quantitative analysis, supplements the qualitative analysis by sufficiently quantifying the main risk contributors to show that risk criteria will not be exceeded.
- Level 3 is a fully quantitative risk analysis.

The approach to multi-level risk assessment proposed in these guidelines for assessment of risk due to ground gases differs in that the preliminary screening and the three levels of assessment are undertaken sequentially, rather than as alternatives. The results of a review at the completion of each stage determine the need to proceed to the next stage.

In this approach, risks are classified after a Level 1 assessment to prioritise risk management over risk assessment for certain low-risk sites. Level 2, still a partially quantitative analysis, here supplements the qualitative analysis by sufficiently quantifying the main risk contributors, allowing relative risk levels to be assigned and mitigation measures to be specified for lower levels of risk. Level 3 remains as a full quantitative risk analysis, but is triggered when Level 2 indicates higher levels of risk.

This approach is consistent with the CIRIA C665, enHealth and ASC NEPM guidance.

4.3.1 Preliminary screening

Preliminary screening should be carried out using a simple risk model developed from the initial CSM compiled as described in Section 3 of these guidelines.

A screening-level risk model identifies:

- potential sources of ground gas
- receptors that could be affected

- possible pathways (linkages) by which gas could reach receptors.

The screening process should provide answers to three questions:

1. Is the model based on sufficient, reliable site information to allow its use for screening purposes?
2. Is there a potential source of bulk ground gas? (See Section 2.1.)
3. Is there a credible pathway between the source and the receptors? (See Section 2.2.)

If the answer to question 1 is 'no', additional information must be obtained before screening can proceed.

If the answer to question 1 is 'yes', and the answer to either question 2 or question 3 is 'no', there should be no risk, meaning further risk assessment is unnecessary and no action to manage bulk ground gas risk is required. In these circumstances, it is only necessary to document the findings of the preliminary screening assessment; no further data collection or assessment is required.

If the answer to all three questions is 'yes', the risk assessment should proceed to Level 1 (Section 4.3.2).

In providing an answer to question 3 and therefore assessing the credibility of a pathway, it is necessary to consider the length of the pathway, its likely continuity (which requires consideration of the geological conditions described in the CSM) and the strength of the source. This process requires applying professional judgement to the site-specific conditions, and documenting the reasoning underlying the judgement. Given the wide range of possible site conditions, it is not appropriate for these guidelines to specify arbitrary distances from particular bulk gas sources, beyond which a pathway ceases to be credible.

4.3.2 Risk analysis and assessment – Level 1

As indicated previously, Level 1 requires an essentially qualitative approach based on identifying hazards and assessing probability. For bulk ground gases, it involves reviewing the CSM and its underlying data, reformulating the risk model and then following the steps shown in Figure 5.

Reviewing data and refining risk models

It is necessary to further review the risk model against the increased requirements of a qualitative risk assessment. Answers are required to the following questions:

- Is the information reliable and representative?
- Have all potential sources of ground gas been identified?
- Can the extent of the sources be adequately defined for the purpose of the model?
- Does the risk model include all credible pathways or links?

It should be noted that while a Level 1 risk assessment is qualitative and does not require measuring ground gas concentrations and flow rates, it requires a risk model based on a good understanding of sub-surface conditions. Acquiring this level of understanding may require intrusive investigations if information is not available from previous geotechnical or hydrogeological investigations.

Identifying hazards

This step involves systematically identifying hazardous events or scenarios (for example, a methane explosion or asphyxiation due to carbon dioxide accumulation), their potential causes and the consequences (in qualitative terms) of such events. These scenarios are then incorporated into the risk model.

The NSW Department of Planning's HIPAP 3 guidelines set out generic procedures for identifying hazards; when dealing with bulk ground gases, the range of hazards that may arise is more restricted, making it appropriate to simplify these procedures.

Estimating consequences

This step relates to assessing the effects of the hazardous events identified in the previous step. While models are available to help estimate the effect of incidents (such as fires and explosions) on people, buildings and the environment, a judgemental assessment that considers the nature of the hazard and

the proposed development is all that is required for a qualitative assessment. For example, it may be recognised that a methane explosion in a ‘standard’ residential setting is likely to result in partial or complete collapse of the building in which it occurs, and could generate up to 10 serious injuries or fatalities, whereas an explosion in a large commercial building may result in 10 to 100 fatalities.

In a qualitative risk assessment, consequences may be divided into broad categories. Typically, four categories are used (minor, mild, medium and severe) as shown in Table 4. Consequences associated with a specific event at a particular site may then be assigned to one of these categories.

HIPAP 3 emphasises the higher societal standards that apply to risks of multiple, as opposed to single, fatalities. This concept is discussed further under ‘Risk communication’ later in this sub-section. In the context of a qualitative risk assessment for ground gas, it is not considered necessary or appropriate to provide a separate consequence category for events that may produce multiple fatalities.

This estimate is necessarily subjective, and requires calibration to individual site circumstances based on professional judgement and the particular requirements of involved parties, who may place greater emphasis on aspects such as business disruption or reputational damage. Therefore, the definitions set out in Table 4 may be modified on a site-specific basis, provided that the modifications are clearly stated and justified.

Table 4 Classification of consequences

Classification	Definition	Examples
Severe	Fatalities, including multiple fatalities Very serious injuries Catastrophic damage to buildings	Explosion causing building collapse
Medium	Long-term damage to human health Serious injuries Major damage to structures	Permanent injuries Structural damage requiring major repair or demolition and rebuild
Mild	More significant non-permanent injuries Significant damage to buildings, structures or services	Fractures, burns, gas inhalation or other injuries requiring medical treatment Severe cracking requiring closure of buildings and urgent repair
Minor	Minor non-permanent health effects Harm that may result in financial loss, business disruption or reputational damage Minor property damage	Minor cuts or bruises requiring first-aid treatment Cosmetic damage to buildings or pavement Damage to landscaping Minor damage to vehicles

Estimating likelihood

This step involves deriving both the probability of incidents occurring and the probability of particular outcomes (or effects) should those events occur.

Likelihood may also be divided into broad categories, as shown in Table 5.

Table 5 Classification of likelihood

Classification	Definition
High likelihood	A credible linkage exists, and a trigger hazardous event is very likely to occur in the short term and is almost inevitable over the full timeframe of concern (typically the effective life of a building or development). The likelihood of the stated consequence is also high.
Likely	A credible linkage exists, and all necessary elements required for a trigger hazardous event to occur are present. Occurrence is not inevitable, but it is possible in the short term, and probable over the full timeframe of concern. The stated consequence is likely.
Low likelihood	A credible linkage exists and circumstances under which a trigger hazardous event could occur are possible. However, it is by no means certain that the event will occur within the timeframe of concern, and it is less likely in the short term. Therefore, there is a low likelihood that the stated consequence will occur.
Unlikely	A credible linkage exists but circumstances are such that it is improbable that a trigger hazardous event would occur within the timeframe of concern. Therefore, it is unlikely that the stated consequence will occur.

With reference to Table 5, it is worth reiterating that zero-likelihood situations – where there is either no potential source of ground gas or no credible pathway (linkage) between the source and the site or building – should already have been eliminated during the preliminary screening stage. In assigning a classification of likelihood, the strength of the source (Section 2.1) and the length and continuity of the linkage (Section 2.2) should be considered, along with any other site-specific factors.

Risk assessment

The consequence and likelihood estimations are cumulatively combined for the various hazardous incident scenarios and events to give a quantified risk level.

This is conventionally carried out using a matrix, as shown in Table 6.

The risk assessment should be carried out for each hazardous incident scenario identified in the risk model.

A full description of the reasoning used and justification for the risk conclusion should be provided, ensuring the process is transparent and amenable to review.

Table 6 Qualitative risk assessment matrix

		Consequence			
		Severe	Medium	Mild	Minor
Probability	Highly likely	Very high risk	High risk	Moderate risk	Moderate/low risk
	Likely	High risk	Moderate risk	Moderate/low risk	Low risk
	Low likelihood	Moderate risk	Moderate/low risk	Low risk	Very low risk
	Unlikely	Moderate/low risk	Low risk	Very low risk	Very low risk

Risk communication

HIPAP 3 provides these comments about risk communication:

Risk results are most commonly expressed in terms of human fatality. The analysis and results can, however, also be expressed in other terms such as levels of injury, property damage or environmental damage.

Human fatality risk results are expressed in two forms, individual risk and societal risk. Individual risk is the risk of death to a person at a particular point. Societal risk is the risk of a number of fatalities occurring.

The societal risk concept is based on the premise that society is more concerned with incidents which kill a larger number of people than incidents which kill fewer numbers.

One reason for undertaking a Level 1 assessment as a separate step, rather than combining it with a screening assessment or going straight from a screening assessment to Level 2, is that a Level 1 report provides an opportunity to demonstrate that these larger issues have been appropriately considered before undertaking the prioritisation step or moving to Level 2. A Level 1 risk assessment also provides an opportunity to screen out those cases where, although a potential source and potentially complete pathway exist, the pathway is so long or of such low conductivity that the risk is assessed as very low.

4.3.3 Risk review and prioritisation – low-risk sites

As described in Section 4.3.1, if – during preliminary screening – the risk model indicates that there is no potential source or viable pathway, there is no need to proceed to a Level 1 risk assessment. Similarly, if the Level 1 assessment indicates that the maximal risk is ‘very low’, then no further assessment should be required.

A higher risk category for any scenario generally indicates a need to proceed to a Level 2 assessment; however, where the risk assessed at Level 1 is ‘low’, there are merits in considering an alternative to a full site assessment followed by a Level 2 risk assessment, as described in Section 4.3.4. This alternative approach involves a more limited site assessment, followed by implementation of basic gas protection measures. However, it removes the opportunity to establish that there is no need for any gas protection measures at all.

Card et al. (2012) described such an alternative approach to assessing low-risk sites in the UK. This alternative ‘empirical approach using TOC’¹⁰ is included as Annex D to BS 8485:2015+A1:2019, with some qualifications and restrictions as to its applicability.¹¹ The approach outlined in these guidelines uses some aspects of the empirical approach developed by Card et al., but has been modified to reflect Australian environmental conditions, and its application has been restricted to a narrower range of circumstances.

This alternative will often appear attractive when dealing with sites that have low ground gas risks because it may avoid some of the direct investigation costs and, often more significantly, the costs of construction delays associated with extended periods of gas monitoring.

The circumstances under which this approach may be applied as an alternative to site assessment and Level 2 risk assessment are limited to those where:

- a Level 1 risk assessment has identified a low level of risk
- the CSM and risk model are robust and underpinned by site-specific geological data, including logs prepared by a geologist using the USCS. This could, for example, be the case where a geotechnical or environmental investigation of the site and, if appropriate, adjacent sites has been completed
- potential sources of ground gas (on-site or off-site) are limited to natural soils with measured low organic carbon content and low hydrogen sulfide risk (specifically excluding reclaimed coastal or estuarine swamps and mangrove flats), or to shallow (with an average depth of less than 3 m and a maximum depth of 5 m) general fill (excluding waste landfill) with minimal timber and other organic matter. The limiting total organic carbon (TOC) concentration is 3%

¹⁰ TOC refers to ‘total organic carbon’.

¹¹ BS 8485:2015+A1:2019 [6.2.1.2].

- adequate short-term ground gas monitoring (a minimum of two events) has been undertaken to support the risk model
- the cost of the proposed mitigation measures is likely to be less than the cost of the additional risk assessment work necessary to decide whether those measures are required. The most likely cases are where such measures can be readily incorporated into the design of a new commercial or industrial building.

Where these circumstances exist, the alternative approach for low-risk sites set out in Table 22 in Appendix 5 may be used. Further information is provided at the end of Section 4.3.4.

The empirical approach using TOC shown in Table 22 may also be used as part of an assessment based on multiple lines of evidence, in conjunction with a Level 2 risk assessment as described below. In this case, application is not restricted to the circumstances outlined above and the approach may be incorporated as part of an iterative investigation process, but a holistic evaluation of all the available evidence must be carried out.

The applicability of the alternative approach differs from BS 8485:2015+A1:2019. In particular, BS 8485:2015+A1:2019 restricts applicability to sites with very low to moderate gas 'hazard', whereas these guidelines restrict applicability to sites with 'low risk', assessed using the process described in Section 4.3.2. The risk-based approach is considered to be more robust; the reason for not extending applicability to sites with moderate risk is clear from the definitions provided in Tables 3 to 5 above.

4.3.4 Risk analysis and assessment – Level 2

As indicated previously, a Level 2 risk assessment requires a semi-quantitative approach. This must be based on site-specific ground gas measurements carried out using the procedures outlined in Section 3.4 of these guidelines. For bulk ground gases, the approach to Level 2 risk assessment is based on the method proposed by Wilson and Card (1999) and outlined in CIRIA C665 and BS 8485:2015+A1:2019. This approach also follows the process shown in Figure 5. The objective is to assess risks to buildings (and their occupants) constructed, or intended to be constructed, on the site; the approach applies regardless of the gas source, but the results must be interpreted in the context of the CSM.

Reviewing data and refining the risk model

It is essential to review the data against the increased requirements of a semi-quantitative risk assessment, and then review and refine the risk model. In addition to reconsidering the Level 1 review questions, answers to the following additional questions are required:

- Is the data reliable and representative?
- Is there sufficient coverage of the site and source areas, taking into account likely geological heterogeneity?
- Is the monitoring period long enough, and does it cover the full range of likely meteorological conditions?

These questions should be posed and answered iteratively, both before and after an initial assessment of the data. In such an iterative review, and where the monitoring period is short or does not cover the full range of likely meteorological conditions, the sensitivity of the interpretation to a credible extension of the measured dataset should be considered.

Determining the gas screening value

The Wilson and Card method uses both gas concentrations and borehole flow rates to define a characteristic situation (CS) for a site based on the limiting borehole gas volumetric flow for methane and carbon dioxide, as measured in the gas monitoring boreholes on the site. The measured borehole flow rates represent gas flow through the surface of the site, forming the basis for this approach. The gas flow from a 50-mm borehole is, very conservatively, assumed to represent the upward flow of gas through soil across a site surface area of 10 square metres (m²) (Pecksen 1986).

CIRIA C665 and BS 8485:2015+A1:2019 use the term 'gas screening value' (GSV) for the site-representative value assessed from the set of limiting borehole gas volumetric flow measurements. GSV is also used in these guidelines. GSV uses units of litres of gas per hour (L/hr).

GSV = maximum borehole flow rate (L/hr) × maximum gas concentration (% v/v)

It is important to emphasise that the GSV is an overall site value, not an individual borehole value or an event value. As is the case for other aspects of contaminated land assessment and management, and as described in Section 2.3.4 of the *Contaminated Sites: Sampling Design Guidelines* (NSW Environment Protection Authority 1995), a large site may be stratified (subdivided) where it is appropriate to do so and the rationale underpinning the stratification is explained. A GSV may then be calculated for each subdivision. The rationale must reflect the gas regime and engineering considerations. For example, if data from site monitoring indicated a maximum flow rate of 3.5 L/hr and a maximum methane concentration of 20% v/v, the site would have a methane GSV of 0.7 L/hr (20/100 × 3.5). The calculation is carried out for both methane and carbon dioxide, and the worst-case value is adopted.

BS 8485:2015+A1:2019 uses the term Q_{hg} for the product of borehole flow and gas concentration measured in an individual borehole during a specific monitoring event. The site-representative GSV should be selected based on a review, carried out in the context of the CSM, of all the Q_{hg} measured across all boreholes during all monitoring events. It should take into account the spatial and temporal coverage of the site; the range and variability of the dataset; the range of meteorological conditions (particularly atmospheric pressure conditions) covered; and geological conditions at the site. BS 8485:2015+A1:2019 recommends that where the dataset is representative and comprehensive, spatially and temporally, the GSV selected should be the maximum Q_{hg} measured in any borehole during any monitoring event. Where the dataset is not representative and comprehensive, BS 8485:2015+A1:2019 recommends carrying out further monitoring to improve the dataset. If it is not possible to improve that dataset, a worst-case GSV should be calculated from the highest flow rate and highest concentration, even if not measured at the same time or in the same borehole. These guidelines also recommend the adoption of this approach, where prudent and reasonable.

The assumption of equivalence between methane and carbon dioxide is made on the basis that the LEL for methane in air is similar to the concentration at which carbon dioxide becomes acutely toxic in air (5% v/v). Because ground gas with a high carbon dioxide content is denser than air and may remain segregated at low points, particularly in basements and other in-ground structures, this is a reasonable precautionary approach. However, experience in NSW has indicated that it may sometimes produce over-conservative outcomes, as has been the case elsewhere.

It is, therefore, appropriate to review the outcome of a Level 2 risk assessment against the CSM, taking into account source and pathways factors, and the details of the current or proposed development.

BS 8485:2015+A1:2019 indicates that the GSV may be judgementally adjusted based on the CSM, taking into account such factors as the proximity of the proposed development to the gas source and the permeability of strata between the gas source and the surface. **These guidelines do not support that suggestion.** Instead, these guidelines recommend adopting a weight-of-evidence approach when a robust CSM indicates that such factors may be relevant. This approach may incorporate a review of pathway factors (including direct measurement of gas permeability, if appropriate); the nature of the gas source and its gas generation potential, and any observed pressurisation effects; and include evaluation of surface emission as well as borehole gas flow data. Rather than adjusting the GSV, a professional judgement is reached based on a holistic evaluation of all available lines of evidence, which is then applied to assign a CS and select gas protection measures. The reasoning must be explicitly stated and fully justified in a site assessment report. Where this approach is used, it is expected that the site would be subject to a site audit.

This approach gives greater transparency and is consistent with other NSW EPA and ASC NEPM guidance, including the approach to risk management outlined in Section 7.2 of Schedule B4 of the ASC NEPM.

Determining the characteristic situation

The CS is normally determined directly from the GSV using Table 7.

If it is considered appropriate to modify the CS based on a weight-of-evidence approach, an initial CS should be determined from Table 7 in the usual way. That value should then be adjusted based on the

evidence presented, ensuring the adjustment is fully justified. It is not expected that the CS would be adjusted up or down by more than one unit.

Where the CS is 1, no further action is required.

Where the CS is 2 or 3, gas protection measures are required. Appropriate gas protection measures for the site should be selected as outlined in Section 5 of these guidelines.

Where the CS is 4, gas protection measures are required, and the need for a Level 3 risk assessment should be considered. If a Level 3 risk assessment is not considered necessary, the reasons for this decision should be documented, and appropriate gas protection measures for the site should be selected, as outlined in Section 5 of these guidelines.

Where the CS is 5 or 6, gas protection measures are required, and a Level 3 risk assessment must be carried out to assess the maximal risk, inform the design of gas protection measures and determine the residual risk following implementation of those measures.

Table 7 Modified Wilson and Card classification

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

1. Site characterisation should be based on monitoring of gas concentrations and borehole flow rates for the minimum periods defined in Section 3.4.
2. The CSM must identify the source of gas and its generation potential.
3. Soil gas investigations should be conducted in accordance with the guidance provided in Section 3.4.
4. Where there is no detectable flow, the lower measurement limit of the instrument should be used.
5. To determine a GSV of <0.07, instruments capable of accurately measuring concentration to 0.5% v/v and flow to 0.1 L/hr are recommended.

Applying the alternative process for low-risk sites outlined in Section 4.3.3 will allow, where appropriate, CS 2 to be assumed based on an abbreviated assessment. This process may be used, optionally, to manage costs, even in cases where further site investigation and a Level 2 risk assessment could have demonstrated CS 1. The justification for any consequent over-design of protective measures is the net cost saving achieved by avoiding the additional monitoring required to support a Level 2 risk assessment. Adopting the conservative approach outlined in Section 4.3.3 and Appendix 5 should minimise the risk of under-design.

4.3.5 Risk analysis and assessment – Level 3

Fully quantitative risk analysis requires the use of mathematical models and probability analysis to give a numerical estimate of risk. Such modelling is very data-intensive. Therefore, quantitative risk analysis is both expensive and time-consuming.

For new developments, quantitative risk analysis is only required to resolve bulk ground gas problems where the CS is 5 or 6. It may be considered worthwhile in other cases if there is a prospect of significantly reducing the cost of protective measures. However, it must be recognised that probability analysis requires assigning probabilities to rare events, and that this is inevitably a subjective process with considerable residual uncertainty. In many cases, the value of a quantitative risk analysis is derived more from a rigorous hazard analysis than from improved estimates of likelihood. The hazard analysis improves understanding of the components of the hazard and permits more effective (or cost-effective) preventive measures to be developed.

Quantitative risk analysis is also required for existing buildings where gas risk has been identified after construction has ended and no gas protection measures are in place.

Quantitative risk analysis is a complex subject, and a full treatment is beyond the scope of these guidelines. HIPAP 6 provides guidance on hazard analysis in the context of potentially hazardous industrial development, including the use of word diagrams, fault trees and event trees to deconstruct the process of hazard development. CIRIA R152 and Appendix A5 of CIRIA C665 describe the use of fault trees and gas generation models, such as GasSim, in quantitative risk assessment of ground gases.

Appendix 5 of these guidelines provides further information and some relevant examples of quantitative risk assessment for ground gases.

4.4 Multi-level risk assessment – trace ground gases

Vapour Intrusion: Technical Practice Note (NSW Department of Environment, Climate Change and Water 2010) provides outline guidance on risk assessment for trace ground gases and includes references for more detailed guidance. These guidelines are intended to complement the technical practice note by incorporating that guidance within the overall risk assessment framework for ground gases.

A multi-level approach, as described for bulk ground gases, is also appropriate for analysis of risk due to trace ground gases. However, because no adequate data are available, either in Australia or internationally, there is no basis for Level 2 risk assessment for mercury and SVOCs. Therefore, it is necessary to progress directly from Level 1 to a full quantitative Level 3 risk assessment for these vapours.

4.4.1 Preliminary screening

Preliminary screening is also an appropriate first step in analysing the risk due to trace ground gases, and is likewise carried out using a simple risk model developed from the initial CSM. As discussed in Section 3, the CSM is based on all the information available at the time. This may be restricted to land-use history and regional hydrogeological data, but typically at least some site-specific geological, hydrogeological and contamination data are available from previous investigations.

As with bulk ground gases, the screening process should provide answers to three questions:

- Is the model based on sufficient, reliable site information to allow its use for screening purposes?
- Is there a potential source of trace ground gas?
- Is there a credible pathway between the source and the receptors?

The answers may be interpreted in the manner outlined in Section 4.3.1. However, in assessing whether a pathway is credible, it is important to recognise that trace ground gas migration is driven primarily by diffusion, not advection, so the credible length of pathways is shorter. CRC CARE (2013) describes a screening distance (depth)–based procedure that may be applied to petroleum vapour intrusion, subject to the conditions and constraints specified in that document.

4.4.2 Risk analysis and assessment – Level 1

As indicated previously, Level 1 requires an essentially qualitative approach that involves reviewing the CSM and its underlying data, reformulating the risk model and then following the steps shown in Figure 5.

Reviewing data and refining the risk model

As with bulk ground gases, the following questions must be answered:

- Is the information reliable and representative?
- Can all potential sources of trace ground gas be identified?
- Can the extent of the sources be adequately defined for the purpose of the model?
- Does the risk model include all credible pathways or links?

Identifying and evaluating hazards

In the context of trace ground gases, hazard identification involves recognising volatile contaminants that are, or are likely to be, present in the source areas, and researching the toxicological and chemical characteristics of those chemicals of potential concern. Depending on the quality of information available, at Level 1 this may be carried out on the basis of broad contaminant groups (for example, volatile petroleum hydrocarbons and chlorinated aliphatic hydrocarbons) or on the basis of specific compounds and concentration ranges (for example, benzene, PCE and mercury).

Estimating exposure

At Level 1, estimating exposure involves a basic assessment of likely pathway continuity, based on available knowledge of site geology, and building construction and ventilation. This leads to a qualitative assessment of migration rates and likely attenuation of the chemicals of potential concern along those pathways. The primary purpose is to scope and guide further investigation, but it may be possible to screen out some potential source–receptor links at this stage. For example, in the case of volatile petroleum hydrocarbons, lateral source–receptor distances greater than about 30 m may indicate that a diffusion link is unlikely and further vapour assessment is not required (Davis et al. 2009a, US Environmental Protection Agency (USEPA) 2002, ASTM International 2015a, 2015b), as referenced in the technical practice note. Similarly, a deep watertable (greater than 7 m below the receptor) may indicate that diffusive transport of petroleum hydrocarbon vapours from a groundwater source is unlikely (Wright 2011, CRC CARE 2013).

Such screening judgements should not be made without an adequate understanding of site geology and infrastructure, because convective transport along high-permeability preferential pathways may still be possible.

4.4.3 Risk analysis and assessment – Level 2

As indicated previously, the approach to Level 2 risk assessment for trace ground gases is semi-quantitative. The assessment must be based on site-specific measurements of contaminant concentrations, carried out using the procedures outlined in Section 3.4 of these guidelines.

Level 2 assessment involves comparing measured or estimated indoor air concentrations of the contaminants of potential concern (identified in Level 1) with screening values. Maximum indoor air concentrations are usually estimated by applying attenuation factors (derived from the scientific literature and site-specific knowledge of geology and building construction) to concentrations of the contaminants of concern measured in crawl spaces or in sub-slab gas, soil gas or groundwater.

As indicated in Section 3.6.3, in the case of some chlorinated hydrocarbons and volatile petroleum hydrocarbons, concentrations measured in soil gas, soil and groundwater may be compared directly with generic HILs for soil vapour and HSLs for soil and groundwater developed for the relevant exposure scenario.

In some situations, it is possible to carry out sampling and subsequent laboratory analysis of indoor air, and therefore measure concentrations directly. In the absence of confounding factors, such as indoor

sources of the chemicals of potential concern, this can provide concentration data at the exposure point and permit a more direct assessment of current health risks. It does not eliminate the need to consider the transport pathway, and it must be recognised that a single measurement may not represent average (time and space) exposure point concentrations.

This is a screening procedure, intended to eliminate sites where Level 3 assessment is not justified.

Indoor sources are likely to be present in a wide range of circumstances, and their potential effect should always be considered.

Reviewing data and refining the risk model

As with Level 2 assessment for bulk ground gases, it is essential to review the data against the increased requirements of a semi-quantitative risk assessment before reviewing and refining the risk model. Answers to the same questions are required:

- Is the data reliable and representative?
- Is there sufficient coverage of the site and source areas, taking into account likely geological heterogeneity?
- Is the monitoring period long enough, and does it cover the full range of likely meteorological conditions?
- Have all sources of trace ground gas been identified?
- Can the extent of the sources be adequately defined for the purpose of the model? In particular, can the minimum horizontal and vertical distances from the source to the receptor be estimated?
- Does the risk model include all credible pathways or links? In particular, is there a possibility that preferred pathways (such as service trenches or ducts, lift shafts, sumps or wet basements) are present?

If the answers to any of these questions are negative, the CSM requires improvement.

Estimating indoor air concentration

The indoor air concentration of the contaminants of potential concern should be estimated by direct measurement (where possible) and/or by applying an appropriate attenuation factor, which is the ratio of the indoor air concentration to concentrations measured in crawl spaces, sub-slab gas, soil gas or groundwater. In selecting an appropriate attenuation factor, the following information should be considered:

- USEPA (2002) used attenuation factors of 0.1, 0.01 and 0.001 between sub-slab gas, soil gas and groundwater concentrations, respectively, and indoor air concentrations. These were based on 85 to 95 percentile values for attenuation factors calculated for paired measurements in a relatively small dataset. They are conservative but were widely used over the following 10 years.
- Since 2002, USEPA has expanded its vapour intrusion database. The current version from June 2012 (USEPA 2012a) has data for 913 buildings, at 41 sites and includes 2929 paired measurements. Some 85% of the measurements relate to residential buildings and 97% relate to chlorinated hydrocarbons. The database is in Excel format and includes filtering tools that may be used to assess the effect of variations in site conditions on attenuation factors.
- USEPA (2012b) provided an analysis of attenuation factors for chlorinated hydrocarbons derived from data in the USEPA vapour intrusion database as of 2010. When calculating the case of sub-slab soil gas to interior air, for the slab-on-grade construction that is most similar to that used for current residential and commercial construction in NSW, the median attenuation factor (for a subset of chlorinated hydrocarbons excluding CE) was 0.003, and the 95th percentile was 0.01.
- The Oregon Department of Environmental Quality (ODEQ) (2010) also analysed the data in the USEPA vapour intrusion database. ODEQ concluded that the data justified an attenuation factor between sub-slab and indoor air of 0.005 for chlorinated hydrocarbons in residential buildings. It suggested that analysis of the limited data for commercial buildings, plus consideration of their likely higher ventilation rates, justified adopting a sub-slab to indoor air attenuation factor of 0.001 for these buildings. Because there was little data for petroleum hydrocarbons, the same attenuation factors were adopted.

- Health Canada (2010) developed groundwater to indoor air and soil vapour to indoor air attenuation factor charts for residential and commercial land use that allow for site-specific variations in soil lithology and depth to groundwater. Soil vapour attenuation factors were based on benzene and range from 0.00009 to 0.00300 for residential settings and 0.00003 to 0.00040 for commercial settings.
- As indicated by Davis et al. (2009a), Health Canada (2010) and others, there is significant potential for petroleum hydrocarbons and chloroethene to be attenuated by oxidation in the vadose zone, where oxygen is present in the soil gas. This may not, however, be the case beneath large buildings or paved areas.
- The rationale underlying the development of the ASC NEPM Interim Soil Vapour HILs is detailed in Sections 5.5.2 and Appendix 6 of Schedule B7 of the ASC NEPM. This approach involved the use of an indoor air to soil vapour attenuation factor. The ASC NEPM references, and presents an extract from USEPA (2012b).
- The ASC NEPM considered the data presented in USEPA (2012a) for chlorinated hydrocarbon vapours in exterior soil gas and sub-slab soil gas. Data for groundwater and crawl spaces were also presented by USEPA (2012a) but were not used in the NEPC analysis. The ACS NEPM noted that: For sub-slab soil vapour attenuation factors for all residential premises, the measured values ranged from 0.00003 to 1, with a median value of 0.003 and a 95th percentile of 0.03. For soil vapour data collected external to an existing residential building (i.e. not directly beneath the building) there is a wider variation in attenuation factors, ranging from 0.00005 to 1.3, with a median value of 0.004 and 95th percentile of 0.3.
- The ASC NEPM adopted a conservative attenuation factor of 0.1 for the derivation of soil vapour HILs to apply to the pathway from sub-slab or shallow soil gas to indoor air in residential or commercial buildings. In doing this, the ASC NEPM recognised the wide variation in attenuation factors measured for shallow soil gas, and that a factor of 0.1 is below (less conservative than) the 95th percentile.
- The interim soil vapour HILs for volatile organic chlorinated compounds provided in Table 1A(2) of Schedule B1 of the ASC NEPM (NEPC 2013) were therefore derived using an indoor air to soil vapour attenuation factor of 0.1. An outdoor air to soil vapour attenuation factor of 0.05 was used.
- USEPA (2015a) is the USEPA's technical guide to assessing and mitigating the vapour intrusion pathway from subsurface vapour sources to indoor air. Section 6.5.3 and Table 6-1 of that guide present a set of attenuation factors for risk-based screening of the vapour intrusion pathway to indoor air from sub-slab soil gas, exterior soil gas, crawl-space air and groundwater. These attenuation factors and their derivation are explained in detail in Appendix A of the guide. The basis for these factors is the database provided in USEPA (2012a).
- The set of attenuation factors included generic factors for sub-slab and near-source (deep) exterior soil gas to indoor air of 0.03, and groundwater to indoor air of 0.001.
- Section A.3.4 of USEPA (2015a) deals with recommended attenuation factors for exterior soil gas. It states, in part, that:

... a comparison of exterior soil gas to sub-slab soil gas concentrations for buildings where both types of samples were collected ... suggests that a substantial proportion of the exterior soil gas data in the database, particularly shallow soil gas data, may not be representative of soil gas concentrations directly underneath a building. On this basis, shallow exterior soil gas sampling data generally are not recommended for purposes of estimating indoor air concentrations and the exterior soil gas attenuation factors in Table A-1 are not recommended for use in deriving generic attenuation factors.

Fundamentally, this means that USEPA (2015a) does not support the use of shallow exterior soil gas sampling.

- It is important to note that the recommendations of the ASC NEPM and USEPA (2015a) are based on different interpretations of the same (USEPA 2012a) dataset. Therefore USEPA (2015a) cannot be considered to supersede the ASC NEPM guidelines.

For consistency with the ASC NEPM, it is, therefore, recommended that:

- where sub-slab gas concentration data are available and soil vapour HILs for the chemicals of concern are provided in the ASC NEPM, the NEPM HILs should be used directly, instead of calculating indoor air concentrations

- where sub-slab gas data are available and soil vapour HSLs or HILs for the chemicals of concern are not provided in the ASC NEPM, an attenuation factor to indoor air of 0.1 should be applied for both petroleum hydrocarbons and chlorinated hydrocarbons
- an additional biodegradation attenuation factor of 0.1 is applied for petroleum hydrocarbons where data are available for soil gas beneath a building at a depth of between 2 and 4 m (or soil gas concentrations are calculated from groundwater concentration data and the watertable is at a depth between 2 m and 4 m and significant fluctuation is unlikely), and where measurements can demonstrate that oxygen is present in the soil profile or that slab dimensions are less than 15 m × 15 m. For depths greater than 4 m, an attenuation factor of 0.01 may be applied.

These attenuation factors should be applied for both residential and commercial buildings unless site-specific information indicates that they are inappropriate (for example, that they are over-conservative), in which case a Level 3 analysis should be carried out to estimate (model) indoor air concentrations on a site-specific basis.

Comparing estimated indoor air concentrations with screening values

The estimated indoor air concentration should be compared with appropriate screening values. Screening values can be sourced from the inhalation toxicity reference values (TRVs) provided in Appendix 2 of these guidelines; directly from Schedule B7 of the ASC NEPM; or from the Australian and international sources listed in Table 4 of Schedule B4 of the ASC NEPM, using the process outlined in Section 5.1.1 of that schedule.

When the conceptual risk model is adequate and estimated indoor air concentrations are negligible in comparison to guideline values, no further risk assessment is required. If estimated indoor air concentrations are not negligible in comparison to guideline values, a Level 3 risk analysis is required.

4.4.4 Risk analysis and assessment – Level 3

A Level 3 risk analysis allows site-specific factors to be fully considered, and is inherently less conservative than a Level 2 analysis based on generic attenuation factors.

Fully quantitative risk analysis for ground gases requires using mathematical models to give a numerical estimate of risk. To be worthwhile, such modelling needs good data. It is essential to use a sound CSM or risk model that meets the requirements for a Level 2 assessment and incorporates realistic values for the dimensions and physical properties of each component of the exposure pathway. The CSM should consider the transport processes – dispersion and/or advection – that are likely to be significant at the site.

Level 3 risk analysis requires measured concentrations of the contaminants of concern in sub-slab gas, soil gas beneath the building or groundwater. When indoor air concentration data are available, they should be used to complement the results of vapour intrusion modelling.

The ready availability of user-friendly software for vapour and gas intrusion modelling has made it a relatively straightforward task, although there are still numerous potential pitfalls, related mainly to over-using default parameters rather than site-specific data.

The Johnson and Ettinger (1991) model, available in numerous forms and within various public-domain and proprietary packages, is most widely used for modelling vapour intrusion to buildings.

The model is essentially a tool for carrying out part of an exposure assessment. However, many of the packages incorporate access to databases that contain both the human exposure parameters necessary to complete the exposure assessment and the toxicological data required for hazard assessment. Provided that these databases are appropriately modified so that they incorporate the values recommended for Australian use – as recommended in enHealth (2012) and Schedule B4 of the ASC NEPM – they can be used to combine the hazard and exposure assessments, and generate a fully-quantitative human health risk assessment.

Although detailed guidance on vapour intrusion modelling is beyond the scope of these guidelines, Appendix 5 provides links to further descriptions and discussions of the Johnson and Ettinger model and relevant examples of its use, as well as an annotated bibliography and links to toxicological data sources.

Schedule B4 of the ASC NEPM provides an outline of the human health risk assessment process. A summary is included in Appendix 5. In the final step of that process, risk characterisation, toxicity assessment and exposure assessment are combined to provide quantitative assessments of risk for threshold and non-threshold chemicals, which are then compared against acceptable risk targets.

For threshold chemicals, this target is the 'no appreciable risk' level, and the comparison is presented as a hazard quotient for individual chemicals and a hazard index. The hazard index represents the sum of the hazard quotients for all threshold chemicals. A hazard index of less than 1 indicates acceptable risk, and as the hazard index rises above 1, the risk becomes increasingly unacceptable.

For non-threshold chemicals, the target is a socially acceptable level of risk, generally stated as a probability of excess cancer occurrence, summed across all non-threshold chemicals of concern. Excess cancer risks of less than 10^{-6} are negligible. In NSW, excess cancer risks of less than 10^{-5} are generally considered acceptable, while risks between 10^{-5} and 10^{-4} require further assessment, monitoring and/or management. Risks greater than 10^{-4} are unacceptable.

Figure 6 summarises the risk assessment process for sites potentially impacted by both bulk and trace ground gases, and also the risk management approaches discussed in Section 5 of these guidelines.

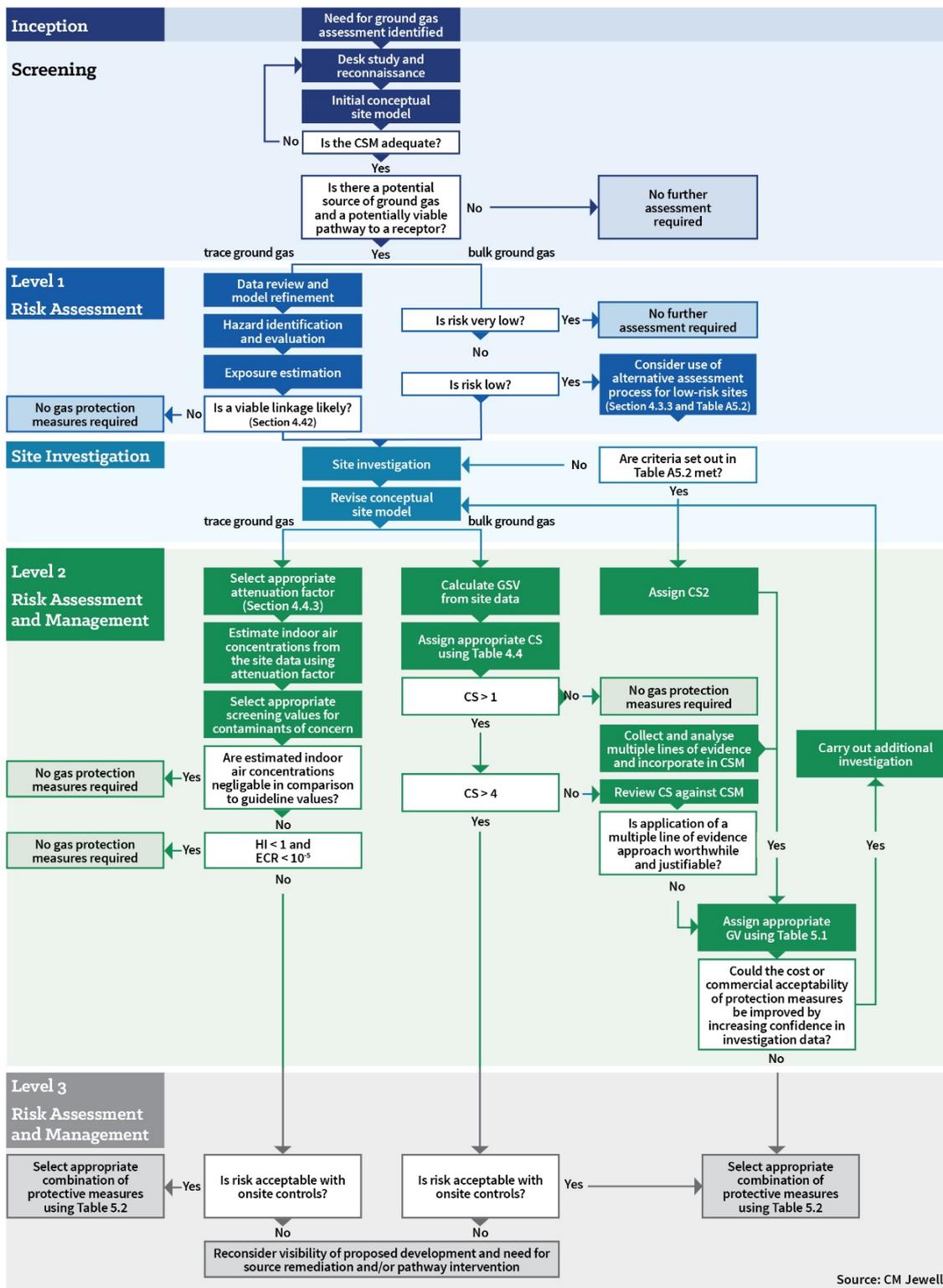


Figure 6 Summary of risk assessment and management process

Source: CM Jewell and Associates Pty Ltd

5. Management options

5.1 Regulatory framework

As discussed in Section 2 of these guidelines, ground gases may originate from a number of sources, both natural and anthropogenic. Some potential anthropogenic sources of ground gas are regulated under existing legislation and administrative arrangements. Where this is the case, these guidelines must be used in conjunction with the existing source-specific regulatory measures.

In NSW, most active and recently closed landfill sites are regulated by an EPL issued under the POEO Act. Such regulation continues until stabilisation criteria have been met. While a landfill site is regulated under an EPL, the terms of the EPL will always take precedence over these guidelines, but these guidelines may still contain information that is useful in developing site-specific management measures.

Although the NSW EPA aims to ensure that an EPL remains in force until a site is stabilised, ground gas problems due to heterogeneous ground conditions may be discovered after regulation under the POEO Act has ceased; these guidelines will apply in such circumstances.

Many older urban landfill sites and some small rural landfill sites have not been regulated by an EPL, and these guidelines will apply when such a site is closed.

Active coal seam gas and petroleum production operations will generally be subject to an exploration or production lease under the *Petroleum (Onshore) Act 1991*. Such operations are subject to the conditions imposed on the lease title, the requirements of the Petroleum (Onshore) Regulation 2016, and any conditions of consent imposed under the *Environmental Planning and Assessment Act 1979* (EP&A Act). However, those documents commonly either contain no conditions or very general conditions in relation to ground gas migration. These guidelines should be adopted in the absence of specific applicable conditions.

Active and closed coal mines are regulated under the *Mining Act 1992*, the Mining Regulation 2016, the *Work Health and Safety (Mines and Petroleum Sites) Act 2013* (WHSMPs Act) and the Work Health and Safety (Mines and Petroleum Sites) Regulation 2014 (WHSMPs Regulation), which are administered by the Division of Resources and Geoscience within the NSW Department of Planning, Industry and Environment.

Work sites other than mines are regulated under the *Work Health and Safety Act 2011* and Work Health and Safety Regulation 2017.

5.2 Approaches to site management

When the results of site investigation and risk assessment indicate that ground gases pose an unacceptable risk, gas protection or risk mitigation measures are required.

Gas protection measures may be applied at a site level, to interrupt the pathway between the source and the receptor outside building footprints, or at the building level. They include:

- passive measures to prevent or restrict gas from migrating or accumulating
- active control measures
- management and/or monitoring.

These measures are described briefly in this section, with more detail in Appendix 6. Passive measures do not require human intervention (other than periodic inspection and maintenance) once installed. Examples include barriers, gas-proof membranes and natural ventilation.

Active measures require continuous operation to control gas concentrations. They include forced ventilation systems, fans and blowers.

Management controls include monitoring systems, alarms and restrictions on building use.

Where the measures involve active or passive venting of gases to the atmosphere, the nature of the emissions, their location and the need for emission controls to reduce methane or VOC concentrations must be considered.

The most appropriate measures must be selected for the particular site by a qualified and experienced professional on the basis of the ground gas regime revealed by site investigations, the nature of development on the site and the assessed risks. The EPA recommends determining the level of protection required for a site based on the CS, as defined in Table 7. Section 5.3 of these guidelines provides a methodology for determining the level of protection, but appropriate professional judgement is also required.

As set out in this section, these guidelines fundamentally require gas protection measures to be:

- designed on a site- and building-specific basis to suit the conditions present, using modelling as necessary
- designed and installed by competent people, in a manner that involves collaboration between designers, suppliers, specialist installers and building contractors
- approached as holistic systems in which the individual components function together to provide both the required primary system performance and adequate redundancy should one component fail.

In keeping with this philosophy, these guidelines do not prescribe the performance specifications of individual components, such as membranes. Designers should be aware of the capabilities of any materials specified and ensure they are appropriate to the overall system design.

5.2.1 Passive protection measures

Passive protection measures are generally preferred where possible because, once they have been installed, minimal management and maintenance are required. Passive protection methods do not require ongoing energy consumption, and generally have a lower carbon footprint than active measures.

Passive protection measures may involve source removal (SR), pathway intervention (PI) and/or building protection (BP), and include:

- fully or partially removing the gas source (SR)
- installing vertical barriers along site boundaries or outside building footprints to prevent lateral gas migration (PI)
- installing vertical sub-surface venting systems to prevent lateral gas migration (PI)
- reviewing and, if appropriate, upgrading the building design, particularly foundations and ventilation systems (BP)
- upgrading and sealing joints and penetrations in reinforced floor slabs (generally in conjunction with other measures) (BP)
- installing gas-proof membranes or other barriers beneath buildings to prevent vertical gas migration into the building (BP)
- installing passive venting systems beneath buildings or incorporating them into the design of ground and sub-ground floors (for example, undercrofts) (BP).

Source removal

Full or partial removal of the source material may be justified for a new development, or a redevelopment involving demolition, where a relatively small volume of gassing fill or natural material is involved. Source materials can be relocated to a licensed landfill. In the case of infrastructure leaks, it may be possible to control the leak at source and reduce ground gas concentrations to acceptable levels using temporary soil vapour extraction, venting or air-sparging systems.

Vertical barriers

Vertical barriers are used to control ground gas migration from a source site, or to prevent migration onto a receptor site. In some circumstances, they may be used to protect building footprints. Many vertical barriers and cut-off walls that have been developed to control groundwater movement can be adapted

to control ground gas migration. Examples include bentonite slurry walls, vertically placed sheet membranes and sealed sheet piles.

Gas barriers must be designed to penetrate to a low-permeability horizon below the gas-bearing layer, or below the watertable, taking watertable fluctuations into account. One significant issue with barriers is that, once installed, gas flow may be diverted around the end of the barrier. Barriers may be installed in conjunction with venting systems to counter this.

Vertical venting

Like vertical barriers, vertical venting systems are used to control lateral migration of ground gases. Vertical venting systems include trenches and well systems, and may be either passive or actively pumped. Vent trenches may be backfilled with granular material, or modular drainage systems may be used. Trenches may incorporate a barrier membrane on the down-gradient side. The choice of system and design will depend on geological and hydrological conditions, the ground gas regime, the nature of the receptors to be protected and site access constraints; modelling may be used to assist with system design.

Membranes

Gas-proof membranes installed beneath buildings may be used as standalone systems or in conjunction with sub-slab venting systems. Membranes may be installed beneath floor slabs or on top of structural slabs and beneath a protective screed. Cushion geofabrics are usually used to support and/or protect the membrane and are required as protection above sub-slab membranes. The most commonly used membranes for protecting buildings from gas are high-density polyethylene (HDPE) (seams are welded in-situ), linear low-density polyethylene (LLDPE) (seams are taped or welded), LLDPE/ethylene vinyl alcohol (EVOH) composites and spray-on bitumastic membranes (seamless). Depending on their application, gas-proof membranes may also function as waterproof membranes.

When selecting and designing a gas-proof membrane, it is essential to consider quality control for the entire membrane and construction process, and to appropriately assess the potential for, and consequences of, membrane damage during and after installation. Membranes should be selected on the basis of specified gas permeability and production quality control; chemical compatibility with the ground gases, soils and potential condensates of concern; manageability, strength and robustness during installation; and long-term durability.

Appendices A6.2.3 and A6.2.4 of these guidelines contain much additional information and many references to recent literature concerning gas resistant membranes and should be consulted before membrane specification.

CIRIA report C748 (CIRIA 2014b) provides guidance on using plastic membranes as VOC barriers, mentioning spray-applied bituminous membranes but providing little information thereon. Much of this guidance is also relevant to using these membranes to protect against bulk ground gases. Annex C of BS8485:2015+A1:2019 provides guidance focussed on bulk ground gases. Lucas and Wilson (2019) specifically discuss aluminium foil core composite gas membranes.

Construction quality assurance (CQA) and construction quality control (CQC) for membranes (and other aspects of ground gas protection) are discussed in Section 5.6 and Appendix A7 of these guidelines. Adequate CQC and CQA are essential components of system design and installation.

It is the clear responsibility of the designer or specifier to ensure that all these factors are appropriately considered, with reference to the scientific and technical literature current at the time, not just information provided by a supplier.

Passive venting

Passive venting systems may involve sub-floor void spaces, proprietary modular drainage systems, or drainage systems, such as perforated pipes or low-profile drains surrounded by gravel blankets or other granular media. Open voids are superior because of the much higher air and gas flows that can be achieved, and because they are less subject to blockage and water-locking. Appropriately-specified modular systems may also have these characteristics. Figures 7 and 8 show examples of sub slab voids.

Advective flows will occur through the inlet and outlet pipes, and any preferred flow paths that develop within the media. This means that if granular media are used, chemicals will transfer into these advective pathways from other parts of the media using diffusion.

Airflow through sub-slab gas drainage systems is maintained through inlet vents (generally placed at or close to ground level) and outlet vents (generally placed at roof level). Cross-flow arrangements should be used whenever possible. It is essential to place inlet vents to avoid damage and inadvertent blockage, and outlet vents to ensure adequate dispersion of vented gas.

Fully passive systems are vented using entirely natural airflow or natural convection, making use of the stack effect. Semi-passive systems use rotating wind-driven cowls. Although such cowls require limited maintenance, periodic inspection is necessary to ensure adequate rotation speeds are maintained.



Figure 7 Polypropylene formers create a sub-slab void

Photograph: CM Jewell & Associates Pty Ltd



Figure 8 Modular drainage system installed beneath membrane

Photograph: CM Jewell & Associates Pty Ltd

Appendix A6 of these guidelines, CIRIA C735 (CIRIA 2014a) and Annex B of BS8485:2015+A1:2019 provide further guidance on ventilation systems.

Foundation slabs

High-quality reinforced concrete slabs, such as post-tensioned slabs (which generally have high resistance to cracking), can be effective barriers against gas migration if all joints and penetrations are adequately sealed. Such slabs may be a component of a combined gas protection system used in conjunction with, for example, a vented sub-slab void space. Whatever their design, all slabs should be inspected after curing, and any cracks should be sealed with an appropriate flexible sealant.



Figure 9 Large vented sub-slab void

Photograph: CM Jewell & Associates Pty Ltd

5.2.2 Active protection measures

Active protection measures may be required when modelling and design studies indicate that passive measures alone cannot reduce risks to an acceptable level on a particular site. Because most active systems incorporate mechanical components (such as fans), regular inspection and maintenance are required, and issues such as noise and vandalism may be more significant than for passive systems. For these reasons, active systems should only be considered for properties where effective long-term management is feasible.

Active systems have ongoing energy consumption requirements and generally a higher carbon footprint than passive systems.

Active protection measures may include:

- sub-slab depressurisation systems
- active venting systems using sub-floor voids or gravel blankets and pipe or modular drainage systems
- active gas extraction wells or trenches
- building over-pressurisation systems
- sub-slab over-pressurisation systems.

Sub-slab depressurisation systems

Sub-slab depressurisation systems use fans or blowers to maintain the pressure in a sub-slab void or blanket below that of the building above. In these circumstances, gas cannot migrate from the sub-slab area to the building. Ground gas will be drawn into the system, and must be vented to the atmosphere in a controlled manner.

Active venting systems

Active venting systems using sub-floor voids or gravel blankets and pipe or modular drainage systems can be considered as fan-assisted versions of the equivalent passive systems described in Section 5.2.1. They function by maintaining an airflow sufficient to dilute and transport any ground gas inflow to the sub-floor space, rather than by maintaining a negative pressure. Systems can be designed to function passively (though less effectively) in the event of mechanical failure.

Vented sumps

Vented sumps are a specific remedial measure for radon intrusion into existing buildings that use the high density of radon. For further information, see BRE (1998).

Active gas extraction wells or trenches

Similarly, active gas extraction wells or trenches may be regarded as mechanically assisted versions of the equivalent passive systems described in Section 5.2.1. They may be required where design studies indicate that passive systems alone will not prevent gas migration. They may also act as design alternatives in well systems to permit wider well spacing. Active systems may be required where the diffusive component of gas flow is significant and it is impractical to incorporate a barrier into the trench design.

Building over-pressurisation systems

Ground gas cannot migrate into a building (or, for example, a basement car park) if the pressure inside can be maintained above the highest ground gas pressure. Such systems are most readily incorporated into the design of new, air-conditioned buildings, but retrofitting may be possible in some cases. The feasibility of such a system has to be assessed in conjunction with the building designers and ventilation engineers.

Sub-slab over-pressurisation systems

In the same way, in buildings with a gas-proof membrane installed beneath a floor slab, it is possible to over-pressurise the sub-slab (sub-membrane) area to prevent ground gas migrating into this space. Such systems require careful design, perimeter gas collection systems and monitoring systems to ensure adjacent buildings are not adversely impacted.

5.2.3 Management controls

Management controls that may be used to mitigate risks associated with ground gases include:

- restrictions on land use
- restrictions on building design or use
- safe work procedures and practices
- monitoring systems
- alarms
- management plans.

In most cases, restrictions on land use and building design or use would be applied through the planning process, as described in Section 6. In some circumstances, and if the land has been declared by the EPA to be significantly contaminated, restrictions may be made subject to regulation under the CLM Act.

Monitoring systems and alarms may be used to supplement other measures for protecting against ground gases – in particular, to demonstrate that those measures are working as designed, and to warn of system failures. Monitoring and alarm systems should preferably not be relied upon as a first line of defence. Exceptions to this would be buildings or structures that are entered infrequently and older buildings where retrofitting other gas protection measures has been impractical. The use of monitoring and alarms in these circumstances should be based on the outcome of a risk assessment.

Monitoring and management controls are also an appropriate approach to manage risks associated with ground gases in service pits, ducts and tunnels; inspection chambers; and other in-ground structures that are classified as confined spaces in Section 5 and regulated under Part 4.3 of the Work Health and Safety Regulation 2017. The regulation imposes specific duties on designers, builders and managers of such structures – in particular, the requirement to maintain flammable gas concentrations at less than 5% of the LEL (0.25% v/v in the case of methane) while work is being carried out.

Management plans should be prepared in most cases where gas protection measures have been implemented. They should be available even for passive measures, to alert building managers and

users to the existence of the systems, and to reduce the risk of inadvertent damage to those systems (for example, by blocking vents or damaging gas-proof membranes with new slab penetrations).

Where active systems are installed, management plans are essential to document inspection, maintenance, monitoring and contingency procedures. They also ensure new staff are appropriately trained, and that knowledge of the systems is not lost as a result of staff turnover.

See Section 6.5 and Appendix 8 for further discussion of management plans.

5.3 Choosing the right approach for the site

As indicated previously, and repeated here for emphasis, a qualified and experienced professional must select the most appropriate measures for the particular site based on the ground gas regime revealed by site investigations, the nature of development on the site, and the assessed risks. Generally, a much wider range of options is available when a new development is planned than when measures must be retrofitted to existing structures. Sometimes it is appropriate to combine a number of measures to provide the required level of protection at a site.

Where site conditions permit, passive gas protection measures should be preferred over active measures or management controls, because they are less likely to fail in the future due to mechanical breakdown or human error and are more energy-efficient. Where active measures are installed, it is essential to prepare a management plan. The difficulty of ensuring long-term compliance with such plans should not be underestimated.

The EPA recommends determining the level of protection required for a site using the following approach, which has been adapted for conditions in NSW from the procedures outlined in BS 8485:2015+A1:2019.

5.3.1 Obtaining a guidance value

The CS obtained from Table 7 and the nature of the existing buildings or proposed development on the site can be used to obtain an appropriate guidance value from Table 8. See Appendix 6 (Section A6.2.1) for a detailed description of the five building categories used in Table 8.

Table 8 Guidance values for gas protection

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

(a) If maximum measured methane concentration exceeds 20% v/v, increase to CS 3.

(b) Residential development is not recommended at CS 4 and above without pathway intervention (for example, source depressurisation or control of lateral migration) external to the buildings and a high level of management. These requirements necessarily preclude low-density residential (NEPM HIL A residential) development.

(c) Evacuation issues and social risks must be considered.

(d) Level 3 risk assessment is required.

5.3.2 Evaluating protection measures

When a guidance value has been obtained from Table 8, proposed gas protection measures, and combinations of measures, may be evaluated using the scores listed in Table 9. A combination of two or more protection measures (no more than one of each type) that are appropriate for the site conditions must be selected so that the combined score equals or exceeds the required guidance value.

It is essential to apply Tables 7, 8 and 9 to a site utilising a sound CSM, knowledge of building design and construction, and reasoned professional judgement. Section 5.2 of these guidelines, and the literature it cites, must be consulted.

Table 9 Scores for protection measures

Measure or system element	Score	Comments
Venting and dilution measures		
Passive sub-floor ventilation with very good performance – the steady-state concentration of methane over 100% of the ventilation layer remains below 1% v/v at a wind speed of 0.3 metres per second (m/s) ^(a)	2.5	The design of the venting layer (i.e. granular medium with inlet/outlet pipes versus open-void or modular drainage system) ^(b) must be considered when modelling steady-state concentrations
Passive sub-floor ventilation with good performance – the steady-state concentration of methane over 100% of the ventilation layer remains below 1% v/v at a wind speed of 1 m/s and below 2.5% v/v at a wind speed of 0.3 m/s) ^(a)	1.5	If post-installation testing of passive ventilation indicates that it cannot meet this requirement, inlets and outlets must be upgraded. If this is unsuccessful, it will be necessary to retrofit an active system
Sub-floor ventilation with active abstraction or pressurisation	2.5	Not appropriate for NEPM HIL A residential settings because robust management systems, including alarms, must be in place to ensure long-term operation and maintenance.,,. Achieving the full score requires a design with adequate redundancy and full coverage of the building footprint.
Ventilated car park (basement or undercroft)	4.0 ^(d)	Assumes that the car park is vented to deal with exhaust fumes in accordance with BCA ^(c) requirements. The design of a car-park and the specifications of its ventilation system need to be considered in assigning an appropriate score of up to four.
Horizontal soil barriers beneath building footprint		
Horizontal clay or amended soil barriers designed to achieve defined permeability and diffusivity of the gases of concern placed, compacted and tested under appropriate engineering supervision	^(d)	Requires appropriate engineering input and integration with the building design from the earliest possible stage. This must consider the effects of any proposed piling on the gas regime
Floor slabs		
Reinforced concrete ground-bearing floor slab or waffle pod slab	0.5	At a minimum, it is good practice to install ventilation in all foundation systems to relieve pressure. Breaches in floor slabs, such as joints, have to be effectively sealed against gas ingress to maintain performance
Reinforced concrete ground-bearing foundation raft slab with limited service penetrations cast into slab	1.0	
Reinforced concrete cast in situ or post-tensioned suspended slab with minimal service penetrations and water bars around all penetrations and at joints	1.5	
Fully tanked basement	2.0 ^(d)	The design of a basement and the specifications of its ventilation system need to be considered in assigning an appropriate score. Fully tanked means designed to be

		waterproof under the range of groundwater conditions likely at the site, to the extent that supplementary internal drainage is not required.
Membranes		
Proprietary gas-resistant membrane with a gas transmission rate for the gases of concern on the site that is certified and appropriate to the overall design of the gas protection system. It should be installed by a specialist to an appropriate level of workmanship with documented internal CQC, including integrity testing (e.g. tracer gas or smoke testing), under independent CQA carried out by a certified specialist ^(e) or appropriately qualified and experienced professional with independent verification of the entire process ^(f)	2.0	Membrane performance depends on the membrane material and thickness specified, design and quality of the installation, protection from and resistance to damage after installation, and the integrity of joints in membranes that require joints. Materials that offer some degree of self-sealing and repair are preferred. Long-term performance depends on the durability of the material, including its resistance to chemical degradation in the environment in which it is installed
Monitoring and detection (alarms)		
Intermittent monitoring using hand-held equipment	0.5	Monitoring and alarm systems are only valid as part of a combined gas protection system. Where fitted, permanent systems should be installed in the underfloor venting system but can also be provided in the occupied space as a back-up
Permanent monitoring system installed in the occupied space of the building	1.0	
Permanent monitoring system installed in the underfloor venting or dilution system	2.0	
Pathway intervention external to building footprint		
Vertical barriers	(g)	Required for residential and public buildings at CS 4 and above
Vertical venting systems (source depressurisation)	(g)	
<p>(a) Verified by post-construction monitoring</p> <p>(b) See Appendix 6</p> <p>(c) Building Code of Australia</p> <p>(d) Score depends on site-specific conditions and design</p> <p>(e) For example, Geosynthetic Certification Institute – Inspectors Certification Program</p> <p>(f) See Appendix 7</p> <p>(g) Score depends on site-specific conditions and design, but scores of 4.0+ should be achievable</p>		

5.4 VOC and mercury vapours

Measures should be installed to protect existing or new buildings against vapour intrusion when:

- the building is located (or proposed to be located) above or close to a source area or groundwater plume that cannot practically be remediated within a reasonable period of time, and
- a Level 3 risk assessment has been carried out for occupiers of the building, and
- the risk assessment indicates a hazard index for threshold chemicals of greater than 1, or a carcinogenic risk for non-threshold chemicals of greater than 10^{-5} , or
- credible changes to the groundwater flow regime could result in the acceptable risk levels for a proposed building being exceeded, and it would, therefore, be rational to incorporate protection measures into the construction.

Tables 7 and 8 were originally developed to assess protection requirements for bulk ground gases. However, the protection measures listed in Table 9 will be effective in managing trace gas intrusion into buildings provided that, at the design stage, an assessment is made of the gas transmission rate and chemical resistance (including long-term durability) of membranes and other materials used in the protection system to the contaminants of concern and environmental conditions at the site. However, the following significant differences exist:

- The intrusion of vapour into buildings is primarily driven by diffusion and by pressure differences created by meteorological conditions and building ventilation; driving pressure at the source is not usually a contributing factor.
- VOC hazards are usually chronic rather than acute; carcinogenic risks are typically assessed over periods of between 30 years (commercial or industrial land use) and 70 years (residential land use).
- In most cases the NSW EPA will require the vapour source to be remediated as much as possible, and therefore the source concentration should decrease with time. This should be considered when selecting protection measures.

Taking these factors into account, together with the need for some redundancy, when protective measures are required against vapour intrusion a level of protection equivalent to that specified for CS 3 (Tables 7 and 8) is generally considered appropriate.

It is necessary to design a vapour risk mitigation system on a site-specific and chemical-specific basis; the following general principles should be applied to the design:

- At least one level of redundancy is necessary (for example, if a sub-slab membrane and a sub-membrane venting system are to be used, each should be independently capable of providing the protection required).
- The vapour flux from the ground into a venting layer must be calculated using an appropriate advective or diffusive transport model.
- The vapour flux through a membrane must be calculated using a value of vapour permeation rate for the specific membrane to the specific chemical of concern that has been measured using an appropriate Australian Standard (AS), British Standard (BS) or European Standard (EN), International Organization for Standardization (ISO) or ASTM Standard Method.
- Honouring the design principles embedded in Table 9 and those applied in the development of the ASC NEPM vapour HILs and HSLs, airflow through a venting system at a wind speed of 1 m/s should be sufficient to maintain concentrations of all chemicals of concern below the relevant vapour HILs and HSLs, or site-specific levels calculated using a Level 3 risk assessment, across 100% of the venting layer. For chemicals that do not have a HIL or HSL, and where no site-specific risk-based levels are available, the design objective should be to maintain concentrations of less than 10 times the relevant inhalation TRVs within the venting layer.
- Post-construction monitoring is required to establish that concentrations within the venting layer, and both concentrations and airflow within risers are in accordance with the design at relevant wind speeds.

See also Section 5.2, Appendix A6 and Appendix A7 of these guidelines and the literature they cite.

Long-term management plans are usually required for vapour risk mitigation systems.

5.5 Radon

In NSW, it is likely that the need for intervention measures to reduce radon concentrations will be assessed after levels persistently exceed the guidelines for indoor air in existing buildings. Because radon flux is primarily driven by diffusion and pressure differences created by meteorological conditions and building ventilation, measures that are effective in managing other ground gases will be effective in managing radon intrusion; the key consideration will usually be the practicability of retrofitting measures to an existing building. However, if a problem is demonstrated in a particular area due to a local geological source, it is possible that new buildings in that area may require protection.

Where the average indoor air concentration of radon in an existing building exceeds the Australian guideline value of 200 Bq/m³ (equivalent to the UK action level) by a factor of two or less, improved building ventilation and the use of a silicone or mastic sealant and/or sealing coating to reduce leakage through the floor may suffice.

For the likely worst case in NSW, where the average indoor air concentration of radon persistently exceeds 200 Bq/m³ by a factor of up to four, a level of protection equivalent to that required for CS 2 (Tables 7 and 8) is appropriate. This should provide protection similar to (or somewhat better than) the *Full Protection* level described in BRE Report BR211 (2007).

Specific measures not listed in Table 9 – for example, the use of vented sumps and building over-pressurisation (Section 5.2.2) – should also be considered.

5.6 Geotechnical considerations

Where gas protection measures are proposed for former landfill, or filled sites in general, the long-term stability of these systems must be considered. Low-density residential development on historically filled land with known ground gas issues is becoming increasingly common in NSW.

Settlement is a key issue; therefore, a good understanding of the related geotechnical issues is essential to determine the best methods for preventing ground settlement, particularly differential settlement. Geotechnical issues are not only a major element of the site investigation process (and site characterisation) but, more importantly, they are also critical in designing the ground gas mitigation system. This is particularly the case where reworking, re-compaction and other ground improvement measures must form a significant component of capping system construction. Similarly, geotechnical controls are an important part of the related CQA (both capping and other ground gas mitigation systems). In this regard, ground improvement parameters that are required from a geotechnical perspective can generally be incorporated into both the investigation and mitigation approaches. This synergy addresses two issues with the same work, reducing project time and cost.

These issues may be less important where the site is to be covered entirely by a slab suspended on piles, although the potential for piling to provide a vertical gas flow pathway needs to be addressed. Wilson and Mortimer (2018) provide a detailed discussion of this issue from a UK standpoint, from which it is apparent that in circumstances where diffusive flow is dominant, neither large displacement-driven piles nor replacement piles are likely to cause preferential pathways for ground gas migration. The exceptions are driven H and I piles, where an open annulus may form. However, flows are unlikely to be significant unless piles are very closely spaced. Where advective flow is dominant, and differential gas pressure relatively high and confined by a thin layer of very stiff clay, annular gas flow may occur, with its significance again dependent on pile spacing.

Settlement issues are important for sites where deep piled foundations may not be feasible, particularly if residential development is proposed.

On these sites, the ground generally requires treatment to reduce the impacts of settlement on structures. Various methods, including high-energy and dynamic compaction, are used on these sites, which may range from major transport infrastructure projects to low-density residential development.

Matters that may need to be addressed include:

- geotechnical investigation requirements, to determine settlement characteristics as well as other data, such as gas permeability of soils
- the types and amounts of settlement both before and after compaction
- settlement monitoring and prediction (and settlement modelling), particularly post-compaction
- material placement methods and certification
- geotechnical site improvement - the types of ground treatment and methods of compaction – for example, dynamic compaction and high-energy compaction
- compaction trials, effective depths of compaction and geotechnical validation
- the sorting of fill materials and removal of geotechnically-unsuitable or hazardous materials before replacement and compaction (as described in Card et al. 2012)
- the organic content of fill materials and its effect on compaction.

Therefore, when selecting gas protection measures and when designing and constructing gas protection systems it is important to consider geotechnical issues. This is particularly the case in relation to current and predicted settlement at any given site, and the sensitivity of proposed gas protection measures to such settlement.

More detailed treatment is beyond the scope of these guidelines. To a significant extent, geotechnical investigation and ground engineering approaches developed in other contexts can be adapted to the particular requirements of gas protection systems and the constraints of individual sites. Applying geotechnical expertise at an early stage and throughout the project is a fundamental requirement.

The suggested further reading in the bibliography (Section 7.3) should be consulted for additional information, including:

- BRE 424 (2015), *Building on Fill: Geotechnical Aspects*
- BRE 447 (2002), *Brownfield Sites: Ground-Related Risks for Buildings*
- Oweis and Khera (1998), *Geotechnology of Waste Management*.

5.7 Independent review of gas protection measures

The contractual arrangements that may be used for construction projects in NSW are varied and complex, and State Environmental Planning Policy No 55 - Remediation of Land (the SEPP) gives planning authorities substantial discretion in the review requirements that need to be included in conditions of consent. Therefore, it is not possible to make these guidelines prescriptive in relation to the review process for constructing ground gas protection measures. This section describes an independent verification and review framework that the NSW EPA considers to be appropriate for installing protection measures on typical sites with moderate or higher ground gas risk (see Table 7). It is expected that such sites would be subject to a site audit.

As with other aspects of contaminated land management, a planning authority may require an accredited site auditor to carry out a review and issue a site audit statement.

When a site auditor is appointed, the auditor is required to oversee the design, installation, CQC, CQA and post-construction validation testing processes, and to review the associated data. A qualified and experienced professional may carry out the peer review for low-risk sites if a site auditor is not appointed (subject to the discretion of the planning authority).

In all cases, it is essential that the selection, design, implementation and testing of protection measures is independently verified and reviewed. This is a multilayered process, beginning with reviewing the design and specifications for the protection systems and CQA program, then reviewing the selection of a qualified installer; the CQC carried out and documented by the installer; the independent CQA oversight of the installation and its validation with appropriate testing; performance monitoring of the completed system; and, ultimately, certification and approval through the site audit and planning process. Independent verification – including CQA oversight of installation, testing and performance monitoring – is therefore a necessary component of constructing systems to protect buildings against hazardous ground gases. CIRIA report C735 (2014a) provides detailed guidance on testing and verifying these systems. Appendix 7 of these guidelines further describes these requirements in a NSW context.

Pre-construction certification is generally carried out through the planning and construction certification process under Part 4A of the EP&A Act, with the principal certifying authority (PCA) issuing a construction certificate before construction. This occurs after providing the PCA with the design, specifications and peer review for the construction, or a Section B site audit statement.

During construction, it is expected that the installer will conduct CQC testing, while CQA is provided by an independent person (a site auditor or an appropriately qualified and experienced person in ground gas protection, if approved by the planning authority).

An independent consultant should conduct post-construction validation testing under the supervision of a qualified and experienced professional.

Where an environmental management plan (EMP) is specified, it is important to ensure it is enforceable and to specify measures for a regular independent review and report on its implementation and effectiveness. If appointed, a site auditor is required to review the EMP and confirm that the measures are appropriate.

Final certification of the installation is generally carried out through the planning construction certification process under Part 4A of the EP&A Act. The PCA will issue an occupation certificate once it has received the CQA report and peer review, or a Section A2 site audit statement.

6. Interfaces with government and other agencies

6.1 Interface with the planning process

Under the requirements of SEPP 55, authorities must consider whether land is contaminated before consenting to any development on that land. Ground gases at concentrations that present a risk to human health fall within the definition of contamination set out in Section 5 of the CLM Act.

In general, authorities should consider whether land that falls within the ambit of SEPP 55 may have been impacted by ground gases. These guidelines should assist with that consideration.

6.2 Interface with the NSW EPA and other relevant authorities under the POEO Act

Section 148 of the POEO Act imposes a general obligation to immediately notify the NSW EPA and other relevant authorities of pollution incidents causing or threatening material harm to the environment. The threshold of 'material harm' is low, being harm that is 'not trivial' or, alternatively, represents potential loss or property damage exceeding \$10,000. Therefore, in many circumstances ground gas detections will meet the notification criteria.

The requirements of Section 148 apply whether or not the premises or activity concerned are subject to an EPL.

'Relevant authority' means any of the following:

- (a) the appropriate regulatory authority
- (b) if the NSW EPA is not the appropriate regulatory authority — the NSW EPA
- (c) if the NSW EPA is the appropriate regulatory authority — the local authority for the area in which the pollution incident occurs
- (d) the Ministry of Health
- (e) SafeWork NSW
- (f) Fire and Rescue NSW.

The 'appropriate regulatory authority' is dependent upon the circumstances of the site, as described in Section 6 of the POEO Act.

Ground gas detections that indicate leakage from identifiable underground petroleum storage systems may trigger notification and other management procedures under that system's Environment Protection Plan.

See also Sections 1.3, 1.4, 3.6.2 and 5.1 of these guidelines.

6.3 Interface with the NSW EPA under the CLM Act

Sites that are significantly impacted by ground gases are likely to require notification to the NSW EPA under Section 60 of the CLM Act. Sites that are the source of ground gases that are migrating across site boundaries are also likely to require notification.

A decision process and checklist for site owners or responsible persons considering reporting contamination under Section 60 is provided in Appendix 1 of the *Guidelines on the Duty to Report Contamination under the Contaminated Land Management Act 1997*.

The provisions of Sections 2.3.6 and 2.3.7 of those guidelines should be considered when deciding on the duty to report, noting that Section 2.3.6 addresses bulk ground gases as well as trace ground gases. The migration of ground gases through natural and anthropogenic media and pathways must be considered in addition to the stated notification triggers.

The site and risk assessment framework outlined in Sections 3 and 4 and the data tabulated in Appendix 2 of these guidelines should be considered and applied when dealing with sites potentially contaminated by ground gases.

Notification is not required if approved management measures are in place to control gas entry into buildings or in-ground services.

6.4 Interface with the NSW site auditor scheme

Some sites that are impacted or potentially impacted by ground gases will require a site audit. This is because a relevant development consent is subject to conditions that require a site audit statement to be issued stating that the site is suitable for the proposed use or, specifically, that appropriate gas protection measures have been implemented.

Other sites may be subject to a site audit due to the terms of a management order or the conditions of a voluntary management proposal approved by the NSW EPA under Part 3 of the CLM Act.

Where gas protection measures are required, appropriate staging of the site audit and other certification requirements is necessary because implementation of gas protection measures are usually integrated with building construction, and the site audit statement(s) cannot be issued until all the measures are built and operational, which is often delayed until the final stages of the construction process.

Because gas protection measures (active or passive) must remain in operation to continually manage the risks associated with ground gases, it is generally appropriate for site auditors to use Section A2 rather than Section A1 of the site audit statement form.

6.5 Environmental management plans

Because environmental management plans (also known as 'long-term management plans') are a vital part of the gas protection measures on many sites impacted by ground gases, the practicality, enforceability, and maintenance of these plans are particularly important and require particular care by site owners, site auditors, and local authorities.

Environmental management plans must be able to be enforced when they are included as a condition on a site audit statement. Where a site auditor is required to certify the appropriateness of an environmental management plan, this should be done using Section A2 of the site audit statement form. The active or passive nature of ground gas management systems should be indicated, as appropriate.

Selection of the most appropriate enforcement mechanism will always be specific to the circumstances of a site. Where circumstances permit, conditions of development consent may be the most effective means of enforcement.

Mechanisms should be developed for regular independent review and reporting on the implementation and effectiveness of management plans. It is generally necessary for a qualified and experienced independent expert to conduct an annual review or audit that includes providing a report to the appropriate planning or regulatory authority. The scope of this review will be site-specific and dependent upon the nature and complexity of the management measures specified in the plan.

While less frequent reviews may be appropriate in some circumstances, an annual reporting period should be considered standard; the appropriateness of longer review cycles needs to be very carefully considered and justified, even when only passive management is required. The advantages of annual review include:

- It is less likely to be overlooked due to personnel changes and consequent corporate memory loss;
- It is easy to include as a recurring event in annual budgets corporate calendars – for both the responsible organisation and the review authority;
- It is more attuned to the timeframe involved in planning and implementation for maintenance and iterations
- In the event of system failure, it minimises exposure duration.

If a management plan deals with potentially explosive or flammable ground gases, it is appropriate to include compliance with the management plan as an 'essential fire safety measure' on the fire safety schedule issued for the building. The outcome of the annual review must then be provided to the local council and the Commissioner of Fire and Rescue NSW in the annual fire safety statement.

Management plans should also contain provisions for notifying the appropriate authorities, which may include the NSW EPA and emergency services, if gas concentrations exceed the levels specified in the plan during post-implementation monitoring.

The review and reporting requirements of a management plan should be specified in the plan. They will then be enforceable through the same mechanism as the other measures required by the plan.

Appendix 8 provides a suggested framework for developing environmental management plans for sites impacted by ground gases.

6.6 Emergency notifications

If an acute or explosive risk from ground gases is suspected, immediate action should be taken to address the risk, including contacting relevant emergency services.

During ground gas investigations, it is possible that the presence of gas that is positively or tentatively identified as originating from leaks in gas mains or other services will be detected. In these circumstances, the service provider and, if appropriate, emergency services (NSW Police and NSW Fire and Rescue) should be notified immediately.

It is expected that any party undertaking intrusive investigations, regardless of their purpose, will have the contact details for relevant service providers.

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7.3 Suggested further reading

Building Research Establishment 1987, *Measurement of Gas Emissions from Contaminated Land*, report prepared by D Crowhurst, BRE, Watford, UK.

A frequently referenced but now somewhat dated manual that still contains some valid information and is helpful for determining the usefulness of older assessments.

Building Research Establishment 2001, Report 414, *Protective Measures for Housing on Gas-Contaminated Land*, report prepared by R Johnson, BRE, Watford, UK.

www.brebookshop.com/addtobasket.jsp?id=93589&publisherid=163.

This manual provides a practical guide to good practice for detailing and constructing passive soil gas protective measures for new and existing residential development. Some aspects are specific to UK conditions and building practices, and not necessarily relevant to NSW conditions, while others are adaptable to local conditions.

Building Research Establishment 2002, Report 447, *Brownfield Development Sites: Ground-Related Risks for Buildings*, report prepared by JA Charles, RC Chown, KS Watts & G Fordyce, BRE, Watford, UK, www.brebookshop.com/addtobasket.jsp?id=139911&publisherid=163.

This is another frequently referenced but dated manual that still contains valid information and is helpful for determining the usefulness of older assessments.

Building Research Establishment 2015, Report 424, *Building on Fill: Geotechnical Aspects*, 3rd edition, report prepared by K Watts and A Charles, BRE, Watford, UK.

www.brebookshop.com/addtobasket.jsp?id=327570&publisherid=163.

This report encompasses BRE's unique experience over more than 40 years in research and consultancy and brings the subject up to date. New material includes:

- research findings and industry experience since publication of the second edition 14 years ago
- additional chapters on ground improvement and treatment using both proprietary and non-proprietary techniques
- six new case histories and updated cases from the second edition
- studies on the behaviour of fills over both a longer time period and a wider range of fills.

Department of the Environment, Transport and the Regions 1997, *Passive Venting of Soil Gases Beneath Buildings Research Report: Guide for Design*, report prepared by Ove Arup & Partners, DETR, London, England, UK.

This report provides detailed information, including a description of relevant design issues and inputs; the results of computational fluid dynamic modelling; and conclusions on a range of gas drainage, ventilation and barrier approaches, including open voids, drainage blankets and membranes.

Interstate Technology and Regulatory Council 2007, *Vapor Intrusion Pathway: A Practical Guideline*, ITRC, Washington DC, USA.

This guideline provides an overview of vapour intrusion issues and covers preliminary screening, site investigation and data interpretation. It briefly covers modelling and comprehensively considers mitigation strategies.

NHBC 2007, *Guidance on Evaluation of Development Proposals on Sites where Methane and Carbon Dioxide are Present*, NHBC, Milton Keynes, England, UK.

This guideline provides useful background reading.

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This reference includes a useful international perspective on gas management in waste repositories.

UK Environment Agency 2004b, *Guidance for Monitoring Trace Components in Landfill Gas*, LFTGN04 v3.0 2010, UK Environment Agency, Bristol, England, UK,
www.gov.uk/government/publications/monitoring-trace-components-in-landfill-gas-lftgn-04.

This is a useful reference that provides guidance on monitoring trace components in Landfill gas and provides the methodology used to collect the data provided in Appendix 3.

UK Environment Agency 2004c, *Guidance on the Management of Landfill Gas*, Publication LFTGN03, UK Environment Agency, Bristol, England, UK,
www.gov.uk/government/publications/management-of-landfill-gas-lftgn-03.

This is a core reference on landfill gas management that provided the basis for current guidance in NSW and Victoria.

UK Government 2014, 'Environmental Permitting: Landfill Sector Technical Guidance',
www.gov.uk/government/collections/environmental-permitting-landfill-sector-technical-guidance.

This is a consolidated collection of all UK Environment Agency landfill guideline documents.

Wilson S, Card G & Haines S 2009, *Ground Gas Handbook*, Whittles Publishing, Dunbeath, Scotland, UK.

This comprehensive and practical manual was originally written to provide guidance to local government contaminated land officers in the UK. Based on CIRIA C665 and BS 8485:2015+A1:2019, with additional material.

Appendix 1

Glossary of ground gas terms

Absorption	The uptake and retention of a fluid (liquid, gas or vapour) into a solid or another fluid
Active ventilation	Ventilation using fans or blowers
Adsorption	The uptake and retention of a fluid or dissolved matter onto the surface of a solid
Advection	Mass transfer of a substance (including contaminants) through the flow of a fluid, such as water, or air under a pressure gradient
Aerobic	A process that occurs in the presence of oxygen
Anaerobic	A process that occurs in the absence of oxygen
Asphyxiation	Unconsciousness or death due to lack of oxygen
Aquifer	A body of saturated rock or soil containing a system of interconnected voids with a hydraulic conductivity sufficient to allow the flow of groundwater at a rate that is significant for the issue under consideration
Aquitard	A saturated but poorly permeable bed, formation or group of formations that does not yield water freely to a bore or spring. An aquitard may transmit appreciable quantities of water to and from an aquifer when an artificial stress, such as pumping, is applied to a system.
Attenuation	The decrease in the concentration of chemicals present in a fluid, generally with flow or with time (for example, pollutants in groundwater as a result of biological activity or adsorption onto the aquifer matrix)
Bentonite	A clay composed mainly of the mineral montmorillonite. It swells to many times its dry volume when it comes into contact with water.
Biochemical (biological) oxygen demand (BOD)	An empirical measure in which standardised laboratory procedures are used to determine the relative oxygen requirement of a microbial population degrading organic material in a water sample. BOD test results indicate levels of organic contamination.
Borehole	A hole drilled in the ground to obtain samples of soil or rock. Permanent groundwater and gas monitoring wells can be installed in a borehole. Boreholes are also used to vent or withdraw gas, or drain or pump water.
Borehole flow rate	The volume of gas per unit time that is escaping from a borehole or standpipe (regardless of composition), usually measured in L/hr
Brownfield site	Previously developed land that may or may not be contaminated
Bulk ground gases	Gases that are major components of ground gas, typically present at percentage concentrations. Alternative terms used in other publications (not strict synonyms) are 'permanent gases' and 'general gases'.
Catalyst	A substance that speeds up a chemical reaction without undergoing any permanent change itself
Chemical oxygen demand (COD)	A measure of a polluting liquid's potential to remove oxygen from the receiving water through chemical oxidation processes (COD is always higher than BOD)
Combustion	A chemical process of oxidation that occurs at a rate fast enough to produce heat and, usually, light in the form of either a glow or flames
Concentration	See 'mass concentration' and 'volumetric concentration'.
Conceptual model	A theoretical representation of the ground below and around a site, including potential gas sources, water and gas migration pathways, receptors and natural barriers to migration

Confined groundwater	Groundwater that is held in an aquifer at a pressure greater than hydrostatic pressure by an overlying confining bed (aquitard). This bed must have a distinctly lower hydraulic conductivity than the aquifer.
Construction quality assurance (CQA)	A planned system of activities that provides the site owner and the NSW EPA with assurance that gas protection measures were constructed as specified in the design. CQA includes inspecting, verifying, auditing and evaluating materials and workmanship to determine and document the quality of the completed work. An evaluation includes details of measures the CQA organisation used to assess whether the installer or contractor complied with project plans and specifications.
Construction quality control (CQC)	A planned system of inspections that directly monitors and controls the quality of gas protection measures to ensure high standards in the constructed or installed system. CQC inspections are normally performed by the system installer or, for natural soil materials, by the earthworks contractor. CQC refers to the measures taken by the installer or contractor to determine compliance with the requirements for materials and workmanship stated in the project plans and specifications.
Contaminant	Any physical, chemical, biological or radiological substance or matter in water or soil that is not of natural origin
Convection	Mass transfer of a gas or liquid due to the combined effects of advection and diffusion. In this document, the term is used solely to refer to buoyancy-driven flow through a stack, where advection is dominant.
Cover	Material used to cover solid waste deposited in landfill
Critical pressure	The pressure above which a solid or liquid cannot be converted to a gas by increasing the temperature
Critical temperature	The temperature above which a gas cannot be converted to a liquid by applying pressure alone
Degradable material	Any material that can biodegrade to produce ground gas (see also 'Putrescible material')
Development	Construction works, which may be buildings or civil engineering structures above or below ground, including ancillary works, installations and open spaces associated with the structures
Diffusion	The mass transfer of a substance from an area of higher concentration to an area of lower concentration. Diffusion is a result of the kinetic properties of particles of matter. The particles will mix until they are evenly distributed.
Diffusivity or diffusion coefficient	A measure of the ease with which one substance may diffuse through another. The dimensions are $[L^2T^{-1}]$ and the units according to the International System of Units (SI) are m^2s^{-1} .
Explosion	A sudden, violent release of energy, usually combined with the generation of high temperatures and the release of gases. An explosion causes pressure waves in the medium in which it occurs.
Factor of safety	A design factor used, in the context of these guidelines, to allow for gas flows greater than those assumed, and for uncertainties in monitoring and modelling gas flows in the ground and the performance of gas protection measures
Fermentation	A metabolic process in which linked reduction and oxidation reactions occur. These processes, performed by microorganisms, release energy. Examples are the production of fatty acids, carbon dioxide and hydrogen from carbohydrates, and the production of methane and carbon dioxide from fatty acids.
Flammable	A substance capable of supporting combustion in air
Flux	Movement of fluid (gas or liquid)
Fracture	Any breakage of a rock mass along a direction or directions not associated with cleavage or fissility

Gas	One of three states of matter, characterised by very low density and viscosity (relative to liquids and solids), with complete molecular mobility and the capability to expand indefinitely to occupy any container with almost complete uniformity. At a given temperature, a gas is distinguished from a vapour because it cannot be liquefied by applying pressure alone (an example is methane at temperatures above its critical temperature of -83°C).
Gas flow rate	The volume of gas moving through a permeable medium or issuing from a monitoring well per unit of time
Gas generation rate	The rate at which a source degrades to produce methane or carbon dioxide gas. This is measured as the volume of gas produced per unit mass or volume of substrate per unit time.
Gas screening value (GSV)	The gas concentration (% v/v) measured in a monitoring well multiplied by the measured borehole flow rate (L/hr)
Geomembrane	A relatively impermeable polymeric sheet or sprayed coating used as a barrier to prevent the migration of groundwater, ground gas or vapour
Ground gas	A general term to include all gases (including methane, VOCs and other vapours) occurring or generated within the ground
Groundwater	The water in the sub-surface zone, comprising both unsaturated (vadose) zone groundwater and saturated (phreatic) zone groundwater. It is referred to as 'ground water' in the USA.
Groundwater table (watertable)	The surface between the zone of full saturation and the zone of aeration or partial saturation, at which the groundwater pressure is atmospheric; the surface of an unconfined aquifer
Volatile Halogenated Compound (VHC)	Volatile organic chemicals containing one or more of the halogens: fluorine, chlorine, bromine or iodine
Hazard	A substance, feature or situation that has the potential to cause harm to the environment, property, humans or animals
Henry's law constant	The relationship between the equilibrium concentration of a gas dissolved in a liquid and its concentration or partial pressure in the gaseous phase. This may be expressed as a volatility constant or its reciprocal, a solubility constant, in a variety of units or as a dimensionless constant.
Hydraulic conductivity (K)	A measure of the ease with which water, in the conditions prevailing in the aquifer, can flow through rock or soil. It is a function of the intrinsic permeability (k) of the material, the density (ρ), the acceleration due to gravity (g), the dynamic viscosity (μ) of water, and the degree of saturation, where $K_{(\text{sat})} = k\rho g/\mu$. It is measured as the flow per unit cross-sectional area under unit hydraulic gradient. The dimensions are length over time [LT^{-1}] and the SI units are ms^{-1} .
Hydraulic gradient	The change in static head per unit of distance in a given direction. If not specified, the direction is generally understood to be that of the maximum rate of decrease in head. It is dimensionless.
Hydrocarbon	A compound containing both hydrogen and carbon. In the context of these guidelines, it includes contaminants, such as fuels, oils and chlorinated solvents.
Infiltration	The movement of water through the ground surface into small voids in either the saturated or unsaturated zone
Ion	An element or compound that has gained or lost an electron, so that it is no longer neutral electrically but carries a charge
Ionisation	The process of changing a particle with no charge into one with a positive or negative charge by removing or adding electrons
Intrinsically safe	An instrument (or equipment) that does not generate an ignition source within the gas atmosphere being monitored
Landfill	Waste or other materials deposited into or onto the land

Landfill gas	A variable mixture of gases generated by decaying organic matter within a landfill site. The principal components are methane and carbon dioxide but there can also be other trace gases and vapours.
Leachate	Liquid produced as a result of water seeping through a landfill and being contaminated by substances in the deposited waste
Lower explosive limit (LEL)	The minimum percentage by volume of a mixture of gas in air that will propagate a flame in a confined space, at normal atmospheric temperature and pressure
Mass concentration (gaseous)	The mass of a particular gaseous constituent in a given volume of a gas mixture. This is typically denoted in units of mg/m ³ or µg/m ³ .
Methanogenic	Methane-producing
Monitoring well	A well installed into the ground (commonly in a borehole but can also be driven into the ground) to monitor groundwater or ground gas
Oxidation	The addition of oxygen, removal of hydrogen or loss of electrons during a chemical reaction
Partial pressure	The pressure exerted by a component of a gas mixture, equal to the total pressure times the mole fraction of the component
Passive ventilation	Ventilation that relies on wind and temperature differences to create air movement
Pathway	The route by which a hazard can reach a receptor
Perched groundwater	Groundwater separated from the main underlying body of groundwater by an unsaturated zone. Where it is unconfined, it has a perched watertable. Perched groundwater is held up by a confining bed with hydraulic conductivity so low that water percolating downwards through it is not able to bring the water in the underlying unsaturated zone above atmospheric pressure. Perched groundwater is a common, though not a necessary, feature of recharge areas.
Permeability (k)	A measure of the ease with which fluids can flow through a rock or soil. While the term is sometimes used as a synonym of hydraulic conductivity (K), the intrinsic permeability is independent of the properties of the fluid and $K = k\rho g/\mu$. The common unit is the Darcy, the dimensions are [L ²] and the SI units are m ² .
Permeation coefficient	A measure of the ease with which a gas can dissolve into and diffuse through a solid; the product of the solubility coefficient and diffusivity. The dimensions are [L ² T ⁻¹] and the SI units are m ² s ⁻¹ .
pH	Hydrogen potential. A measure of the acidity or alkalinity of a solution; numerically, the negative logarithm of the hydrogen ion activity and equal to 7 for neutral solutions at 25°C, increasing with alkalinity and decreasing with acidity
Piezometric surface	See 'potentiometric surface', which is the preferred term.
Porosity (ϕ or η)	A dimensionless measure of the voids within a rock or soil (spaces in the material not occupied by solid matter). This may be expressed quantitatively as the ratio of the volume of the voids to the total volume of the rock or soil. With respect to the movement of water, only the effective porosity (that due to interconnected voids) is significant. Many confining beds are distinguished from aquifers by their low effective porosity and/or extremely fine pore size – high specific retention rather than differences in total porosity.
Potentiometric surface	An imaginary surface defined by the potentials at all points on a given plane within an aquifer. Where the hydraulic gradient perpendicular to the plane is much less than the hydraulic gradient parallel to the plane, it is reasonable to apply the concept of potentiometric surface to the aquifer as a whole. This term is preferred to the synonym 'piezometric surface'.
Putrescible material (putrescible waste)	Material (generally organic material) that can biodegrade in a landfill to produce ground gas and leachate components
Receptor	Anything that could be affected by a hazard, including the environment, property, humans and animals
Reduction	The removal of oxygen, addition of hydrogen or addition of electrons during a chemical reaction

Risk	The probability that harm will occur as a result of exposure to a hazard
Solubility	The mass of the dissolved solid or gas that will saturate a unit volume of a solvent under stated conditions
Solubility constant	The ratio between the equilibrium dissolved phase concentration of a gas in a solid or liquid phase and its concentration or partial pressure in the gaseous phase (C_L/C_G), reciprocal of the volatility constant
Surface emission rate	The rate at which gas is emitted from a unit area of the ground surface; that is, the volume of gas per unit time per unit area, typically measured in L/m ² /h
Trace ground gases	Minor constituents of ground gas, typically present at ppm or ppb concentrations
Toxicity reference value (TRV)	A value for the toxicity of a substance with which measured concentrations (e.g. mg/m ³) or calculated intakes (e.g. mg per kg body weight per day) can be compared for risk assessment purposes
Transmissivity (T, KD)	The rate at which the water in an aquifer is transmitted through a unit width of aquifer under a unit hydraulic gradient. It is the product of the average hydraulic conductivity and saturated thickness of the aquifer and is equal to the summation of the hydraulic conductivity across a unit width of the saturated part of the aquifer perpendicular to the flow paths. The dimensions are [L ² T ⁻¹] and the SI units are m ² s ⁻¹ .
Unified Soil Classification System (USCS)	Standard system for describing the lithology and physical properties of soils
Upper explosive limit (UEL)	The maximum percentage by volume of a mixture of gas in air that will propagate flame in a confined space, at a normal atmospheric temperature and pressure
Vadose zone	The zone containing water at a pressure less than atmospheric pressure, including soil water, intermediate vadose water and capillary water. This zone is limited above by the land surface and below by the surface of the zone of saturation – that is, the watertable.
Vapour	At a given temperature, a vapour can be distinguished from a gas because it can be liquefied by applying pressure alone
Viscosity (μ)	A measure of the resistance of a fluid to being deformed by either shear stress or extensional stress. It is commonly perceived to mean thickness or resistance to flow. However, viscosity describes a fluid's internal resistance to flow and may be thought of as a measure of fluid friction. The dimensions are [ML ⁻¹ T ⁻¹]. The SI physical unit of dynamic viscosity is the Pascal second (Pa·s), which is identical to 1 kg·m ⁻¹ s ⁻¹ .
Void space	The space between solid particles, occupied by a gas
Volatile organic compound (VOC)	Compounds with a relatively high vapour pressure at ambient temperature. The European Union definition is any organic compound with an initial boiling point less than or equal to 250°C.
Volatilisation	The process whereby a liquid contaminant is converted into vapour
Volatility constant	The ratio between the concentration or partial pressure of a gas in the gaseous phase and its equilibrium dissolved phase concentration in a solid or liquid (C_G/C_L), reciprocal of the solubility constant
Volumetric concentration	The proportion of the total volume of void space (or a gas mixture) occupied by a particular gas (typically denoted as % v/v, ppm or ppb)

Appendix 2

Physical, chemical and toxicological properties of ground gases

Table 10 Hazardous bulk ground gases – physical and chemical properties

Properties of some hazardous bulk ground gases							
Name	Methane	Carbon dioxide	Carbon monoxide	Hydrogen	Hydrogen sulfide	Hydrogen cyanide	Ammonia
Formula	CH ₄	CO ₂	CO	H ₂	H ₂ S	HCN	NH ₃
CAS No.	74-82-8	124-38-9	630-08-0	1333-74-0	7783-06-4	74-90-8	7664-41-7
Physical and chemical properties							
Hazard	Flammable, explosive, asphyxiating	Asphyxiating, toxic	Toxic, flammable, explosive	Flammable, explosive, asphyxiating	Toxic, flammable, explosive	Toxic, flammable	Toxic, corrosive
Description	Colourless, odourless and flammable gas important greenhouse gas	Colourless, odourless and toxic gas; important greenhouse gas	Colourless, toxic, odourless and flammable gas	Colourless, odourless and flammable gas	Colourless, flammable and toxic gas. Releases a rotten egg odour at low concentrations (<1 ppm) but is odourless at concentrations above about 50 ppm due to anaesthesia of the olfactory system	Colourless, toxic gas; faint bitter almond-like odour	Colourless, toxic gas with characteristic, irritating pungent odour; burns in oxygen
Formation	Anaerobic degradation of organic material (biogenic); high-temperature or high-pressure transformation of organic material (thermogenic)	Aerobic and anaerobic degradation of organic material; action of acidic water in carbonate rocks; respiration of soil bacteria	Incomplete combustion of organic materials, including methane, in landfill waste; the reduction of carbon dioxide by nascent hydrogen	Fermentation; chemical reaction between water and metals in the ground	Reduction of sulfate by bacteria in the presence of organic matter in anaerobic environments (e.g. landfills, swamps, sewers and confined groundwater); other anaerobic bacteria produce H ₂ S by digesting amino acids containing sulfate, commonly present in volcanic gases and geothermal waters	Degradation of cyanohydrins in vegetables and fruits; degradation of plastics containing nitrogen; synthesised by reaction of methane and ammonia; action of acid on organic cyanide salts	Fixation of atmospheric nitrogen by soil enzymes; degradation of amino acids in organic waste by soil bacteria; gasworks wastes

Properties of some hazardous bulk ground gases

Name	Methane	Carbon dioxide	Carbon monoxide	Hydrogen	Hydrogen sulfide	Hydrogen cyanide	Ammonia
Formula	CH ₄	CO ₂	CO	H ₂	H ₂ S	HCN	NH ₃
CAS No.	74-82-8	124-38-9	630-08-0	1333-74-0	7783-06-4	74-90-8	7664-41-7
Physical and chemical properties							
Molecular mass (g/mol)	16.04	44	28.01	2	34	27	17
Density (kg/m ³)	0.71	1.98	1.25	0.085	1.53	0.687	0.68
Buoyancy in air	+ve	-ve	-ve (near neutral)	+ve	-ve	+ve	+ve
Boiling point (°C)	-164	-78.6 (sublimation)	-191.5	-252.8	-60.7	25.7	-33.35
Solubility in water (mg/L)	23	1450	21.4	1.62 (at 21°C)	4100	Completely miscible	899,000
Viscosity (Pa.s)	1.03 × 10 ⁻⁵	1.40 × 10 ⁻⁵	1.66 × 10 ⁻⁵	8.70 × 10 ⁻⁶	1.00 × 10 ⁻⁵	1.00 × 10 ⁻⁵	9.80 × 10 ⁻⁶
Diffusion coefficient in air (m ² /s)	1.50 × 10 ⁻⁵	1.39 × 10 ⁻⁵	1.96 × 10 ⁻⁵ (at 9°C)	6.10 × 10 ⁻⁵	1.88 × 10 ⁻⁵	1.68 × 10 ⁻⁵	1.98 × 10 ⁻⁵
Diffusion coefficient in water (m ² /s)	1.49 × 10 ⁻⁹	1.92 × 10 ⁻⁹	1.79 × 10 ⁻⁹	4.50 × 10 ⁻⁹	2.23 × 10 ⁻⁹	1.68 × 10 ⁻⁹	2.23 × 10 ⁻⁹
Sorption coefficient log K _{oc} (log L/kg)	9.0 (estimated)	-	3.47 × 10 ⁻¹	-	-	-	-
Octanol/water partition coefficient log K _{ow} (log ratio)	-	-	1.78	-	0.23	-0.25	0.23
Hansen Solubility Parameters	14.0	15.7	11.5	5.1	17.9	12.3	13.7
δ _P (MPa ^{-0.5})	0.0	6.3	4.9	0	6.0	17.6	15.7
δ _H	0.0	5.7	0	0	10.2	9.0	17.8
Henry's law volatility constant (m ³ .atm/mol)	7.05 × 10 ⁻¹	2.99 × 10 ⁻²	1.02 × 10 ⁰	1.28 × 10 ⁰	9.87 × 10 ⁻³	8.97 × 10 ⁻⁵	1.67 × 10 ⁻⁵
Henry's law volatility constant (dimensionless)	2.88 × 10 ¹	1.22 × 10 ⁰	4.16 × 10 ¹	5.24 × 10 ¹	4.03 × 10 ⁻¹	3.67 × 10 ⁻³	2.52 × 10 ⁻¹

Table 11 Hazardous bulk ground gases – hazardous properties

Properties of some hazardous bulk ground gases							
Name	Methane	Carbon dioxide	Carbon monoxide	Hydrogen	Hydrogen sulfide	Hydrogen cyanide	Ammonia
Formula	CH ₄	CO ₂	CO	H ₂	H ₂ S	HCN	NH ₃
CAS No.	74-82-8	124-38-9	630-08-0	1333-74-0	7783-06-4	74-90-8	7664-41-7
Hazardous properties							
Lower explosive or flammable limit (% v/v in air) ¹²	5	Not flammable	12.5	4	4.5	5.6	16.5
Upper explosive or flammable limit (% v/v in air)	15	Not flammable	74.2	74	45.5	40	27
Acute toxicity	Non-toxic (but can cause asphyxiation by displacing oxygen)	Headaches and shortness of breath at 2% v/v on mild exertion and 3% at rest, becoming severe at 5%. ¹³ Loss of consciousness at 10% v/v. Fatal at 17–30% within 1 minute	Binds strongly to haemoglobin and causes cellular hypoxia and other toxic effects. Symptoms apparent at or below 100 ppm include headaches. Higher concentrations cause seizure, coma and death	Non-toxic (but can cause asphyxiation by displacing oxygen)	Causes watering eyes, blurred vision, shortness of breath and sore throat at 20–150ppm. Causes pulmonary oedema, headache, dizziness, coma and death at 400–500 ppm	Highly toxic. Inhalation and skin contact results in nausea, seizure and death	Irritates skin, eyes and throat, and causes coughing, burns, lung damage and death
Workplace exposure standards (Safe Work Australia WESAC 2018)	1.25% v/v (WHSMPs Regulation 2014) 5% of LEL in confined spaces (WHS Reg 2017)	TWA ¹⁴ : 9000 mg/m ³ 5000 ppm STEL ¹⁵ : 54,000 mg/m ³ 30,000 ppm	TWA: 34 mg/m ³ 30 ppm	None	TWA: 14 mg/m ³ 10 ppm STEL: 21 mg/m ³ 15 ppm	TWA: 11 mg/m ³ 10 ppm	TWA: 17 mg/m ³ 25 ppm

¹² Explosive limits can be affected by the concentrations of other gases (particularly oxygen) and water vapour, and by temperature, pressure and volume of gas containment.

¹³ Law et al. 2010

¹⁴ Time-weighted average

¹⁵ Short-term exposure limit

Properties of some hazardous bulk ground gases							
Name	Methane	Carbon dioxide	Carbon monoxide	Hydrogen	Hydrogen sulfide	Hydrogen cyanide	Ammonia
Formula	CH ₄	CO ₂	CO	H ₂	H ₂ S	HCN	NH ₃
CAS No.	74-82-8	124-38-9	630-08-0	1333-74-0	7783-06-4	74-90-8	7664-41-7
Hazardous properties							
Guidelines for air Quality (World Health Organization Occupational and Environmental Health Team 2000b)	–	–	100 mg/m ³ (90 ppm) for 15 minutes 60 mg/m ³ (50 ppm) for 30 minutes 30 mg/m ³ (25 ppm) for 1 hour 10 mg/m ³ (10 ppm) for 8 hours	–	0.007 mg/m ³ (aesthetic) 0.15 mg/m ³ (health)	0.003 mg/m ³	–
Chronic inhalation TRV	–	–	–	–	0.002 mg/m ³ (USEPA)	0.0008 mg/m ³ (USEPA)	0.5 mg/m ³ (USEPA) 0.07 mg/m ³ (ATSDR ¹⁶)
Approximate odour threshold (ppm v/v)	Odourless	Odourless	Odourless	Odourless	0.005	0.6	0.04
Notes	Explosive limit changes when oxygen concentration reduces. Methane is non-flammable when the carbon dioxide concentration reaches 24.5% v/v. Oxidises to carbon dioxide through bacterial action	See USEPA (2000) and Law et al. (2010) for discussion of acute effects	See Shochat and Lucchesi (2017) for discussion of acute effects	–	Desensitises sense of smell after short period of exposure	As with hydrogen sulfide, short exposure can result in loss of smell	Both anhydrous ammonia and aqueous ammonia solutions containing greater than 5% ammonia may produce flammable vapour mixtures in air

¹⁶ US Agency for Toxic Substances and Disease Registry

Table 12 Hazardous trace ground gases and vapours – physical and chemical properties

Properties of some hazardous trace ground gases and vapours										
Name	Benzene	Toluene	ortho-Xylene	meta-Xylene para-Xylene	1,2,3-trimethylbenzene	1,2,4-trimethylbenzene	1,3,5-trimethylbenzene	Ethylbenzene	Naphthalene	Mercury
Formula	C ₆ H ₆	C ₇ H ₈	C ₈ H ₁₀	C ₈ H ₁₀	C ₉ H ₁₂	C ₉ H ₁₂	C ₉ H ₁₂	C ₈ H ₁₀	C ₁₀ H ₈	Hg
CAS No.	71-43-2	108-88-3	95-47-6	108-38-3/ 106-42-3	526-73-8	95-63-6	108-67-8	100-41-4	91-20-3	7439-97-6
Physical and chemical properties ^{a,b}										
Hazard	Flammable, toxic	Flammable, toxic	Flammable, toxic		Flammable, toxic			Flammable, toxic	Flammable, toxic	Toxic
Description	Volatile, colourless liquid with a sweet odour	Volatile, colourless liquid with a sweet odour	Volatile, colourless liquid with a sweet odour		Volatile, colourless liquid with a distinctive strong, sweet odour			Volatile, colourless liquid with an aromatic odour	Crystalline, aromatic, white, solid hydrocarbon with the odour of mothballs	Silvery liquid metal partitioning to colourless, odourless vapour
Common sources	Fuel spills are the main source in ground; also present in cigarette smoke and urban air	Fuel spills are the main source in ground	Fuel spills are the main source in ground		Spills of fuel, dry-cleaning fluids and other solvents are main source in ground; also used as feedstock in chemical and pharmaceutical manufacturing			Fuel spills are the main source in ground	Fuel spills, gasworks	Spills and leaks from industrial processes; electrical equipment and medical or scientific instruments
Molecular mass (g/mol)	78.1	92.4	106.2	106.2	120.2	120.2	120.2	106.2	128.2	200.6
Vapour buoyancy in air	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve
Boiling point (°C)	80	111	144	139/138	176	169	165	136	218	357
Vapour pressure (mmHg ¹⁷)	94.8	28.4	6.61	8.29/8.84	1.69	2.10	2.48	9.6	0.085	1.96 × 10 ⁻³

¹⁷ Millimetres of mercury.

Properties of some hazardous trace ground gases and vapours											
Name	Benzene	Toluene	ortho-Xylene	meta-Xylene para-Xylene	1,2,3-trimethylbenzene	1,2,4-trimethylbenzene	1,3,5-trimethylbenzene	Ethylbenzene	Naphthalene	Mercury	
Formula	C ₆ H ₆	C ₇ H ₈	C ₈ H ₁₀	C ₈ H ₁₀	C ₉ H ₁₂	C ₉ H ₁₂	C ₉ H ₁₂	C ₈ H ₁₀	C ₁₀ H ₈	Hg	
CAS No.	71-43-2	108-88-3	95-47-6	108-38-3/ 106-42-3	526-73-8	95-63-6	108-67-8	100-41-4	91-20-3	7439-97-6	
Physical and chemical properties ^{a,b}											
Solubility in water (mg/L)	1750	515	178	161/162	75.2	57.0	48.2	169	31	0.06	
Solubility in water (mg/L)	1750	515	178	161/162	75.2	57.0	48.2	169	31	0.06	
Liquid density (kg/m ³)	876 at 20°C	862	875	860/857	894 at 20°C	876 at 20°C	862	863	1030 at 20°C	13,500	
Liquid viscosity (Pa.s)	6.52 × 10 ⁻⁴	5.9 × 10 ⁻⁴	7.6 × 10 ⁻⁴	5.8/6.0 × 10 ⁻⁴	–	2.01 × 10 ⁻³	6.92 × 10 ⁻³	6.3 × 10 ⁻⁴	–	1.526 × 10 ⁻³	
Vapour viscosity (Pa.s)	7.5 × 10 ⁻⁶	7.0 × 10 ⁻⁶	–	–	–	–	–	–	–	1.7 × 10 ⁻⁵	
Diffusion coefficient in air (m ² /s)	8.95 × 10 ⁻⁶	8.78 × 10 ⁻⁶	6.89 × 10 ⁻⁶	6.84/6.82 × 10 ⁻⁶	6.13 × 10 ⁻⁶	6.07 × 10 ⁻⁶	6.02 × 10 ⁻⁶	6.85 × 10 ⁻⁶	5.9 × 10 ⁻⁶	3.07 × 10 ⁻⁶	
Diffusion coefficient in water (m ² /s)	1.03 × 10 ⁻⁹	9.20 × 10 ⁻¹⁰	8.53 × 10 ⁻¹⁰	8.44/8.42 × 10 ⁻¹⁰	8.02 × 10 ⁻¹⁰	7.92 × 10 ⁻¹⁰	7.84 × 10 ⁻¹⁰	8.46 × 10 ⁻¹⁰	8.38 × 10 ⁻¹⁰	6.30 × 10 ⁻¹⁰	
Sorption coefficient log K _{oc} (log L/kg)	1.77	2.13	2.58	2.57/2.57	2.80	2.79	2.78	2.65	3.30	-	
Octanol/water partition coefficient log K _{ow} (log ratio)	2.13	2.73	3.12	3.20/3.15	3.66	3.63	3.42	3.15	3.30	0.62	
Hansen Solubility Parameters (MPa ^{-0.5})	δ _D δ _P δ _H	18.4 0.0 2.0	18.0 1.4 2.0	17.8 1.0 3.1	17.6 1.0 3.1	– – –	18.0 1.0 1.0	– – –	17.0 6.0 1.4	19.2 2.0 5.9	– – –

Properties of some hazardous trace ground gases and vapours										
Name	Benzene	Toluene	ortho-Xylene	meta-Xylene para-Xylene	1,2,3-trimethylbenzene	1,2,4-trimethylbenzene	1,3,5-trimethylbenzene	Ethylbenzene	Naphthalene	Mercury
Formula	C ₆ H ₆	C ₇ H ₈	C ₈ H ₁₀	C ₈ H ₁₀	C ₉ H ₁₂	C ₉ H ₁₂	C ₉ H ₁₂	C ₈ H ₁₀	C ₁₀ H ₈	Hg
CAS No.	71-43-2	108-88-3	95-47-6	108-38-3/ 106-42-3	526-73-8	95-63-6	108-67-8	100-41-4	91-20-3	7439-97-6
Physical and chemical properties ^{a,b}										
Henry's law volatility constant (m ³ .atm/mol) ^c	5.48 × 10 ⁻³	6.58 × 10 ⁻³	4.93 × 10 ⁻³	7.05 × 10 ⁻³	3.40 × 10 ⁻³	5.81 × 10 ⁻³	7.05 × 10 ⁻³	7.59 × 10 ⁻³	4.49 × 10 ⁻⁴	7.59 × 10 ⁻³
Henry's law volatility constant (dimensionless)	2.24 × 10 ⁻¹	2.69 × 10 ⁻¹	2.02 × 10 ⁻¹	2.88 × 10 ⁻¹	1.39 × 10 ⁻¹	2.37 × 10 ⁻¹	2.88 × 10 ⁻¹	3.10 × 10 ⁻¹	1.83 × 10 ⁻²	3.10 × 10 ⁻¹

a. Data sources for chemical data: generally, the US Department of Energy Risk Assessment Information System (RAIS) (<https://rais.ornl.gov>) and/or CRC Handbook of Chemistry and Physics.

b. All values are at standard temperature and pressure (1 atmosphere or 101.325 kPa, and 25°C or 273.15°K) unless otherwise shown.

c. Henry's law volatility constants were sourced as solubility constants directly from Sander (2015) and converted to volatility constants in the units shown here using the factors provided by Sander.

Table 13 Hazardous trace ground gases and vapours – hazardous properties

Properties of some hazardous trace ground gases and vapours										
Name	Benzene	Toluene	o-Xylene	m-Xylene p-Xylene	1,2,3- trimethyl- benzene	1,2,4 trimethyl- benzene	1,3,5- trimethyl- benzene	Ethylbenzene	Naphthalene	Mercury
Formula	C ₆ H ₆	C ₇ H ₈	C ₈ H ₁₀	C ₈ H ₁₀	C ₉ H ₁₂	C ₉ H ₁₂	C ₉ H ₁₂	C ₈ H ₁₀	C ₁₀ H ₈	Hg
CAS No.	71-43-2	108-88-3	95-47-6	108-38-3/106-42-3	526-73-8	95-63-6	108-67-8	100-41-4	91-20-3	7439-97-6
Hazardous properties										
Lower explosive or flammable limit (% v/v in air)	1.2	1.1	0.9	1.1/1.1	0.8	0.9	1.0	0.8	0.9	Not combustible
Upper explosive or flammable limit (% v/v in air)	7.1	7.1	6.7	6.6/7.0	6.6	6.4	5.0	6.7	5.9	Not combustible
Approximate odour threshold (ppm v/v) ^d	1.5	8	1		0.4			2	0.3	–
Acute inhalation toxicity ^d	Causes CNS (central nervous system) depression, drowsiness, dizziness and unconsciousness	Causes CNS depression, drowsiness, dizziness and unconsciousness	Causes CNS depression, dizziness, confusion and loss of balance		Causes CNS depression, headaches, nausea and vomiting, with dizziness, lack of coordination, anxiety and confusion at higher concentrations			Causes CNS depression and irritation to eyes, nasal mucous membrane and respiratory tract	Causes headaches, confusion, excitement, nausea and vomiting; possible dysuria, haematuria and acute haemolytic reaction	Causes gastro-intestinal, renal and central nervous system effects
Workplace exposure standards (Safe Work Australia WESAC 2018) (mg/m ³)	TWA: 3.2	TWA: 191 STEL: 574	TWA: 350 STEL: 665		TWA: 123			TWA: 434 STEL: 543	TWA: 52 STEL: 79	TWA: 0.025
Chronic inhalation TRV (units as shown) ^e	0.006 (mg/m ³) ⁻¹ 0.03 mg/m ³ (ASC NEPM/USEPA)	5 mg/m ³ (ASC NEPM/WHO)	0.87 mg/m ³ (ASC NEPM/USEPA)		0.06 mg/m ³ (USEPA)			1.3 mg/m ³ (NEPM/ATSD)	0.003 mg/m ³ (ASC NEPM/USEPA)	0.0003 mg/m ³ (USEPA)

Properties of some hazardous trace ground gases and vapours										
Name	Benzene	Toluene	o-Xylene	m-Xylene p-Xylene	1,2,3- trimethyl- benzene	1,2,4- trimethyl- benzene	1,3,5- trimethyl- benzene	Ethylbenzene	Naphthalene	Mercury
Formula	C ₆ H ₆	C ₇ H ₈	C ₈ H ₁₀	C ₈ H ₁₀	C ₉ H ₁₂	C ₉ H ₁₂	C ₉ H ₁₂	C ₈ H ₁₀	C ₁₀ H ₈	Hg
CAS No.	71-43-2	108-88-3	95-47-6	108-38-3/106-42-3	526-73-8	95-63-6	108-67-8	100-41-4	91-20-3	7439-97-6
Hazardous properties										
Soil vapour HSL – residential (ASC NEPM) ^f (mg/m ³)	1	1300		220		–		330	0.8	–
Soil vapour HSL – recreational (ASC NEPM) ^f (mg/m ³)	360	NL		NL		–		NL	410	–
Soil vapour HSL – commercial (ASC NEPM) ^f (mg/m ³)	4	4800		840		–		1300	3	–

e. Data sources for chronic toxicity data: TRV shown as ASC NEPM preferred where listed in Schedule B1, plus original TRV data source. Where the TRV source is USEPA, data are accessible via the Integrated Risk Information System (IRIS) on the USEPA website (www.epa.gov). See Friebe and Nadebaum (2011) for full references. Non-threshold TRVs are italicised.

f. In sand, 0 m to <1 m depth.

Table 14 Hazardous trace ground gases and vapours – identification, character and sources

Properties of some hazardous trace ground gases and vapours										
Name	Tetrachloroethene (PCE)	Trichloroethene (TCE)	cis-1,2-dichloroethene (cis 1,2,DCE)	Chloroethene (CE or VC)	Tetrachloro-methane (TeCM or CT)	Trichloro-methane (TCM)	Dichloro-methane (DCM)	1,1,1-trichloroethane (1,1,1-TCA)	1,1-dichloroethane (1,1-DCA)	1,2-Dichloroethane (1,2-DCA or EDC)
Formula	C ₂ Cl ₄	C ₂ HCl ₃	C ₂ H ₂ Cl ₂	C ₂ H ₃ Cl	CCl ₄	CHCl ₃	CH ₂ Cl ₂	C ₂ H ₃ Cl ₃	C ₂ H ₄ Cl ₂	C ₂ H ₄ Cl ₂
CAS No.	127-18-4	79-01-6	156-59-2	75-01-4	56-23-5	67-66-3	75-09-2	71-55-2	75-34-3	107-06-2
Identification, character and sources										
Synonyms	Perchloroethene (PERC)	Trichloroethene, ethylene trichloride, trilene	cis-1,2-dichloroethene, cis-acetylene dichloride	Vinyl chloride ⁹	Carbon tetrachloride ⁹	Chloroform ⁹	Methylene chloride	Methyl chloroform	Ethylidene dichloride	Ethylene dichloride
Description	Volatile, colourless liquid with a mildly sweet odour	Volatile, colourless liquid with a sweet odour	Volatile, colourless liquid with a sharp, harsh odour	Colourless gas with a slightly sweet odour	Volatile, colourless liquid with a sweet odour	Volatile, colourless liquid with a pleasant, sweet odour	Colourless liquid with a mild, sweet odour	Volatile, colourless liquid with a pleasant, sweet odour	Volatile, colourless, oily liquid with a sweet odour	Volatile, colourless, oily liquid with a pleasant, sweet odour
Common sources	Chemical spills; used widely in dry-cleaning and degreasing	Chemical spills; used widely in cleaning and degreasing; degradation product of PCE	Chemical spills; used as a manufacturing intermediate for other chlorinated solvents; degradation product of PCE and TCE	Used in manufacturing; released by degradation of PVC, related polymers and other chlorinated solvents (PCE, TCE and DCE)	Used in the past as a chemical manufacturing intermediate, solvent and fire suppressant	Used in the past as a chemical manufacturing intermediate, solvent and anaesthetic; degradation of carbon tetrachloride	Used in the past as an industrial solvent and paint stripper, and in the manufacture of photographic film; degradation of carbon tetrachloride and chloroform	Used as a cold-cleaning and vapour degreasing solvent. Also present in many household products, including aerosol sprays, glues and lubricants	Used as an intermediate in the manufacture of 1,1,1-TCA; also used as a cleaning and degreasing solvent and in the manufacture of plastic wrap, adhesives, and synthetic fibres	Primarily used in the production of vinyl chloride and other chemicals; used in solvents in closed systems for various extraction and cleaning purposes
Hazard	Toxic	Toxic	Flammable, toxic	Flammable, toxic	Toxic	Toxic	Flammable, toxic	Toxic	Flammable, toxic	Flammable, toxic

Table 15 Hazardous trace ground gases and vapours – physical and chemical properties

Properties of some hazardous trace ground gases and vapours										
Name	Tetrachloro-ethene (PCE)	Trichloro-ethene (TCE)	cis-1,2-dichloro-ethene (cis 1,2-DCE)	Chloro-ethene (CE or VC)	Tetrachloro-methane (TeCM or CT)	Trichloro-methane (TCM)	Dichloro-methane (DCM)	1,1,1-trichloro-ethane (1,1,1-TCA)	1,1-dichloro-ethane (1,1-DCA)	1,2-dichloro-ethane (1,2-DCA or EDC)
Formula	C ₂ Cl ₄	C ₂ HCl ₃	C ₂ H ₂ Cl ₂	C ₂ H ₃ Cl	CCl ₄	CHCl ₃	CH ₂ Cl ₂	C ₂ H ₃ Cl ₃	C ₂ H ₄ Cl ₂	C ₂ H ₄ Cl ₂
CAS No.	127-18-4	79-01-6	156-59-2	75-01-4	56-23-5	67-66-3	75-09-2	71-55-2	75-34-3	107-06-2
Physical and chemical properties										
Molecular mass (g/mol)	165.8	131.4	96.9	62.5	153.8	119.4	84.9	133.4	99.0	99.0
Vapour buoyancy in air	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve
Boiling point (°C)	121	87.2	60	-13.9	76.8	61.1	40	74.0	57.4	83.5
Vapour pressure (mmHg)	18.5	69	200	2980	115	197	435	124	227	78.9
Solubility in water (mg/L)	200	1000	6.41 × 10 ³	2700	793	7950	1300	1290	5040	8600
Liquid density (kg/m ³)	1620 at 20°C	1460 at 20°C	1280 at 20°C	908	1590	1480	1330 at 20°C	1340	1180 at 20°C	1250
Liquid viscosity (Pa.s)	8.9 × 10 ⁻⁴	5.3 × 10 ⁻⁴	4.5 × 10 ⁻⁴	N/A	9.1 × 10 ⁻⁴	5.4 × 10 ⁻⁴	4.1 × 10 ⁻⁴	7.9 × 10 ⁻⁴	4.6 × 10 ⁻⁴	7.8 × 10 ⁻⁴
Vapour viscosity (Pa.s)	-	-	-	-	-	1.01 × 10 ⁻⁵	-	-	-	-
Diffusion coefficient in air (m ² /s)	7.2 × 10 ⁻⁶	8.2 × 10 ⁻⁶	8.8 × 10 ⁻⁶	1.06 × 10 ⁻⁵	5.71 × 10 ⁻⁶	1.04 × 10 ⁻⁵	1.01 × 10 ⁻⁵	6.48 × 10 ⁻⁶	8.36 × 10 ⁻⁶	8.57 × 10 ⁻⁶
Diffusion coefficient in water (m ² /s)	9.46 × 10 ⁻¹⁰	9.10 × 10 ⁻¹⁰	1.13 × 10 ⁻⁹	1.20 × 10 ⁻⁹	9.78 × 10 ⁻¹⁰	1.09 × 10 ⁻⁹	1.17 × 10 ⁻⁹	9.60 × 10 ⁻¹⁰	1.06 × 10 ⁻⁹	1.10 × 10 ⁻⁹
Sorption coefficient log K _{OC} (log L/kg)	2.19	2.10	1.60	1.75	1.64	1.50	2.17	1.64	1.50	1.60
Octanol/water partition coefficient log K _{OW} (log ratio)	3.40	2.42	1.86	1.38	2.83	1.97	1.25	2.49	1.79	1.48
Hansen Solubility Parameters (MPa ^{-0.5})										
δ _D	18.3	18.0	17.0	16.0	16.1	17.8	18.2	16.8	16.5	19.0
δ _P	5.7	3.1	8.0	6.5	8.3	3.1	6.3	4.3	7.8	7.4
δ _H	0.0	5.3	3.2	2.4	0.0	5.7	6.1	2.0	3.0	4.1
Henry's law volatility constant (m ³ .atm/mol)	1.64 × 10 ⁻²	9.87 × 10 ⁻³	3.95 × 10 ⁻³	2.53 × 10 ⁻²	2.82 × 10 ⁻²	3.95 × 10 ⁻³	2.74 × 10 ⁻³	1.67 × 10 ⁻²	6.17 × 10 ⁻³	1.27 × 10 ⁻³
Henry's law volatility constant (dimensionless) (ratio)	6.72 × 10 ⁻¹	4.03 × 10 ⁻¹	1.61 × 10 ⁻¹	1.03 × 100	1.15 × 100	1.61 × 10 ⁻¹	1.12 × 10 ⁻¹	6.84 × 10 ⁻¹	2.52 × 10 ⁻¹	5.17 × 10 ⁻²

Table 16 Hazardous trace ground gases and vapours – hazardous properties

Properties of some hazardous trace ground gases and vapours										
Name	Tetrachloroethene (PCE)	Trichloroethene (TCE)	cis-1,2-dichloroethene (cis 1,2-DCE)	Chloroethene (CE or VC)	Tetrachloromethane (TeCM or CT)	Trichloromethane (TCM)	Dichloromethane (DCM)	1,1,1-trichloroethane (1,1,1-TCA)	1,1-dichloroethane (1,1-DCA)	1,2-dichloroethane (1,2-DCA or EDC)
Formula	C ₂ Cl ₄	C ₂ HCl ₃	C ₂ H ₂ Cl ₂	C ₂ H ₃ Cl	CCl ₄	CHCl ₃	CH ₂ Cl ₂	C ₂ H ₃ Cl ₃	C ₂ H ₄ Cl ₂	C ₂ H ₄ Cl ₂
CAS No.	127-18-4	79-01-6	156-59-2	75-01-4	56-23-5	67-66-3	75-09-2	71-55-2	75-34-3	107-06-2
Hazardous properties										
Lower explosive or flammable limit (% v/v in air)	Not flammable	Not flammable	9.7	3.8	Not flammable	Not flammable	13.0	7.5	5.6	6.2
Upper explosive or flammable limit (% v/v in air)	Not flammable	Not flammable	12.8	31	Not flammable	Not flammable	23	15.5	11.4	15.6
Approximate odour threshold (ppm v/v)	1 ^h	50	17	3000	10–50	200	160–620	44	120	6–10
Acute inhalation toxicity	Eye, nose and throat irritation, and CNS ¹ depression; prolonged exposure to high concentrations may result in coma and death	Eye, nose and throat irritation, and CNS suppression; prolonged exposure to high concentrations may result in coma and death	Respiratory tract, skin and eye irritation, and CNS depression; prolonged exposure to high concentrations may result in coma and death	CNS depression; prolonged exposure to high concentrations may result in coma and death	Nausea, vomiting, irregular heartbeat, CNS depression, kidney damage, liver damage, convulsions, coma and death	Nausea, vomiting, irregular heartbeat, CNS depression, kidney damage, liver damage, convulsions, coma and death	CNS depression and liver damage; human fatalities recorded	Nausea, vomiting, irregular heartbeat, CNS depression, kidney damage, liver damage, convulsions, coma and death	Nausea, vomiting, irregular heartbeat and CNS depression; continued inhalation may result in coma and death	CNS depression; continued inhalation may result in coma and death
Workplace exposure standards (Safe Work Australia WESAC 2018) (mg/m ³)	TWA: 340 STEL: 1020	TWA: 54 STEL: 216	TWA: 793	TWA: 13	TWA: 0.63	TWA: 10	TWA: 174	TWA: 555 STEL: 1110	TWA: 412	TWA: 40

Properties of some hazardous trace ground gases and vapours										
Name	Tetrachloroethene (PCE)	Trichloroethene (TCE)	cis-1,2-dichloroethene (cis 1,2-DCE)	Chloroethene (CE or VC)	Tetrachloromethane (TeCM or CT)	Trichloromethane (TCM)	Dichloromethane (DCM)	1,1,1-trichloroethane (1,1,1-TCA)	1,1-dichloroethane (1,1-DCA)	1,2-dichloroethane (1,2-DCA or EDC)
Formula	C ₂ Cl ₄	C ₂ HCl ₃	C ₂ H ₂ Cl ₂	C ₂ H ₃ Cl	CCl ₄	CHCl ₃	CH ₂ Cl ₂	C ₂ H ₃ Cl ₃	C ₂ H ₄ Cl ₂	C ₂ H ₄ Cl ₂
CAS No.	127-18-4	79-01-6	156-59-2	75-01-4	56-23-5	67-66-3	75-09-2	71-55-2	75-34-3	107-06-2
Hazardous properties										
Chronic inhalation TRV (units as shown)	0.2 mg/m ³ (NEPM/WHO 2006)	0.004 (mg/m ³) ⁻¹ 0.002 mg/m ³ (NEPM/USEPA)	0.007 mg/m ³ (NEPM/USEPA)	0.0088 lifetime 0.0044 adult (mg/m ³) ⁻¹ (NEPM/USEPA)	0.006 (mg/m ³) ⁻¹ 0.1 mg/m ³ (USEPA)	0.023 (mg/m ³) ⁻¹ (ATSDR) 0.0977 mg/m ³ (USEPA)	1 × 10 ⁻⁸ (mg/m ³) ⁻¹ 0.006 mg/m ³ (USEPA)	5 mg/m ³ (NEPM/USEPA)	0.0016 (mg/m ³) ⁻¹ (California EPA)	0.026 (mg/m ³) ⁻¹ (USEPA)
Soil vapour HIL – residential (ASC NEPM) (mg/m ³)	2	0.02	0.08	0.03	–	–	–	60	–	–
Soil vapour HIL – recreational (ASC NEPM) (mg/m ³)	40	0.4	2	0.5	–	–	–	1200	–	–
Soil vapour HIL – commercial (ASC NEPM) (mg/m ³)	8	0.08	0.3	0.1	–	–	–	230	–	–

h. Rapid desensitisation may occur.

i. Symptoms of CNS suppression and depression include dizziness, light-headedness, headaches, nausea and loss of coordination.

Appendix 3

Trace components of landfill gas

The data in the following table are sourced from the UK Environment Agency (2004a), which references UK Environment Agency 2002. The concentrations recorded represent a 'typical' UK landfill, and are based on data from a large number of sites. Similar, though less comprehensive, data are also provided by the USEPA (2005).

The probability density function is incorporated in the current version of the GasSim model. LogU denotes log-uniform and LogT denotes log-triangular.

Table 17 Trace components of landfill gas

Concentration distribution of priority trace components in landfill gas											
Priority chemical	Concentration (mg/m ³)										
	Min.	Max.	Range	Mode	Median	Mean	Toxicity score	Toxicity ranking	Odour score	Odour ranking	Probability density function (PDF) (GasSim)
Chloroethene	1.1	730	728.9	–	31	102.1	550	1	–	–	LogT (1.1,31,730)
Benzene	3.1	73	69.9	15	15	18.4	500	2	–	–	LogT (3.1,15,73)
Chloroethane	<0.02	5.3	5.28	0.03	0.03	0.49	400	3	–	–	LogU (1E-30,5.3)
2-butoxy ethanol	<0.04	<0.05	>0.01	<0.05	<0.05	<0.05	200	4	–	–	LogU (1E-30,0.05)
Arsenic	0.0006	0.43	0.4294	–	0.0074	0.0511	175	5	–	–	LogT (1E-4,0.0074,0.43)
1,1-dichloroethene	<0.03	19	18.97	2.8	0.28	2.24	90	6	–	–	LogT (0.03,2.8,19)
Furan	0.02	6.2	6.18	–	0.82	1.23	90	7	–	–	LogT (0.02,0.82,6.2)
Trichloroethene	0.25	88	87.75	–	1.65	8.59	90	8	–	–	LogT (0.25,1.65,88)
Hydrogen sulfide	2.4	580	577.6	53	53	111.1	88	9	110	1	LogT (2.4,53,580)
1,1-dichloroethane	<0.02	3.9	3.88	0.28	0.28	0.57	80	10	–	–	LogT (0.02,0.28,3.9)
Carbon disulfide	0.9	170	169.1	1.4	13	34	80	11	60	3	LogU (0.9,170)
cis-1,2-dichloroethene	0.13	46	45.87	3.9	2.2	5.71	72	12	–	–	LogT (0.13,3.9,46)
trans-1,2-dichloroethene	<0.02	2.6	2.58	–	0.26	0.44	72	13	–	–	LogT (0.02,0.24,2.6)
1,3-butadiene	<0.02	<0.02	>0.00	<0.02	<0.02	<0.02	70	14	–	–	LogU (1E-30,0.02)
Methanal	0.026	0.188	0.162	0.072	0.068	0.07	70	15	–	–	LogT (0.026,0.068,0.188)
Tetrachloromethane	<0.02	<0.02	>0.00	<0.02	<0.02	<0.02	70	16	–	–	LogU (1E-30,0.02)
Mercury	0.00017	0.00133	0.00116	–	0.0005	0.00058	50	17	–	–	LogU (0.00017,0.00133)
Methanethiol	<0.3	<0.3	>0.0	<0.3	<0.3	<0.3	–	–	90	2	LogU (1E-30,0.3)
Dimethyl disulfide	<0.03	12	11.97	0.17	0.17	1.02	–	–	45	4	LogT (0.03,0.17,12)
Butyric acid	<0.08	17.5	17.42	<0.10	<0.10	1.85	–	–	45	4	LogT (1E-30,0.1,17.5)
Ethanethiol	<0.08	<0.08	>0.00	<0.08	<0.08	<0.08	–	–	40	6	LogU (1E-30,0.08)
Ethanal	0.075	2.546	2.471	0.084	0.225	0.431	–	–	40	6	LogU (0.075,2.546)
Ethyl butyrate	0.41	42	41.59	11	3.5	7.22	–	–	36	8	LogU (0.41,42)
1-pentene	0.24	21	20.76	3.5	3.5	5.49	–	–	36	8	LogT (0.24,3.5,12)
Dimethyl sulfide	<0.03	24.3	24.27	–	0.73	3.69	–	–	32	10	LogT (0.03,0.73,24.3)
1-butanethiol	<0.06	<0.08	>0.02	<0.08	<0.08	<0.08	–	–	32	10	LogU (1E-30,0.08)
1-propanethiol	<0.04	0.09	>0.05	<0.05	<0.05	<0.05	–	–	30	12	LogU (1E-30,0.09)

Appendix 4

Further guidance on site assessment methodology

This appendix should be used in conjunction with Section 3 of these guidelines.

As indicated in that section and elsewhere in the body of these guidelines, it is essential that planning for site assessment and monitoring work is based on a desk study, a site reconnaissance and an adequate conceptual site model. This appendix provides summary guidance concerning field methods and examples of some of the equipment available in NSW (as of the date of publication).

A4.1 Investigation techniques

Gas monitoring wells constructed in drilled boreholes remain the mainstay of ground gas investigations. However, a number of other available techniques are summarised in Table 18. Implants (tubing tips), flux chambers and passive sampling devices are most commonly used for trace gas assessment, often in conjunction with monitoring wells.

Table 18 Investigation techniques

Technique	Applicability	Advantages	Disadvantages
Driven probe	All gases, shallow soils (hand-driven probe), where there are rig limitations or obstructions (Geoprobe)	Rapid temporary installation for screening surveys, low cost, suitable for restricted spaces	Limited installation depth in most soils, refusal on hard objects, can't be effectively sealed, some types are difficult to clean, not possible to measure flows, only provides qualitative concentration data
Membrane Interface Probe (MIP)	Methane, hydrocarbon gases, VOCs	Relatively fast three-dimensional screening, excellent vertical resolution, allows correlation with geological and geochemical characteristics	Relatively expensive, restricted to unconsolidated formations, small number of specialist contractors
Monitoring well – 50 mm uPVC	All gases, most geological and cultural settings	Standard materials and fittings, wide range of compatible down-hole water and gas sampling equipment available	Relatively expensive, needs drilled bore, headroom requirement, greatest space requirement
Monitoring well – small diameter (≈19 mm)	All gases, most geological and cultural settings, multi-level wells	Can be installed with push-tube or hand equipment, cheaper, requires less space, multi-level installations are possible	Screens may need to be specially cut, too small for many types of sampling and measurement equipment
Implant (stainless steel tip on small-diameter flexible tubing)	All gases, sub-slab and cavity sampling, widely used for VOCs	Easy to install, low-sorption Teflon or low-density polyethylene (LDPE) tubing, durable stainless-steel tips, multi-level installations possible	Easily blocked by water and sediment, difficult to clean, not suitable for flow measurement
Flux chamber	All gases, surface emissions or emissions through base of a pit	Direct measurement of surface emissions, various levels of sophistication or improvisation possible	Requires considerable skill to set up and operate, strongly influenced by soil moisture and barometric

Technique	Applicability	Advantages	Disadvantages
			pressure, potential for leaks may require use of tracer gas
Passive devices	Trace gases, screening-level investigations	Simple, easy to install, relatively cheap	No direct measurement of concentration, difficult to apply in risk assessment
Ambient measurement	All gases, buildings, manholes, drains, confined spaces	Direct measurement of concentrations in exposure zone	Access difficulties, interference from in-building sources
Surface emission measurement	Bulk gases – typically closed landfills, other filled ground	Direct, wide-area measurement, possible to link directly to GPS and data logger	Interference, strongly influenced by soil moisture, temperature and barometric pressure, difficult to pick up small sources, such as cracks

A4.2 Sampling/monitoring network design

Although network design is inevitably a compromise between coverage and cost, an adequate number of rationally placed sampling points is fundamental to a credible investigation. As with other aspects of site assessment, it is essential that network design is based on a desk study, site reconnaissance and an adequate conceptual site model. As with other types of environmental investigation, it is important to consider the three-dimensionality of gas flow, and to isolate and separately screen horizons when appropriate.

Table 19 Network design

Technique	Assessment/ monitoring situation	Requirements
Monitoring wells and implants	Source areas	Source composition, lateral dimensions, depth, capping and internal compartmentalisation, gas pressure, gas composition
	Boundaries	Adequate assessment of up-gradient (source) and down-gradient (off-site migration) boundaries, as indicated by conceptual model
	Profile	Adequate sampling of geological profile as indicated by conceptual model, with focus on most transmissive zones and exposure pathways (e.g. sub-slab). Consider including some multi-level wells that isolate individual stratigraphic units
	Spatial cover	At assessment stage, adequate coverage of areas of site indicated to be significant by conceptual model
Flux chamber	Surface	Relevant for external areas where exposure may occur. May sometimes be used in conjunction with other techniques in internal areas (e.g. cracked slabs). May be used to provide an additional line of evidence to confirm CSM in complex situations
	Intermediate levels	Relevant if risk assessment is being conducted and flux through an intermediate horizon provides useful input to exposure calculations
Passive devices	Ambient air	Time-averaged relative concentrations, may indicate high-risk areas within buildings
	Sub-slab or shallow soil	Qualitative screening tool
Ambient measurement	Inside buildings	Direct measurement of concentrations within rooms, with focus on small or poorly ventilated areas, slab penetrations, etc.
	Confined spaces	Direct measurement for pre-access screening or pathway assessment. Drains, services, wall cavities, roof spaces
Surface emission measurement	Closed landfill, filled ground	Carbon dioxide and/or methane measured for risk assessment or used as a surrogate for trace gases and vapours. Adequate investigation pattern with focus on cracked areas, impacted vegetation, etc. Carry out under appropriate soil moisture and atmospheric pressure conditions. May be used to provide an additional line of evidence to confirm CSM in complex situations

A4.3 Gas monitoring well design and construction

Casing/tubing is usually screw-jointed unplasticised PVC pressure pipe, which is generally available with 0.4-mm factory-cut slots for screened sections.

Screens should be placed across permeable horizons of interest and appropriately gravel-packed. Where relevant, isolate and separately screen potential gas-transmissive horizons. Either bentonite cement or bentonite pellet seals are placed in the annulus between the standpipe and the borehole wall; if pellets are used they must be hydrated by pouring water into the annulus above the pellets. The nature of site soils and the site surface must be considered and the upper annulus/surface seal must be adequate to ensure that air is not drawn into the uppermost screen during sampling.

Wells are fitted with a cap that is tapped to take a quick-connect nipple (or a manual valve and nipple) that seals the well and allows easy connection to a measurement instrument.

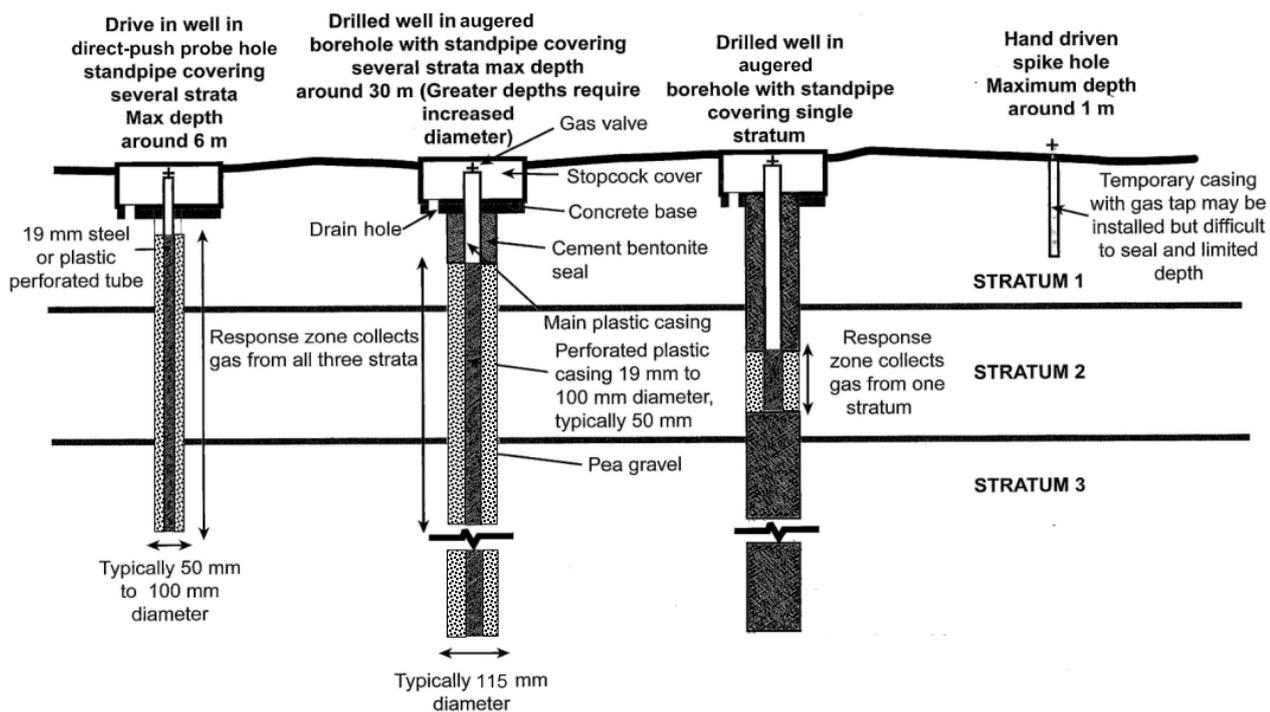


Figure 10 Key features required for a gas monitoring well

Source: Modified from Wilson et al. 2009

A4.4 Ground gas sampling and measurement techniques and instrumentation

Depending on the gas being sampled, measurements may be taken using field instrumentation, or samples may be obtained using sorbent tubes or SUMMA canisters. These may be submitted for laboratory analysis, using standard quality assurance or quality control protocols and assessment of data quality indicators.

Field measurement equipment

Field instrumentation is usually used to measure bulk ground gas concentrations, pressure and borehole flow rates. Initial, maximum and steady concentrations, absolute and differential pressures, and flow rate are typically recorded.

Other common applications include surface emission measurement, flux chamber measurement (either standalone or in conjunction with SUMMA cannister or absorption tube sampling), and the measurement of gas concentrations and flow rates in gas and vapour risk mitigation systems installed in buildings.

A4.4.1 Gas concentration measurement

Measurement methodology

A fairly wide range of equipment for monitoring ground gases is available to buy locally and internationally. However, care is required to select the appropriate instrument for a particular task.

Many consultants choose to rent equipment for ground gas monitoring; a relatively small selection of instruments is currently available to rent in NSW.

The following sections cover the most commonly used field analytical methods – infrared absorption, laser instruments, electrochemical cells, photo-ionisation detectors, flame-ionisation detectors and field gas chromatographs.

Infrared absorption

The most widely used field analytical method for the bulk gases methane and carbon dioxide is infrared absorption (IR). Most portable gas analysis instruments specifically designed for landfill and contaminated land applications (for example, Landtec's GA5000 and GEM5000, and Gas Data's GFM430 and GFM436) use this method for methane and carbon dioxide, as do the Ion Science GasClam 2 and Amisense GasfluX continuous monitoring instruments.

The absorption of infrared radiation at specific wavelengths by a fixed volume of gas contained within a cell in the instrument is proportional to the methane and carbon dioxide concentrations. Instruments based on this technique have a wide range (0 to 100% v/v) and generally good resolution across this range, except at very low concentrations.

Two approaches are used to separate the IR output from a lamp into specific wavelengths: dispersive separation, which uses prisms or diffraction gratings, and non-dispersive separation (NDIR), which uses optical filters. Filters are significantly more efficient, giving NDIR instruments a performance advantage. Most of the available instruments appear to use NDIR, although this is not always indicated in instrument specifications.

IR instruments are affected by water vapour; other hydrocarbons may interfere with methane measurements. Some instruments (for example, the GFM436) have a hexane channel to allow correction for hydrocarbon interference.

Laser instruments

Laser gas detection instruments were originally developed to detect leaks in natural gas distribution systems, but their portability and high sensitivity make them well suited to measuring methane surface emissions in landfill and contaminated land applications. The operating principle is specific wavelength infrared adsorption, as with the landfill gas meters described above. The instruments can be supplied as a complete kit, including a sampling probe, and can be directly coupled to a GPS and data logger. Intrinsically safe versions are available. Gazomat's Inspectra Laser is an example of this type of instrument.

Electrochemical cells

Electrochemical cells (ECs) are typically used to measure concentrations of oxygen, hydrogen, carbon monoxide, ammonia and hydrogen sulfide. ECs can be configured for a broad or narrow range of concentrations. The cells have a limited life and are subject to poisoning.

ECs are frequently combined with infrared absorption in the same field instrument (for example, Landtec's GA5000 and GEM5000 and Gas Data's GFM430 and GFM436).

Photoionisation detector

Photoionisation detector (PID) instruments are widely used to screen for the presence of VOCs. An ultraviolet lamp is used to ionise VOC vapour molecules by electron removal. A wide range of compounds can be detected, depending on the energy of the lamp installed – typically 10.6 eV, but higher-energy (11.7 eV), lamps are available. Lamps that are 11.7 eV are expensive and have a short life; therefore, rental instruments are generally supplied with 10.6 eV lamps. However, some commonly

encountered chlorinated hydrocarbons (including carbon tetrachloride, chloroform, dichloromethane, 1,1 dichloroethane and 1,2-dichloroethane) cannot be ionised with a 10.6 eV lamp. Methane has a minimum photo-ionisation energy of 12.6 eV and cannot be detected with an 11.7 eV lamp either.

Typically, a PID instrument is calibrated with isobutylene, and may then be configured to 'read as' a specified compound, such as benzene or PCE. However, these instruments measure total ionisable gases and cannot quantify individual compounds in a mixture.

PID instruments readily available to rent in NSW include RAE System's MiniRAE 3000 and its higher-resolution ppbRAE 3000, and Ion Science's Tiger.

Flame-ionisation detector

Like the PID, a flame-ionisation detector (FID) can be used to screen for VOCs as total ionisable gases. An advantage of using this instrument is that it will detect a wider range of compounds, including gases such as methane) that have high ionisation potentials.

The instruments can be used to measure open-air and surface emission concentrations, but not all models are intrinsically safe for use in confined spaces. The instruments are difficult to transport by air and require some oxygen in the measured atmosphere.

FIDs have frequently been used to measure surface emissions, although alternatives are now available.

FID instruments readily available to rent in NSW include the Photovac MicroFID series.

Field gas chromatograph

Portable gas chromatographs (GCs) have been available for many years. They are miniaturised versions of the laboratory instruments, and may be equipped with FID or, more commonly, PID detectors. When properly calibrated, they can quantify a wide range of VOCs and gases. However, the calibration and operation of a GC in the field is not straightforward. Optimally, the instrument should be permanently installed in a vehicle and operated by a specialist to provide the consistent operating conditions required to generate reliable and repeatable data.

A4.4.2 Flow, pressure and temperature measurement

A borehole's flow rate and pressure are generally measured using the accessory instruments integrated into current landfill gas meters. A number of alternatives are available.

The GA5000 has an internal flow measurement option that measures the pressure drop across a known resistance. Instantaneous, average and peak flows can be output. This instrument can also be used with an optional vane anemometer. It has built-in sensors to measure barometric pressure, and borehole pressure relative to barometric pressure. Temperature is measured using a separate probe.

The GEM5000 is a similar instrument to the GA5000, with additional features to facilitate monitoring and management of landfill gas extraction systems. It has more options for flow measurement, which include using orifice plates and pitot tubes.

Gas Data's GFM430 will also internally measure static pressure, atmospheric pressure and differential pressure (dynamic and static) and flow rate. It can be used with an external Schiltknecht vane anemometer and/or temperature probe.

To use an external anemometer or temperature probe, the borehole casing will need to be equipped with an additional port, below the cap, to permit the probe's entry. In most circumstances, the measurement range of the internal flow option will be more appropriate than that of an external vane anemometer.

Flow measurement in riser pipes connected to subfloor gas or vapour venting systems is generally carried out using a hot-wire anemometer. An access port must be installed in the riser; this can be used for both concentration and flow measurements.

TSI's VelociCalc hot-wire anemometers are available to rent. These instruments measure flow rates of 0 to 30 m/s and temperature, and include sophisticated data logging. They are available with telescopic probes, which are particularly useful for flow measurements in mitigation system riser pipes.

While intrinsically safe hot-wire anemometers were previously available, they now appear to have been withdrawn from the Australian market. Therefore, a gas concentration measurement should be carried out before a flow measurement.

Flow is measured by inserting the anemometer probe through the port and making a pass across the full width of the riser. As flows will vary with wind speed, a number of passes should be made, and the average velocity calculated. This is then converted to flow by multiplying by the cross-sectional area of the riser.



Figure 11 Measuring flow in a riser using hot-wire anemometer (TSI VelociCalc)

Source: C.M. Jewell & Associates Pty Ltd

The following sections provide examples of field instruments that are available to buy or rent in NSW. Their inclusion does not imply endorsement; rather, they are used to illustrate the available range. As with other types of equipment, at each price point the major manufacturers and distributors tend to offer instruments with similar basic capabilities but some unique features.

Examples of IR absorption/EC instruments

Landtec's **GA5000** is currently the most widely used instrument for borehole concentration and flow measurement. It is available to rent in NSW.

The GA5000 is an IR absorption instrument (for methane and carbon dioxide) that measures:

- methane 0 to 100% v/v with low-level accuracy of 0.5%
- carbon dioxide 0 to 100% v/v.

It can be combined with optional ECs to measure:

- oxygen 0 to 25% v/v
- carbon monoxide 0 to 2000 ppm
- hydrogen sulfide 0 to 10,000 ppm
- hydrogen 0 to 1000 ppm
- ammonia 0 to 1000 ppm
- flow measurement range 0 to 20 L/hr, 0.3 L/hr resolution.



Figure 12 Landtec's GA5000 instrument

Information: www.landtecnica.com/product/ga5000/

Gas Data's **GFM430** is available in NSW and has better resolution than the GA5000 for low-level methane and flow rates.



Figure 13 Gas Data's GFM430 instrument

Information: www.gasdata.co.uk/products/landfill-gas-analyser

The GFM430 can measure:

- methane 0 to 100% with low-level accuracy of 0.2%
- carbon dioxide 0 to 100%
- oxygen 0 to 25%
- atmospheric pressure 800 to 1200 mbar, 1 mbar resolution
- static pressure -200 mbar to +200 mbar, 1 mbar resolution
- differential pressure +1000/-1000 Pa
- flow measurement range +30 to -30 L/hr, 0.1 L/hr resolution.

It can be combined with optional ECs to measure:

- hydrogen sulfide 0 to 1500 ppm
- carbon monoxide 0 to 1000 ppm
- nitrogen dioxide 0 to 20 ppm
- sulfur dioxide 0 to 100 ppm
- hydrogen 0 to 1000 ppm
- hydrogen cyanide 0 to 100 ppm
- ammonia 0 to 1000 ppm
- nitric oxide 0 to 100 ppm
- VOC (PID) 0 to 2000ppm
- temperature (with external probe) -10 to 100°C.

The Envision gas analyser is a landfill gas management unit that measures methane and carbon dioxide using NDIR, and oxygen using an electrochemical cell. It also measure static and differentil pressure and is a multirange instrument with good low-level accuracy.



Figure 14 The Envision gas analyser

Information: www.raeco.com/products/gasmonitoring/Elkins-Earthworks-Envision/Elkins-Earthworks-Envision-ds-2012.pdf

Ion Science's **GasClam 2** is designed to be installed in a 50-mm borehole to allow continuous, unattended data collection. It is available on the rental market in NSW.



Figure 15 Ion Science's GasClam 2

Information: www.ionscience.com

The GasClam 2 measures methane (0–100%) and carbon dioxide (0–100%) concentrations by IR absorption. It is available with optional low-range (0–5%) methane and carbon dioxide sensors and as 0.5 to 1% resolution and $\pm 2\%$ accuracy for these gases. It measures oxygen, carbon monoxide and hydrogen sulfide by EC. A PID unit measuring total VOCs is also available.

The instrument also measures borehole pressure, atmospheric pressure, temperature and, optionally, water depth. A telemetry module for remote, continuous data download is available.

The GasClam 2 is intrinsically safe and can be installed in 50-mm boreholes. It allows up to three months continuous unattended data collection, with programmable borehole venting.

The gas monitor's sampling frequency can be set at user-defined intervals – varying from two minutes to once daily – and set to alert. Data are downloaded to a PC or viewed remotely using the optional General Packet Radio Service (GPRS) telemetry system.



Figure 16 The Ambisense GasfluX

Information: <https://ambisense.net/gasflux/>

The Ambisense **GasfluX** is also available to rent in NSW. It measures methane and carbon dioxide concentrations by NDIR with $\pm 2\%$ accuracy and oxygen, carbon monoxide and hydrogen sulfide by EC. An optional PID VOC module is available.

The GasfluX measures gauge (differential) and barometric pressure, temperature and humidity, and also provides continuous measurement of borehole flow from -7 to 60 L/hr. It is the only instrument currently available to do this.



Figure 17 Gazomat's Inspectra Laser

Information: www.gazomat.com/

Gazomat's **Inspectra Laser** is available to rent in NSW.

The **Inspectra Laser** is a methane-only measurement instrument designed to detect natural gas leaks, but it is easily adapted for monitoring surface emissions. Measurement is via specific wavelength adsorption from an IR laser beam.

The measurement ranges are 0 to 10,000 ppmv and 0.1% to 100% v/v; the detection threshold is 1 ppmv methane. This instrument is supplied as a kit with a probe. It can be integrated with a GPS and data logger.

Examples of PID instruments

RAE Systems' **MiniRae 3000** is widely used and available to rent in Australia. It is a direct-reading VOC monitor that can be supplied with 9.8, 10.6 or 11.7 eV ultraviolet lamps. It has measurement ranges of 0.1 to 15,000 ppmv with a 10.6 eV lamp, and 0.1 to 1000 ppmv with an 11.7 eV lamp. It has resolution of 0.1 ppmv and precision of $\pm 3\%$ at the calibration point.

The instrument is normally calibrated to an isobutylene standard in three ranges (0 to 99 ppm, 100 to 1999 ppm and 2000 to 10,000 ppm). It has built-in correction factors for 102 VOCs.

RAE Systems' **ppbRAE 3000** is a higher resolution version. It has a range of 1 ppb to 10,000 ppm (with a 10.6 eV lamp), with resolution of 1 ppb and precision of $\pm 3\%$ at the calibration point.



Figure 18 RAE Systems' MiniRae 3000

Information: www.aesolutions.com.au

Example of an FID instrument

Infinicon/Photovac's **MicroFID II** is no longer manufactured but is available to rent in NSW. It is intrinsically safe and has an operating range of 0.1 to 30,000 ppmv and resolution of 1 ppmv. It detects VOCs, methane and other saturated and unsaturated hydrocarbon gases.



Figure 19 Infinicon/Photovac's MicroFID II

A4.5 Site assessment methodology

This section provides basic guidance on site assessment methodologies. It is not intended to be comprehensive.

Table 20 provides a summary of ground gas sampling and site measurement methods

The following sub-sections provide more detailed information and cross-references for some field methods referred to in this guideline.

Table 20 Ground gas sampling and site measurement methodologies

Technique	Method	Gases	Applicability
In situ reconnaissance of gas presence, distribution and qualitative concentration	Membrane Interface Probe (MIP)	Methane and VOCs – both PID and FID tools will distinguish them	Deployed using push-tube (Geoprobe) equipment; applicable to unconsolidated formations, subject to usual equipment restrictions; risk of probe damage needs to be considered in fill; would generally run a full suite of tools, including EC and halogen specific detector (XSD), to aid interpretation
Field analysis – bulk gases	IR	CH ₄ , CO ₂	Most circumstances where these gases may be present and are primary contaminants of concern
	EC	O ₂ , H ₂ , CO, H ₂ S	
	FID	CH ₄ , hydrocarbon gases	Screening where gas composition is unknown. Intrinsically safe models are available
	GC	CH ₄ , CO ₂ , O ₂ , H ₂ , CO, H ₂ S hydrocarbon gases	Long-term monitoring where costs of set-up and use of specialist personnel are justified

Technique	Method	Gases	Applicability
	Fourier-transform infrared (FTIR)	CH ₄ , CO ₂ long path	Closed landfills, coal-seam gas operations, long-term or wide-area monitoring where set-up costs are justified
	Laser	CH ₄ long path	
	Forward-looking infrared (FLIR)	CH ₄ , CO, some VOCs	Infrared real-time imaging of surface emissions and system leakage. Closed landfills, coal-seam gas operations, gas control systems. Portable hand-held camera
Flow and pressure measurement – bulk gases	Mass flow	All gases, borehole measurement	Most circumstances
	Vane anemometer	All gases, in-building measurement	Ventilation and sub-floor mitigation systems
	Hot-wire anemometer	All gases, in-building measurement	Ventilation and sub-floor mitigation systems where there is minimal cross-current interference
Field measurement – trace gases	PID	Some VOCs, some hydrocarbon gases	Screening; OHS monitoring where gas composition is unknown
	FID	CH ₄ , VOCs, hydrocarbon gases	
	GC	CH ₄ , VOCs, hydrocarbon gases	Assessment or long-term monitoring where set-up costs and use of specialist personnel are justified
Sampling – bulk gases	SUMMA canisters	All gases (H ₂ S requires fused silica-lined canisters)	Passive technique that is particularly useful for time-integrated sampling but may also be used for grab sampling
	Tedlar bags	All gases	Active technique that is particularly useful for grab sampling, but may also be used for time-integrated sampling
Sampling – trace gases	SUMMA canisters	TO-14A/TO-15 VOCs	Passive technique that is particularly useful for time-integrated sampling but may also be used for grab sampling. Long holding times
	Tedlar bags	All gases	Active technique that is particularly useful for grab sampling but may also be used for time-integrated sampling. Short holding times
	Sorbent tubes	VOCs	Active technique that requires accurate and reliable measurement of flow rate and correct tube selection for analytes of concern
	Passive samplers	VOCs	Passive and generally qualitative technique that is useful for screening and time-integrated sampling

A4.5.1 Borehole flow and gas concentration measurement

Measurements of gas flow rates and concentrations are almost always carried out using an IR landfill gas meter, with supplementary EC cells if appropriate. Sometimes, a separate PID instrument is also used. Flow is usually measured using the internal capability of the meter or a separate flow pod. In most borehole measurement circumstances, using an anemometer will not offer a significant (or any) advantage in terms of accuracy.



Figure 20 GA5000, MiniRae and Velocicalc in use for subslab and riser measurements

Source: C.M. Jewell & Associates Pty Ltd

All instruments should be calibrated according to the manufacturer's instructions before starting to take measurements – date, time and site information should be entered. Background concentrations, barometric pressure, temperature and, if appropriate, wind-speed readings should then be obtained.

As indicated in this guideline, ground gas monitoring wells should be sealed and fitted with a quick-connect nipple to allow easy connection of the measurement instrument. Most instruments have a programmed measurement sequence. Where possible, the sequence for measurements should be:

- atmospheric pressure
- static (shut-in) borehole pressure or vacuum
- initial flow
- initial differential pressure
- initial, peak and steady gas concentrations
- final flow
- final differential pressure.

Measurements should continue for a period that is sufficient to allow steady readings of concentration to be obtained. This period will be site-specific and operator judgement will be required.

Note: if the borehole pressure is below the atmospheric pressure, the flow will be negative (into the bore). This situation usually indicates barometric pumping. In this circumstance, measured gas concentrations are clearly not representative of ground conditions and should be flagged as such. However, the magnitude of negative pressure and flows are useful measurements and should be recorded.

A4.5.2 Surface emissions mapping

Surface emissions mapping using portable equipment can be used to locate emissions hotspots and defects in capping, and as an additional line of evidence to support a borehole measurement.

A procedure for landfill gas surface emissions monitoring is provided in Section 5.2 of the NSW EPA's *Environmental Guidelines: Solid Waste Landfills* (2nd edition 2016). This procedure should be used for former landfill sites and, with modifications where necessary, forms an appropriate starting point for planning emissions monitoring programs on non-landfill sites. For non-landfill sites, grid spacing, instrumentation and investigation triggers would be chosen based on the CSM.

In essence, the EPA procedure requires an operator to traverse the site surface on foot along a series of parallel lines, taking measurements of methane concentration close to the ground surface at intervals along the lines equivalent to the line spacing, therefore creating a square grid of measurements. The measuring instrument and associated equipment, such as a GPS and data logger, can be mounted on a chest sling and backpack, while the gas inlet is through a handheld extendable probe held just above the ground surface.

If the equipment is integrated with a GPS and data logger, the data can be downloaded to a spreadsheet and contoured using a package such as Surfer to produce a surface emissions map for the site.

The key recommendations in the landfill guidelines are shown below.

- Methane should be measured in the atmosphere 5 cm above the landfill surface.
- Testing should be conducted in a grid pattern across the landfill surface at 25-m spacings.
- Depressions in the cover material, or surface fissures away from the sampling grid, should also be investigated.
- The monitoring should be performed on calm days (with winds below 10 km/h) and preferably during periods of relatively low and stable atmospheric pressure (for example, less than 101.3 kPa).
- The measurement instrument should be capable of detecting methane gas in sufficiently low concentrations to ensure confidence in the results. For surface gas monitoring, this concentration is 20 ppmv.
- The device should be properly zeroed and calibrated according to the manufacturer's instructions before any measurements are taken.
- A flame ionisation detector is usually used.
- The trigger for further investigation is methane detected at concentrations above 500 ppmv.

On non-landfill sites, spacing will depend on site conditions. In NSW, the best conditions for monitoring will generally be in the early morning. Laser IR absorption equipment comfortably meets the recommended detection threshold, is methane-specific, and may be used as an alternative to an FID.

A4.5.3 Flux chamber measurement

Flux chambers, also known as *flux boxes* and *flux hoods*, can be used for directly measuring gas and vapour emissions from a site surface. This method can be used as part of a multiple-lines-of-evidence approach, in conjunction with emissions mapping and borehole measurements.

Section 6.2 of Davis et al. (2009b) describes both static and dynamic flux chamber methods. Much of this information is also in Hartman (2003).

The static chamber method requires placing the flux chamber on the site surface. Gas or vapour can pass into the chamber through the open base, but cannot escape. This allows vapours to be trapped and a static ground gas concentration to build up in the chamber. Samples are extracted for analysis at intervals so the rate of increase in the concentration can be calculated. The sample extraction point must be placed so the sample is representative of the gas concentration in the box – typically near the centre.

The UK Environment Agency (2010) published a detailed procedure for a passive flux box method for measuring surface emissions from landfill surfaces that is the standard approach in the UK.

It has the advantage of using an improvised flux box construction from readily available materials. Detailed assembly instructions are provided. The procedure assumes the use of an FID to measure the build-up of the gas concentration in the box, but there is no reason why a methane-specific logging IR laser instrument with a low detection threshold and good resolution could not be used.

As with other flux chamber methods, an effective seal against the ground surface is a key requirement.

The key variable is the rate of change of the gas concentration within the box. Once the box is set up and sealed, the gas concentration in the box is measured, typically at 30-second to 60-second intervals, for a period of about 30 minutes. The concentrations are plotted against time and the gradient calculated. The flux, Q , is then calculated as:

$$Q = \frac{V}{A} \frac{dc}{dt}$$

where V is the volume of the box, A is the surface area and $\frac{dc}{dt}$ is the rate of change of gas concentration within the box. Instrument readings in ppmv need to be converted to mg/m^3 to calculate mass flux, typically expressed as $\text{mg}/\text{m}^2/\text{s}$.

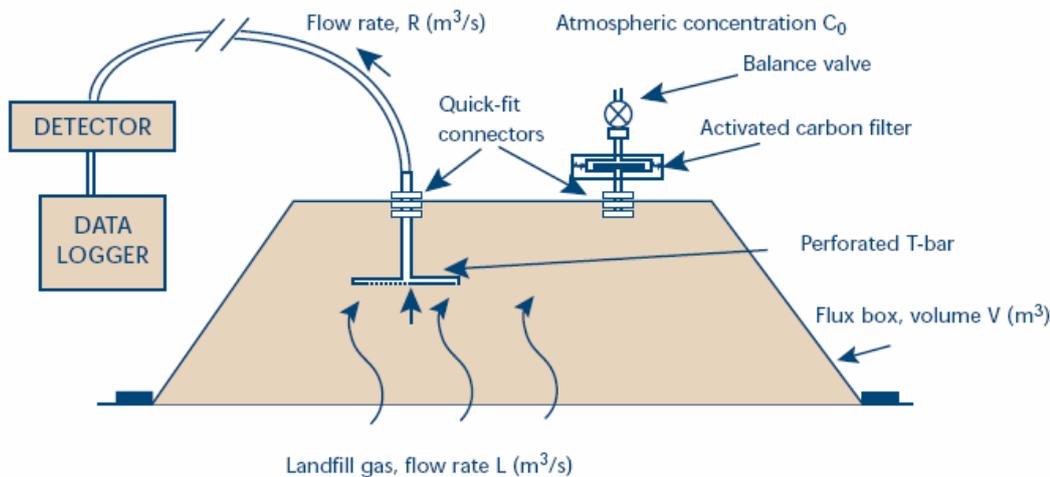


Figure 21 Schematic diagram of a passive flux box

Source: UK Environment Agency (2010)

The dynamic chamber method involves using an inert sweep gas that is continually introduced into the chamber, with an equivalent amount of gas allowed to escape. The system is assumed to reach a steady-state concentration after four or five chamber-residence times, where one residence time equals the chamber volume divided by the sweep-gas flow rate. At steady state, the contaminant concentration in the outlet gas is equivalent to the concentration in the chamber. The concentration in the outlet gas is monitored with an appropriate instrument (FID or laser IR), or a sample of the outlet gas is collected for analysis (for example, in a SUMMA canister), depending on the required detection level for the contaminants of concern.

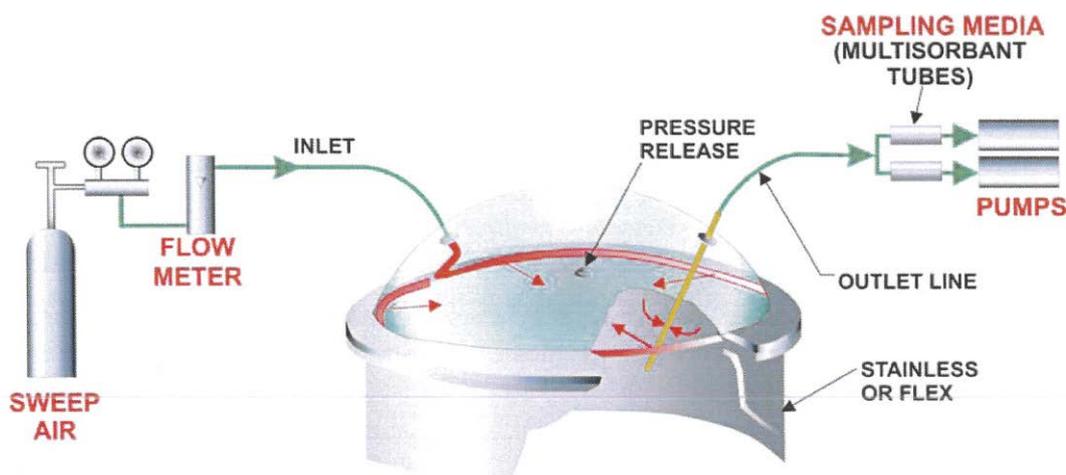


Figure 22 Schematic diagram of dynamic flux chamber

Sources: Davis et al./CRC CARE 2009b

At steady state, the mass flow of gas into the chamber from the land surface is equal to the mass flow rate (concentration \times measured flow rate) through the outlet, and the surface flux is that flow rate divided by the area of the chamber base.

The static flux chamber method has the substantial advantages of offering simplicity, low cost and greater sensitivity. Its main disadvantage is that if the chamber concentration is allowed to increase to a significant proportion of the sub-surface concentration, gas flow into the chamber will be restricted and the flux underestimated. This would usually be detectable by the concentration versus time plot being a curve trending towards an asymptotic concentration, rather than being a straight line. The dynamic chamber overcomes this disadvantage, but at the cost of greater complexity, greater expense and a significant loss of sensitivity due to dilution by the sweep gas.

Whichever approach is adopted, it should consider the following points.

- Measurements must be taken at enough locations to provide representative coverage of the site.
- Diurnal and longer-period variations in flux due to temperature and barometric pressure changes should be considered, and appropriate conditions selected, as for surface emissions measurement using a mobile probe.
- Emission rates from soil may decrease immediately after rain, so measurements should generally not be taken in the seven days after a rain event of more than 7 mm.
- Aerobic biodegradation of methane and petroleum hydrocarbon vapours in the near-surface may cause measurements taken on open ground to significantly underestimate sub-surface flux.

Consequently, these methods should be considered in the context of the CSM and development proposals for a site. Generally, it is most appropriate to use them as a component of an approach that considers multiple lines of evidence.

Appendix 5

Further guidance on risk assessment

Table 21 provides further guidance on risk assessment.

Table 21 Risk assessment

Level	Issue	Requirements
Qualitative assessment	Principles	The basic principles of risk assessment are set out in AS/NZS ISO 31000:2009 <i>Risk Management – Principles and Guidelines</i> .
	Multi-level risk assessment	Multi-level risk assessment is described in the NSW Department of Planning and Infrastructure (2011) <i>Assessment Guideline: Multi-Level Risk Assessment</i> .
	Gas screening values	Gas screening values are described in CIRIA C665. The volumetric gas flow rate from a borehole (L/hr) is multiplied by the gas concentration (% v/v).
	Gas CS	CSs are assessed from the gas screening value and the CSM.
Quantitative assessment – event-based (bulk ground gases)	Probability modelling	Quantitative risk assessment for bulk ground gases, if carried out at all, is generally restricted to hazard analysis, and does not extend far into consequence analysis. Detailed guidance on ground gases is provided in CIRIA R152. Hazard and consequence analysis in a more general hazardous industry context for NSW is provided in HIDAP 6.
	Fault trees	Fault tree analysis is useful in identifying combinations of equipment and materials failures and human error that can lead to an incident. It uses a logic diagram that starts with an undesirable event and works downwards until the range of possible causes have been identified. The end result of a fault tree is a list of combinations of equipment and procedural failures, for which appropriate failure rate data exists or can be generated, that are sufficient to result in the 'top event'. The fault tree can be used to estimate the likelihood or probability of the top event occurring. It is also a useful hazard identification tool.
	Event trees	Event tree analysis is usually an integral part of a hazard analysis. It is useful for consequence analysis, frequency analysis and risk summation, but can also be valuable in the hazard identification process, both in giving the analyst an appreciation of the way in which incidents may develop and in allowing an assessment of the adequacy of protective equipment and procedures. Beginning with an initiating event, the technique analyses the various event sequences that may develop. As an incident develops, various routes may be taken, depending on the behaviour of personnel and equipment, as well as natural alternative routes, such as wind direction and weather conditions. The end result is a list of final outcomes and the event sequences required to produce them.
	Gas generation models	A fairly large (>10) number of landfill gas generation models are available. GasSim is widely used in the UK, whereas LandGem is used in the USA. Other models include EPER (France) and LFGGEN (US).

Quantitative assessment – toxicity-based	Issue identification	This involves reviewing the available data to identify chemicals of potential concern, potentially exposed populations, exposure pathways and point concentrations.
	Hazard identification	As outlined in Schedule B4 of the ASC NEPM, hazard identification examines the capacity of an agent to cause adverse health effects in humans and animals. It is an essentially qualitative description based on the type and quality of the data, complementary information (for example, structure–activity analysis, genetic toxicity and pharmacokinetic factors) and the weight of evidence from these various sources. Key issues include nature, the reliability and consistency of human and animal studies, the available information on the mechanisms of toxic effects, and the relevance of animal studies to humans.
	Toxicity assessment	<p>The core task of toxicity assessment is to define the quantitative dose–response relationship between exposure and the effects of concern. The determination of whether there is a hazard is often dependent on whether a dose–response relationship is present. Key issues include:</p> <ul style="list-style-type: none"> • the relationship between the extrapolation models selected and available • information on biological mechanisms • the selection of appropriate datasets from those that show the range of possible potencies in laboratory animals and humans • the basis for selecting interspecies scaling factors to account for scaling doses from experimental animals to humans • the relevance of the exposure routes used in the studies to a particular assessment, and the interrelationships of potential effects from different exposure routes • the relevance of the expected duration of exposure and the exposure durations in the studies forming the basis of the dose–response assessment • the potential for differing susceptibilities in population sub-groups. <p>In general, chemicals of concern are divided into two groups: threshold chemicals, for which the level of exposure poses no appreciable risk of an adverse effect; and non-threshold chemicals, for which no such threshold can be assumed. In Australia, a non-threshold relationship is generally assumed only for chemicals that are genotoxic carcinogens.</p>
	Exposure assessment	<p>As outlined in Schedule B4 of the ASC NEPM, exposure assessment involves estimating the magnitude, frequency, extent and duration of exposure in the past, present and future. It also identifies exposed populations, particularly sensitive sub-populations and exposure pathways.</p> <p>The process involves:</p> <ul style="list-style-type: none"> • analysing contaminant releases • identifying exposed populations • identifying potential exposure pathways • estimating exposure concentrations for each pathway • estimating contaminant intakes for each pathway for a range of scenarios. <p>The ASC NEPM is the primary reference for Australian purposes, but enHealth (2012a) and USEPA (1989, 1991, 2009, 2015a and 2015b) are also relevant.</p>

	Vapour intrusion models	<p>The Johnson and Ettinger (J&E) (1991) model is a one-dimensional analytical model designed to assess convective and diffusive vapour flow from the ground into a building. It is widely used in Australia, and a number of commercial derivations, such as RISC, are available.</p> <p>USEPA (2004) developed a spreadsheet model based on the J&E algorithms, which was refined for use within an Australian framework in Part 4 of Friebel and Nadebaum (2011).</p> <p>The Farmer et al. (1980) model and later developments of this model are also sometimes used in Australia.</p> <p>The USEPA (1996) model, and derivations, can be used to assess outdoor air concentrations.</p> <p>Modelling of biodegradation will be worthwhile in some circumstances for methane and hydrocarbon vapours, including BTEX.</p>
	Toxicological data sources	<p>enHealth (2012a) provides a list of toxicological data sources. These are classified as level 1, 2 or 3 sources, with Level 1 recommended. An order of preference for Level 1 sources is provided.</p>
Risk characterisation		<p>Risk characterisation is the final step in the risk assessment process, in which toxicity assessment and exposure assessment are combined to provide quantitative assessments of threshold and non-threshold risk, which are then compared against acceptable risk targets.</p> <p>For threshold chemicals, this target is the 'no appreciable risk' level, and the comparison is presented as a hazard quotient for individual chemicals, and a hazard index, which represents the sum of the hazard quotients for all threshold chemicals of concern. A hazard index less than 1 indicates acceptable risk, and as the hazard index rises above 1, the risk becomes increasingly unacceptable.</p> <p>For non-threshold chemicals, the target is a socially acceptable level of risk, generally stated as a probability of excess cancer occurrence, summed across all non-threshold chemicals of concern. Excess cancer risks of less than 10^{-6} are negligible. In NSW, excess cancer risks of less than 10^{-5} are considered acceptable, while risks between 10^{-5} and 10^{-4} require further assessment, monitoring and possible action. Risks greater than 10^{-4} are unacceptable.</p>

Table 22 Alternative process for low-risk sites

Requirement	Details	Criteria
Desk study and reconnaissance	As set out in Sections 3.1 and 3.2 for all sites	NA
Initial CSM	As set out in Section 3.3	NA
Screening-level risk assessment	As set out in Section 4.3.1	If no potential source or credible pathway is identified, no further investigation and no gas mitigation measures are required. Exit the process at this point.
Initial site investigation	Must include site-specific geological data, including logs prepared by a geologist using the USCS	
Refined CSM and risk model	As set out in Section 3.5	Potential sources of ground gas (on- or off-site) must be limited to natural soils with measured low organic carbon content and low hydrogen sulfide risk (specifically excluding reclaimed coastal or estuarine swamps and mangrove flats) or to shallow (<3-m average depth and <5-m maximum depth) general fill (excluding waste landfill) with minimal timber and other organic matter.
Level 1 risk assessment	As set out in Section 4.3.2	If risk is very low, no further assessment is required. You may assume CS 1 and exit at this point. If the risk is moderate or above, proceed to a Level 2 risk assessment. Risk must be low to proceed further with the alternative process below.
Further site investigation (may be combined with initial investigation)	Short-term ground gas monitoring (a minimum of two events) to support the risk model	GSV must be below <0.7 and meet other CS 2 criteria.
	Test pit excavation in all potential source areas (minimum of five pits per area) with geological descriptions of materials encountered and estimations of the percentage of each material	There must be minimal waste, timber and other organic materials, except chitter.
	Laboratory total organic carbon (TOC) analysis of sub-10 mm fraction of representative sample from each pit, corrected to the proportion of the total sample	TOC concentration must be <3% w/w.
Review results	Professional review of results	You may assume CS 2 if all criteria are met.

Appendix 6

Further guidance on risk mitigation and site management

As stated in Section 5, mitigation and management measures must be:

- designed on a site- and building-specific basis to suit the conditions present
- designed and installed by competent people, in a manner that involves collaboration between designers, suppliers, specialist installers and building contractors
- approached as holistic systems in which the individual components function together to provide both the required primary system performance and adequate redundancy should one component fail.

This appendix is divided into two sections. The first deals with site protection measures – specifically, removing the source of ground gas and interrupting the transmission pathway between the source and receptor site, which is termed ‘pathway intervention’. The second section deals with building protection measures, which include structural elements of building design and construction, and gas projection systems that may be incorporated in foundations or installed in buildings.

A6.1 Site protection measures

Table 23 summarises source and pathway control measures.

Table 23 Site protection measures

Approach	Method	Requirements
Source removal	Excavation and visual/instrumental validation of removal of potential source materials	Removal or remediation of the gas source to the extent that it no longer presents a ground gas hazard. As with any other remediation program and in accordance with the SEPP and relevant NSW EPA guidance, this will normally require: <ul style="list-style-type: none"> • planning (including, in most cases, preparing a Remedial Action Plan) • implementation, in accordance with NSW EPA guidelines and the requirements of the Protection of the Environment Operations (Waste) Regulation 2014 • validation.
Source control	In-ground barriers – horizontal	Essentially, these are capping systems – in this context, used in conjunction with source depressurisation systems. Materials selection and detailed design must be based on an adequate CSM. Construction quality assurance and validation are necessary. Designs may include compacted clay, geosynthetic clay, high-density polyethylene (HDPE) and linear low-density polyethylene (LLDPE) membranes, spray-on bituminous membranes, concrete and asphalt pavement, and combinations of these materials. A basic requirement is that the barrier must be sufficiently impermeable to reduce gas flow to an acceptable level. It is essential to consider the effect of the barrier or cap in the lateral diversion of gas that formerly escaped vertically into the atmosphere. Controlled venting, flaring or use of gas may be required to manage this risk. Other key concerns are the effect of the cap on drainage, durability, resistance to desiccation and erosion, and resistance to anthropogenic damage and to damage caused by tree roots and burrowing animals.

	Passive venting	<p>In this context, passive venting involves vent trenches or borehole systems that permit ground gases to vent to the atmosphere either convectively or with the aid of wind-driven fans or cowls, therefore interrupting lateral migration of ground gases.</p> <p>Materials selection and detailed design must be based on an adequate CSM and usually a quantitative gas flow model. Construction quality assurance and validation are necessary.</p> <p>A basic requirement is that the system provides control of the full depth over which gas migration is likely to occur.</p> <p>Important considerations are the relative importance of advection versus diffusion in gas migration, the capture radius of the system and components, and the effect of fluctuations in groundwater levels.</p> <p>This method may be used in combination with horizontal and/or vertical barriers.</p>
	Source-area venting systems	<p>In this context, source-area venting systems, such as landfill gas extraction systems, are designed to reduce the gas pressure and/or concentration in the source area and therefore reduce the driving force for gas migration.</p>
	Monitoring	<p>Generally, this involves installing a system of gas monitoring wells along the boundary of the source. Periodic manual monitoring is normal, although automatic alarmed or telemetric systems are possible. These may be standalone systems, but frequently they are used to supplement other systems, such as barriers.</p>
Pathway intervention	In-ground passive barriers – vertical	<p>These are impermeable barriers to prevent the lateral movement of ground gases.</p> <p>Designs may include secant pile walls, slurry walls, sheet-pile walls and vertical membranes. Membrane materials include HDPE, LLDPE and other polymers.</p> <p>Materials selection and detailed design must be based on an adequate CSM. CQA and validation are necessary.</p> <p>A basic requirement is that the barrier must extend to a depth below which gas migration is unlikely to occur. This may be the base of a permeable horizon, the top of bedrock or below the lowest predicted level of the watertable.</p> <p>The potential to redirect gas flow around the end of the barrier, and the effects on drainage and groundwater flow, must be considered.</p> <p>This method may be used in combination with passive or active venting.</p>
	Active venting barriers	<p>In this context, active venting barriers are vent trenches or borehole systems that force ground gases to vent into the atmosphere through the use of electrically or mechanically driven fans or pumps, therefore interrupting lateral migration of ground gases.</p> <p>Materials selection and detailed design must be based on an adequate CSM and usually a quantitative gas flow model. CQA and validation are necessary.</p> <p>A basic requirement is that the system provides control of the full depth over which gas migration is likely to occur.</p> <p>Important considerations are the capture radius of the system and components, methods of managing the consequences of mechanical failure and the effect of fluctuations in groundwater levels.</p> <p>This method may be used in combination with vertical barriers and passive venting.</p>

A6.2 Building protection measures

Protection measures in buildings include those incorporated in the structural design of the building and its foundations; the design of building ventilation systems, membranes and other barriers; and passive and active foundation ventilation and pressurisation systems.

Building protection measures should be selected based on the:

- ground gas regime at the site
- proposed use of the building and its design – factors that are closely related but are nevertheless widely variable.

A6.2.1 Building use and design

Schedule B7 of the ASC NEPM describes four generic land-use scenarios (HILs A, B, C and D) that form the basis for the HILs and HSLs developed for soil and soil vapour contamination. The land-use categories used to certify site suitability within the NSW site auditor scheme are based on these scenarios. These are:

- **HIL A** – residential with a garden or accessible soil; childcare centres and primary schools
- **HIL B** – residential with minimal opportunities for soil access; secondary schools
- **HIL C** – public open spaces and recreation areas
- **HIL D** – commercial and industrial premises.

HILs A, B and D are generally relevant to buildings, with construction of buildings (such as clubhouses and toilets) within an HIL C scenario being a special case. The risks associated with direct exposure to contaminated soil were a primary consideration in the definition of the HIL scenarios; there is a partial but not full correlation with the risks due to exposure to ground gases.

BS 8485:2015+A1:2019 describes four building types (types A, B, C and D) that form the basis for selecting ground gas protection measures in the UK. These are:

- **Type A building** – private ownership with no building management controls on alterations to the internal structure, the use of rooms, the ventilation of rooms or the structural fabric of the building; some small rooms present
- **Type B building** – private or commercial properties with central building management control of any alterations to the building or its uses but limited or no central building management control of building maintenance, including the gas protection measures; multiple occupancy; small- to medium-sized rooms with passive ventilation of rooms and other internal spaces throughout ground floor and basement areas
- **Type C building** – commercial buildings with central building management control of any alterations to the building or its uses and central building management control of building maintenance, including the gas protection measures; single occupancy of ground floor and basement areas; small- to large-sized rooms with active ventilation or good passive ventilation of all rooms and other internal spaces throughout ground floor and basement areas
- **Type D building** – industrial-style buildings having large volume internal space(s) that are well ventilated; corporate ownership with building management controls on alterations to the ground floor and basement areas of the building and on maintenance of ground gas protective measures.

Australia has developed styles of building construction, occupancy and use that accord with the local climate and lifestyles, which differ in some respects from those common in the UK. For the purpose of these guidelines, five types of building have been defined. These are:

- **low-density residential** – usually but not exclusively single-storey dwellings on a separate land title (commonly Torrens title) with single occupancy; no building management and no post-occupancy controls on room use, ventilation or alterations to the internal structure; limited controls on building design and construction due to exempt and complying development provisions in NSW; construction for new buildings is predominantly slab-on-ground, but also suspended floors with crawl space and partial or full basements, particularly on sloping sites; correlates closely with residential component of HIL A and with BS 8485:2015+A1:2019 Type A,

but the median size (footprint area) of new houses in Australia is significantly larger than in the UK

- **medium- and high-density residential** – multiple-occupancy low-, medium- or high-rise townhouses and apartments; usually on a strata title and subject to by-laws, with maintenance of the external structure of the building and common areas managed and controlled by an owner’s corporation; includes some public housing and some mixed-occupancy developments, and developments with commercial occupancy of the ground floor; frequently includes basement or undercroft car parking; may involve ground-bearing or piled foundations; usually air-conditioned, with active ventilation of basement car parking; correlates reasonably well with HIL B and partially with BS 8485:2015+A1:2019 Type B
- **public buildings, schools, hospitals and shopping centres** – similar in many respects to standard commercial buildings; generally low- to medium-rise rather than high-rise; particular constraints regarding building evacuation in an emergency; frequently includes basement or undercroft car parking; may involve ground-bearing or piled foundations; almost always air-conditioned, with active ventilation throughout (does not apply to many existing schools); correlates generally with HIL D but includes primary schools and childcare centres, which are HIL A; correlates partially with BS 8485:2015+A1:2019 Type C
- **standard commercial buildings** – includes offices and some shops, industrial subdivisions and smaller showrooms; building management control of any alterations to the building or its uses and central building management control of building maintenance, including gas protection measures; single or multiple occupancy of ground floor and basement areas; frequently includes basement or undercroft car parking; may involve ground-bearing or piled foundations; small- to large-sized rooms with active ventilation or air-conditioning in all buildings, except those on industrial subdivisions, which will have good passive ventilation; correlates generally with HIL D and BS 8485:2015+A1:2019 Type C
- **large commercial and industrial buildings** – includes warehouses, most factories, big-box retail stores, large showrooms, and hardware or garden centres; characterised by large, open, high-volume buildings; often single-storey; may have basement, roof or exterior parking; corporate ownership, owner-occupied or leased; generally easy evacuation; may involve ground-bearing or piled foundations; correlates well with HIL D and BS 8485:2015+A1:2019 Type D.

A6.2.2 Modification of building design

Table 24 summarises gas protection measures that may be incorporated in building design. These are generally passive measures that do not require maintenance following the building’s completion. However, ventilation systems require maintenance, and the condition of slabs may need to be inspected periodically.

Table 24 Protection measures incorporated in building design

Building	Method	Requirements
Low-density residential	Planning controls	Implementation of ground gas management in new low-density residential developments in NSW poses significant challenges. The adoption of the Standard Instrument – Principal Local Environment Plan and the State Environmental Planning Policy (Exempt and Complying Development Codes) 2008 (ECDC SEPP) has left planning authorities with limited options to control the design and construction of individual low-density dwellings once a subdivision certificate has been granted. This is because such construction is considered a ‘complying development’ if it meets the requirements of the code, which includes compliance with the Building Code of Australia (BCA) but does not include any specific provisions relating to ground gas. General requirements are set out in Part 3 of the ECDC SEPP.
	Foundations	Basements and partial basements should be avoided in new low-density residential developments where ground gas is an issue. Suspended floor

Building	Method	Requirements
		construction with open sides provides significant ventilation and protection from ground gas.
	Slabs	Adequate reinforcement to limit cracking, in accordance with the BCA, is required for complying developments and other developments requiring consent.
	Ventilation	To comply with the BCA, as a minimum, natural ventilation should be uprated if possible when ground gas is an issue.
	Other aspects	Very limited control over post-completion alterations, although they are subject to Part 4 of the ECDC SEPP. Little reliance should be placed on structural components that can readily be damaged or altered.
Medium- and high-density residential	Planning controls	These buildings are not exempt or considered complying developments and, therefore, require consent under Part 4 of the EP&A Act.
	Foundations	Where a basement, undercroft or open-sided ground level is provided, ground gas protection can be substantially enhanced. Drained basements may be problematic due to the exsolution of ground gas from groundwater as well as permeability to ground gas. These factors should be considered, and fully tanked designs are preferable. Nevertheless, in most cases, ventilation that complies with BCA requirements is adequate to deal with potential ground gas ingress.
	Slabs	Concrete floor slabs are often the first and sometimes the only line of defence against ground gas intrusion. Concrete has measurable vapour permeability and diffusivity (fresh concrete would never dry if it did not), but most intrusion occurs through cracks, poorly sealed expansion joints and gaps around service penetrations. Post-tensioned structural slabs have higher resistance to vapour penetration than raft slabs, although cracking is not unknown and regular inspection during the tensioning period is required. A number of concrete mix additives that claim to reduce the liquid and vapour permeability of concrete are available. If a slab is to be relied on as a component of a gas management system, it is essential to seal all joints and penetrations, preferably with water bars, and carry out an independent inspection.
	Ventilation	To comply with the BCA at a minimum, air-conditioning is standard in new developments. Natural and active ventilation should be uprated if possible when ground gas is an issue; Building Sustainability Index (BASIX) requirements have to be considered.
	Other aspects	Body corporate by-laws and planning consent requirements provide significant control of structural alterations. Additional controls may be applied through management plans and covenants with reasonable, though not absolute, confidence.
Public buildings, schools, hospitals and shopping centres	Planning controls	These buildings generally require specific planning approval.
	Foundations	These buildings have a wide range of foundations to suit ground conditions. These may include piled foundation designs that need attention from a ground gas perspective, pre-construction ground improvement, and conventional ground-bearing foundations.
	Slabs	These buildings generally have slabs constructed to high engineering standards, including post-stressed slabs and thick, well-reinforced slabs with high vehicle load-bearing capacity. There are usually opportunities to uprate slabs to assist with ground gas protection in this type of development. Most intrusion occurs through cracks, poorly sealed expansion joints and gaps around service penetrations. Post-tensioned structural slabs have higher resistance to vapour penetration than raft slabs, although cracking is not unknown and regular inspection during the tensioning period is required. A number of concrete mix additives that claim to reduce the liquid and vapour permeability of concrete are available.

Building	Method	Requirements
		If a slab is to be relied on as a component of a gas management system, it is essential to seal all joints and penetrations, preferably with water bars, and carry out an independent inspection.
	Ventilation	To comply with the BCA, at a minimum, air-conditioning is almost universally included in new developments.
Standard commercial buildings	Planning controls	These buildings may be considered complying developments under Part 5 of the ECDC SEPP.
	Foundations	These buildings have a wide range of foundations to suit ground conditions. These may include piled foundation designs that need attention from a ground gas perspective, pre-construction ground improvement and conventional ground-bearing foundations.
	Slabs	<p>These buildings generally have slabs constructed to reasonable but not necessarily high engineering standards.</p> <p>There are usually opportunities to uprate slabs to assist with ground gas protection in this type of development.</p> <p>Most intrusion occurs through cracks, poorly sealed expansion joints and gaps around service penetrations. Post-tensioned structural slabs have higher resistance to vapour penetration than raft slabs, although cracking is not unknown and regular inspection during the tensioning period is required. A number of concrete mix additives that claim to reduce the liquid and vapour permeability of concrete are available.</p> <p>If a slab is to be relied on as a component of a gas management system, it is essential to seal all joints and penetrations, preferably with water bars, and carry out an independent inspection.</p>
	Ventilation	To comply with the BCA, at a minimum, air-conditioning is standard in new developments. Natural and active ventilation should be uprated if possible when ground gas is an issue; BASIX requirements have to be considered.
Large commercial and industrial buildings	Planning controls	These buildings may be considered complying developments under Part 5 of the ECDC SEPP.
	Foundations	These buildings have a wide range of foundations to suit the ground conditions. These may include piled foundation designs that need attention from a ground gas perspective, pre-construction ground improvement and conventional ground-bearing foundations. However, these buildings frequently have a lightweight construction with lower foundation requirements.
	Slabs	<p>These buildings generally have slabs constructed to high engineering standards, including post-stressed slabs and thick, well-reinforced slabs with high vehicle load-bearing capacity.</p> <p>There are usually opportunities to uprate slabs to assist with ground gas protection in this type of development.</p> <p>Most intrusion occurs through cracks, poorly sealed expansion joints and gaps around service penetrations. Post-tensioned structural slabs have higher resistance to vapour penetration than raft slabs, although cracking is not unknown and regular inspection during the tensioning period is required. A number of concrete mix additives that claim to reduce the liquid and vapour permeability of concrete are available.</p> <p>If a slab is to be relied on as a component of a gas management system, it is essential to seal all joints and penetrations, preferably with water bars, and carry out an independent inspection.</p>
	Ventilation	Generally, these buildings have a high volume relative to the floor area, with good ventilation, but may include small rooms that require additional ventilation.

A.6.2.3 General gas-resistant membrane considerations

Gas-resistant membranes are thin sheets of material used to restrict the entry of ground gases. They form part of the gas protection system for buildings. These membranes are not impermeable. Gases can pass through membranes by advection and diffusion; both of these processes may occur together but their relative importance depends on the gas regime at the site, the nature of the gas and the composition of the membrane.

When there is differential pressure across the membrane, advection will dominate. This is most likely to occur where bulk ground gases are present. The transmission rate depends on the pressure gradient across the membrane, its permeability to the gas and the frequency of defects. Conversely, in the absence of differential pressure, transmission occurs primarily by diffusion. Diffusion alone is unlikely to transmit bulk ground gases through an intact (defect-free) membrane at a rate high enough to cause acute risks in an affected building. However, due to the much lower chronic toxicity values for trace ground gases, diffusive transmission of these gases may generate significant risks.

Once a gas has penetrated the surface of the membrane, the rate of diffusion depends on the concentration gradient across the interior of the membrane and the ease with which the gas can diffuse through the free volume between its molecules or crystals. Mechanistically, the gas molecules must partition (dissolve) into the membrane surface and then migrate through the intermolecular spaces in its interior in a Brownian motion, before desorbing from the opposite surface. The combination of these processes is termed 'permeation', and the permeation coefficient of a gas through a solid material (SI unit m^2/s) is the product of the partition constant and the diffusivity. Unless a gas can first dissolve into the membrane surface, diffusive transport cannot occur.

Factors that contribute to the solubility component of the permeation coefficient are the polarity of the gas and the membrane material (solubility will be greater if both are polar or both non-polar) and the size and shape of the gas molecule. Smaller and more streamlined molecules penetrate the surface of the membrane more easily than larger, bulky molecules; very large molecules may be excluded. Molecular size and shape also affect the diffusion component, as does the molecular structure (crystallinity) of the membrane and its free volume. More detailed discussion of the mechanism of gas transport through membranes is provided in Section 2 of CIRIA C748 and Chapter 13 of Hansen (2007).

When selecting an appropriate membrane for ground gas protection at a site, it is important to consider the permeation rate of the gases of concern through different membranes, as well as the risk of membrane deterioration due to chemical attack. In an initial assessment, the polarity of the membrane material relative to that of the gases of concern provides a reasonable guide to the permeation rate. Polar solutes will dissolve more readily in polar solvents, and vice versa. In this case, the gas is the solute and the membrane the solvent.

Polarity of a solute gas can be assessed from the chemical and physical data provided in Appendix 2. High $\log K_{ow}$ (>1) and low Hansen δ_P indicate non-polar solutes. Most gases discussed in these guidelines fall into this category. Conversely, low $\log K_{ow}$ and high Hansen δ_P indicate polar solutes.

An indication of the polarity of polymer membranes can be obtained by considering the monomers from which they are formed. Alkenes (ethene and propene) are non-polar, and so are the respective polymers, polyethylene and polypropylene. Conversely, polymerised alcohols, ethers and amides are polar, like the monomers.

At a more advanced level, the Hansen Solubility Parameters (HSPs) for gases and membrane materials can be used to model gas–membrane interactions. The three HSPs represent the three major types of interactions common in organic materials: respectively, non-polar or dispersive interactions (δ_D), polar cohesive energy (δ_P) and hydrogen bonding (δ_H). A fourth, experimentally determined parameter, the interaction radius (R_0), is available for many polymers. HSPs for gases are provided in Appendix 2, and parameters are provided in Table 26 for the membranes listed in those tables.

Chapter 1 of Hansen (2007) provides an equation for calculating a difference parameter (R_a) between two materials (in this case a gas and a membrane material) using their HSP:

$$(R_a)^2 = 4(\delta_{D2} - \delta_{D1})^2 + (\delta_{P2} - \delta_{P1})^2 + \delta_{H1} - \delta_{H2})^2$$

This method is also summarised in CIRIA C748.

A relative energy difference (RED) is then calculated between the two materials as the ratio of Ra and the tabulated parameter Ro:

$$\text{RED} = R_a/R_o$$

The interpretation is as follows:

RED < 1 – the gas is likely to permeate the membrane

RED ≈ 1 – borderline condition

RED > 1 – the gas is unlikely to permeate the membrane.

The HSP approach may be used as a relatively simple screening technique to help select a suitable membrane, as permeation data are difficult to obtain from membrane suppliers. It should be noted that the HSPs provided were derived by Hansen using a combination of experimental work and calculation. Much of the work involved concentrated permeants; as aspects of permeation – particularly entry resistance – have a concentration dependency, the resistance of membranes to dilute gas mixtures may be underestimated.

CIRIA C748 recommends testing the permeation of candidate membranes in accordance with ISO 15105-2:2003. In NSW, such testing should be considered when there is any doubt about the suitability of a proposed membrane for a ground gas protection application.

A6.2.4 Types of gas-resistant membrane

Two types of gas-resistant membrane are described in this section. These are cold spray-applied barriers and loose-laid polymer (plastic) sheet geomembranes.

Spray-applied barriers

In southern Australia, where (with some exceptions) weather conditions are usually favourable for their use, cold spray-applied bitumastic or asphaltic barriers are currently the most commonly used membranes for protecting buildings against the entry of hazardous ground gases. When properly applied, they are effective for bulk ground gases and some commonly encountered VOCs.

Due to the problems encountered in applying and curing these membranes in wet conditions, they are not frequently used in the UK. The standards and procedures used for their specification, application and testing in Australia were originally developed in the USA, particularly for methane protection in Los Angeles, California.

A number of products are available in Australia, including Liquid Boot and Geo-Seal. The former is a water-based asphaltic emulsion modified with chloroprene (2-chloro-1,3-butadiene), while the latter is a water-based asphaltic emulsion modified with a sulphonated co-polymer. Both are mixed with a catalyst on-site to initiate curing. These membranes may also serve as water barriers. They may be applied directly to the upper or lower surface of a slab but are more commonly applied to a geotextile (non-woven polypropylene in the case of Liquid Boot) placed under or over the slab. The former placement is preferred, as the slab will provide ongoing protection.

It is possible to retrofit spray-on membranes to the top surface of existing slabs during major building renovations.

The advantages of spray-on membranes include the ease of sealing around penetrations and complex edges, the ease of bonding to structural elements and resistance to damage; they are to some extent self-repairing, as the asphaltic co-polymer coating remains plastic. Defects can readily be repaired by over-spraying, puttying or patching. The main disadvantage is the difficulty of maintaining a constant membrane thickness during on-site application. This can be effectively managed by using a skilled operator and appropriate CQA testing.

The cured thickness for spray-applied membranes is generally 1.5 mm (60 mil) for gas-only applications (2.0 mm with the base geotextile), or 2.0 mm (2.5 mm) when the gas protection function is combined with waterproofing. Loose-laid protective geotextiles, with a thickness of 1.5 mm, are used below and above the membrane. These systems have a methane transmission rate of <40 ml/day/m²/atm, measured as required by ASTM D1434-82 (2015).

Both CETCO (Liquid Boot) and REGENESIS (Geo-Seal) also offer composite barrier systems where the base geotextile is replaced with a geomembrane or geomembrane–geotextile composite. Liquid Boot Plus uses a 0.5-mm LLDPE/ethylene vinyl alcohol (EVOH)/LLDPE composite geomembrane, and Geo-Seal uses a HDPE/polyamide/HDPE base membrane and loose-laid HDPE protective cover.

These composites can provide protection against a wider range of gases; see below for a summary of the membrane components and Table 25 for further information.

Loose-laid polymer (plastic) sheet membranes

A number of gas-resistant membranes are available on the international market; some of these are also available from Australian suppliers. Similar membranes are used for both landfill gas and leachate control and, in some cases, in water retention and hydrocarbon secondary containment applications. Note that the bentonite geocomposite membranes that are widely used in leachate applications are not suitable to use for building protection from ground gases due to the difficulty of achieving and maintaining hydration, and the lack of an adequate confining load. The low-cost commodity plastic sheeting sold as 'builders' film' or 'builders' plastic' (typically 0.1 to 0.2 mm thick) is not suitable for use in gas protection systems.

The sheet membranes most commonly used in Australia are:

- HDPE, with joints welded on-site
- LLDPE, also with welded joints
- LLDPE/EVOH composite.

Other sheet membranes available in Australia are:

- flexible polypropylene (fPP), with joints welded on-site
- low-density polyethylene (LDPE), with lapped and taped joints
- polyester-reinforced LDPE composite membrane with an aluminium core
- HDPE/polyamide composite.

Most of these membranes are available in a range of thicknesses. Table 25 gives membrane properties.

Other geomembranes that are used for gas protection overseas – including chlorosulphonated polyethylene (CSPE or Hypalon), PVC and coated polyester – are available in Australia but appear to be used only as waterproofing membranes.

The primary considerations in selecting membrane specifications for a particular site are:

- membrane permeation by the gases of concern
- chemical resistance
- mechanical strength and elongation at break
- tear and puncture resistance during and after installation
- the requirements for joining and patching sheets (welding or tape)
- the thickness required to meet permeation and strength requirements
- the process of sealing around penetrations and the availability of accessories to do this
- the overall practicality of installation.

These characteristics are all functions of both material composition and thickness. Their relative importance will vary between sites and will depend on the:

- gas hazard at the site
- role and importance of the membrane in the total gas protection system
- potential exposure of the membrane to chemicals of concern (concentration and phase – gas/vapour, condensate, dissolved phase, NAPL)
- potential exposure of the membrane to aggressive environments (acidic or alkaline conditions, UV radiation, temperature extremes, etc.)
- tensile loads on the membrane
- overall scale and complexity of the installation and detailing required

- potential for post-installation damage.

Resistance to damage during and after installation is always a major consideration because small punctures or tears in a membrane will result in a drastic increase in the overall gas transmissivity of the installation.

Annex C of BS 8485:2015+A1:2019 and CIRIA C748 provide further information on the general performance and specifications of plastic membranes used as gas barriers. Lucas and Wilson (2019) discuss the durability of aluminium-core LDPE composite membranes.

Table 25 Loose-laid polymer sheet geomembranes for ground gas protection – general characteristics (properties as stated by manufacturers/suppliers)

Material	Available thickness range (mm)	Thickness commonly used for gas protection (mm)	Tensile strength (N/mm)	Tear strength (N)	Elongation at break (%)	Puncture resistance (N)	Joining	Advantages	Disadvantages	Comments	Some known Australian manufacturers/suppliers
HDPE	0.75–2.5	1.0	26	120	700	380	On-site welding	High chemical resistance, high puncture resistance, generally robust	Rigid, difficult to handle on-site, difficult to detail, difficult to repair	Specialist welding and weld testing required	GSE Curtis
LDPE	0.2–1.0	0.5	10	83	700	250	Lap/tape, extrusion welding possible	Cheap, good chemical resistance, flexible	Relatively high gas permeability, very easily damaged, degraded by UV light	Thin (0.2–0.4 mm) commodity membranes (usually imported from China or India as concreting membrane) are generally not adequate for gas control	Monarflex Curtis
LDPE/ medium-density poly-ethylene (MDPE) co-polymer	0.4	0.4	9	100	800	–	Lap/tape	Moderate gas permeability, high chemical resistance, flexible, relatively low cost	Easily damaged during and after installation	Not widely available	Rhinoplast
LLDPE	0.5–2.0	0.75	20	70–100	850	205	On-site welding or lap/tape	Moderate gas permeability, high chemical resistance, flexible,	Easily damaged during and after installation	Readily available	GSE Permathene Curtis

Material	Available thickness range (mm)	Thickness commonly used for gas protection (mm)	Tensile strength (N/mm)	Tear strength (N)	Elongation at break (%)	Puncture resistance (N)	Joining	Advantages	Disadvantages	Comments	Some known Australian manufacturers/suppliers
								relatively low cost			
LLDPE/EVOH co-extruded	0.5	0.5	Not available in consistent units	63 x 66	464	240	Lap/tape overspray	Low diffusion and permeation coefficients for non-polar chemicals (most VOCs)	–	Readily available	CETCO (VI-20)
fPP	0.3–1.5	1.5	22	65	900	250	On-site welding	Low gas permeability, high chemical resistance, flexible	Easily damaged during and after installation	–	Permathene Curtis
Reinforced LDPE composite with aluminium core	0.4–0.8	0.4	14–44	216–400	–	–	Lap/double-sided tape	Lowest gas permeability and VOC permeation, flexible, relatively low cost	LDPE degraded by UV light, core can corrode if exposed to alkaline conditions (cement)	Aluminium core has very low methane transmission rate and VOC permeation rates, but the composite is not particularly robust	Visqueen Protech Monarflex

Table 26 Loose-laid polymer sheet geomembranes for ground gas protection – gas transmission and permeation

Material	Thickness (mm)	Methane gas transmission rate (GTR) ^a (ml/m ² /d/atm) (m/Pa.s)	Permeation coefficient P _g at 23°C (m ² /s × 10 ¹⁰) ^b								
			Benzene	Toluene	Ethylbenzene	m- and p-xylene	o-xylene	PCE	TCE	DCM	1,2-DCA
HDPE	2.0	150	0.1	0.3	0.5	0.6	0.4	–	–	–	–
LDPE	0.5	700	–	–	–	–	–	–	–	–	–
LDPE/MDPE co-polymer	0.4	150	–	–	–	–	–	–	–	–	–
LLDPE	0.76	320–690	1.0	1.8	1.6	1.4	1.1	–	–	–	–
LLDPE	0.53	–	0.7 0.1 _(v)	1.1 0.2 _(v)	0.8 0.3 _(v)	0.9 0.3 _(v)	0.8 0.2 _(v)	–	–	–	–
fPP	1.5	65	–	–	–	–	–	–	–	–	–
PVC	0.76	–	1.3	3.6	7.8	7.5	4.7	–	–	–	–
Reinforced LDPE composite with aluminium core	0.4	0.001	–	–	–	–	–	–	–	–	–
32mol% EVOH co-polymer	0.015	–	0.00190	0.00250	0.00130	0.00110	0.00110	0.00300	0.00350	0.00330	0.00200
44mol% EVOH co-polymer	0.02	–	0.00023	0.00026	0.00016	0.00015	0.00014	0.00040	0.00038	0.00036	0.00015
LLDPE/EVOH/LLDPE co-extruded five-layer	0.53 (EVOH 0.002)	–	0.00004	0.00005	0.00006	0.00007	0.00004	–	–	–	–
LLDPE/EVOH/LLDPE co-extruded five-layer	0.53 (EVOH 0.002)	–	0.018 0.001	0.030 0.002	0.056 0.001	0.048 0.006	0.041 0.003	–	–	–	–
LLDPE/polyamide/LLDPE co-extruded five-layer	0.38 (PA 0.002)	–	0.07–0.10 0.02 _(v)	0.11–0.14 0.02–0.03 _(v)	0.21 0.05–0.07 _(v)	0.22 0.06–0.07 _(v)	0.20 0.03–0.04 _(v)	–	–	–	–

^a Manufacturer's literature, generally to ASTM International 2015c

^b Islam and Rowe 2001, Jones and Rowe 2006, and McWatters and Rowe 2009, 2010 and 2015

_(v) Measured in the vapour phase – all other permeation coefficient values measured in aqueous phase. Vapour phase values may be estimated by multiplying by the dimensionless Henry's Law volatility constant.

Table 27 Cold spray-applied geomembranes for ground gas protection

Material	Available thickness range (mm)	Thickness commonly used for gas protection (mm)	Methane gas transmission rate (GTR) (ml/m ² /day/at m) and as (m/Pa.s)	Tensile strength (N/mm)	Tear strength (N)	Elongation at break (%)	Puncture resistance (N)	Joining	Advantages	Disadvantages	Comments	Known Australian manufacturer/ supplier
Chloroprene-modified asphaltic spray-on	1.5–2.0 (sprayed and, therefore, variable)	1.5	<40 <4.7 × 10 ⁻⁵	Depends on geofabric base used	Lap/over-spray	Bonds to structure if required; effectively seamless; easy to install where complex detailing is required; easily repaired; has some self-healing capability	Requires specialist installation; difficult to maintain constant thickness; manufacturers do not provide adequate data on gas permeability/ GTR	Probably the best combination of physical robustness, system integrity and ease of installation; manufacturers unwilling to provide test data for GTR, other than a statement that the product meets the City of Los Angeles Criterion quoted in Column 4	Liquid Boot			
Chloroprene-modified asphaltic spray-on with LLDPE/EVO H/LLDPE base												
Sulphonated asphaltic spray-on												Geo-Seal
Sulphonated asphaltic spray-on with HDPE/ polyamide/ HDPE base												

Table 28 Passive and active venting

Approach	Method	Requirements
Passive protection – building	Passive venting	<p>Passive venting uses either void spaces beneath the occupied levels of buildings or drainage blankets installed beneath floor slabs.</p> <p>The most common types are:</p> <ul style="list-style-type: none"> • open-sided undercrofts • open, accessible voids beneath suspended concrete floor slabs (either pre-cast or cast in-situ) • inaccessible voids created beneath cast in-situ slabs using void formers • gas drainage layers formed by perforated or slotted pipes, or modular drainage systems surrounded by a gravel blanket • continuous cellular modular drainage layers. <p>The essential feature of passive systems is that gas is removed and externally vented by airflow through the void or drainage layer that is driven by convection, wind-induced pressure and suction, or wind-driven cowls.</p> <p>The advantage of these systems over active systems is that they are not vulnerable to power, mechanical or maintenance failures and therefore provide more robust protection. In most circumstances, this is likely to be more acceptable to auditors and regulators.</p> <p>A disadvantage is that it can sometimes be difficult to design passive systems for a specific building that will work under a full range of weather conditions.</p> <p>It should be noted that although wind-driven cowls are not vulnerable to power outages, they are not completely passive systems and may be affected by mechanical and/or maintenance failures. For example, cowls can be damaged during storm events and bearings can wear over time and eventually seize, preventing the cowl from spinning if not maintained.</p> <p>Passive venting systems must be designed on a site-specific basis by:</p> <ul style="list-style-type: none"> • modelling the gas flux from the ground into the venting layer under a representative range of conditions • calculating the airflow required through the venting layer (ventilation rate) required to maintain the gas concentration at the design level • designing a ventilation system to provide this flow under the design weather conditions, with adequate redundancy • designing a monitoring system. <p>The gas flux from the ground may be modelled using the Johnson and Ettinger model or similar. Required airflow may be calculated using the principles set out by the UK Department of the Environment, Transport and the Regions (DETR 1997) and Annexe B of BS 8485:2015+A1:2019 (which draws on and extends the DETR modelling). Normal design principles may be applied to the ventilation system, using specified cowl performance over an appropriate range of wind speeds (based on meteorological data for the site), with an allowance for redundancy to compensate for cowl failure due to airflow dead spots and bearing issues. The monitoring system should allow for sampling within the venting layer and for sampling and measuring airflow within riser pipes.</p>

	Monitoring and alarms	Automatic alarmed or telemetric gas monitoring systems may be installed within buildings or confined spaces – typically in the smallest rooms – and set to trigger an alarm at conservative concentrations. These are not recommended as a standalone system but are frequently used to supplement other systems, particularly active venting systems.
Active protection – building	Active venting/sub-slab depressurisation	<p>Void spaces and drainage blankets can be designed to be mechanically vented, which provides more effective ventilation over a wider range of weather conditions and enables smaller dimensions to be used.</p> <p>Mechanically vented basements, particularly basement car parks, may be used as a component of a gas management system.</p> <p>The advantages and disadvantages of active systems are essentially the converse of those that apply to passive systems. It is difficult to develop and enforce robust environmental management plans that will ensure active systems are maintained appropriately over the life of the building, regardless of changes in personnel or building ownership.</p> <p>Active ventilation systems may be more acceptable as part of a composite system that has a passive component, such as a barrier.</p>
	Building over-pressurisation	<p>The air-conditioning system of a building can be designed to maintain air pressure in the building above that in the ground. This may provide supplementary protection (for example, in combination with a barrier).</p> <p>The energy efficiency and running costs of such systems are significant considerations.</p>
	Sub-slab over-pressurisation	<p>Sub-slab over-pressurisation systems work by pumping air into a void or blanket beneath a building to achieve a positive pressure relative to the pressure of gas in the ground, therefore preventing gas migrating from the ground into the void.</p> <p>These systems are usually used in conjunction with a membrane or other barrier, and are only suitable for some ground conditions, as they are uneconomic when soil permeability is high.</p> <p>Appropriate system design and monitoring are required to ensure the system does not force gas into service trenches or other buildings.</p>

Appendix 7

Verification and construction quality assurance

This appendix sets out general procedures for independent verification (IV) and CQA of the design and installation of ground gas protection measures. In this context, IV relates to the whole process of independent review and certification, while CQA relates to the specific processes employed to ensure the measures are built and tested in accordance with the approved design, and that this compliance is recorded. CQC is generally provided by the installer of the gas protection measures.

The NSW EPA (2016a) and, particularly, the Environment Protection Authority Victoria (2015) provide guidance on CQC and CQA for the construction of landfill sites, including geomembrane installation. Aspects of this guidance are relevant to the installation and CQA of geomembranes in ground gas protection systems – Appendix D of the Environment Protection Authority Victoria’s (2015) guidance may be particularly useful in preparing CQA plans. However, a holistic approach to CQA for the whole gas protection system, not just the membrane, is required.

CIRIA C735 provides detailed information on testing and verifying ground gas protection systems, particularly with regard to testing loose-laid plastic membranes. As this information is not repeated here, the CIRIA document should be consulted when developing verification plans for systems incorporating these membranes. The CIRIA document does, however, have a strong UK focus. The UK has a different regulatory regime to NSW, and the spray-applied membranes common in NSW are not widely used in the UK. It is not, therefore, a substitute for locally developed guidance. Interestingly, in its brief review of overseas experience, CIRIA C735 comments on the formal auditing systems used in Australia.

These guidelines have been developed from a local perspective; the NSW site auditor scheme is central to quality assessment and certification in contaminated land management in NSW, and it is central to the verification approach outlined in these guidelines.

This appendix has been written on the basis that a site auditor is overseeing the design and installation of ground gas protection measures. Where design or installation of ground gas protection measures is subject to the consent of a planning authority, it is recommended that auditor involvement be made a condition of consent. Where installation is not subject to planning consent, it is recommended that a site auditor be engaged on a non-statutory basis. The site audit system is an integral part of the framework for managing contaminated land in NSW, and the safeguards embedded in that system make involvement of a site auditor the most effective means of ensuring that risks due to hazardous ground gases are effectively managed.

These guidelines do not prescribe the process required for reviewing the construction of ground gas protection measures because the recommended validation approach must be sufficiently flexible to apply to the range of contractual arrangements that may be used for construction projects in NSW. The following sections of this appendix outline a recommended approach.

A7.1 Verification of design

A site auditor will review the investigation of the ground gas regime at the site and the proposed design for protection measures in accordance with Sections 4.2.3 and 4.3.12 of the *Guidelines for the NSW Site Auditor Scheme* (3rd edition) (NSW Environment Protection Authority 2017 (the auditor guidelines) and these guidelines.

As required by the auditor guidelines, the site auditor will check that the assessment of hazardous ground gases has been adequate in scope and duration, has been carried out competently, and that the data acquired has been correctly interpreted and incorporated into the CSM. They will also confirm that the assessment has complied with all notification requirements specified in the CLM Act and POEO Act (or orders made under those acts), the auditor guidelines and any applicable planning consent.

The site auditor will then confirm that the design of ground gas protection measures is appropriate to adequately mitigate the identified risks, taking into consideration the ground gas regime and existing or proposed development at the site, and the potential for off-site gas migration. The requirements of any applicable planning consent, and any requirements of the CLM Act and EP&A Act, must also be considered.

The design will include:

- plans and specifications for the physical measures to be constructed or installed
- a CQA program to confirm that the measures are constructed in accordance with the design
- an outline of the ongoing management measures required, and how these will be implemented and enforced.

The site auditor will document their verification of the design in an interim advice letter or Section B site audit statement.

Ground gas protection systems cannot be certified by a site auditor until the building is complete, which can complicate arrangements for final certification. However, this process can still be regulated through appropriate conditions of consent. Generally, a PCA will not issue final occupation certificates until a site auditor has certified that the system has been successfully installed and operates correctly, typically with a Section A2 site audit statement.

If a site auditor is not appointed, which may be the case on low-risk sites (subject to the discretion of the planning authority), a qualified and experienced professional may conduct a peer review.

A7.2 Construction quality assurance

A7.2.1 Independence

Ideally, ground gas protection measures should be installed by certified specialists who are responsible for CQC. CQA should be provided by certified specialists or qualified and experienced persons who are fully independent of the installer of the protection measures. In NSW, there are no state standards for the qualification and certification of installers, although some trade qualifications are relevant to some aspects of the work. The installers are generally trained and have their competence assessed by the companies that perform the installation work. Some geomembrane installation specialists operating in NSW have staff certified under the North American Geosynthetic Certification Institute-Inspectors Certification Program for Geosynthetic Materials and Compacted Clay Liners (GCI-ICP). However, there are few independent CQA contractors certified in post-installation testing of membranes. Given the ideal may not currently be attainable and practical, alternative options are necessary.

Depending on the scope and scale of the work, the options available are as follows.

Option 1

- Structural protection measures are installed by the general construction contractor, and an independent consultant observes and certifies the construction of these measures as they relate to ground gas protection.
- Specific ground gas protection measures, such as membranes and ventilation systems, are installed by a specialist contractor who is responsible for CQC, or by a general contractor (or subcontractor) working under the direction of the specialist contractor. The specialist contractor is responsible for training and assessing personnel. An independent consultant supervises installation and provides CQA (including documentation). The independent consultant may be the system designer and should be a qualified and experienced professional with expertise in ground gas protection systems. If available, possibly from interstate, an independent certified membrane inspector may provide this aspect of CQA.
- The installer tests installed components, with all testing supervised by the independent consultant, who provides CQA documentation.

- The independent consultant tests and monitors the completed systems.
- The site auditor oversees all these operations at an audit level. An audit level of supervision requires the site auditor to witness a sufficient number of operations, including a sample of all operations, to be satisfied that the work is being carried out competently and that reliable records are being kept.
- All the CQA documentation is subsequently reviewed by the site auditor, who establishes that the work has been completed to a satisfactory standard and that any necessary corrective action has been identified, completed and checked.
- The site auditor certifies the process through a site audit report and site audit statement.

Option 2

As for Option 1, except for the following:

- The installer tests installed components, with all testing supervised by a separate CQA team employed by the installer, who provides CQA documentation.
- Testing and monitoring of completed systems is then carried out by a consultant engaged for that purpose.
- The site auditor oversees all these operations. This requires a significantly higher level of engagement by the site auditor throughout the installation and testing process.

Generally, Option 2 would be most appropriate for relatively straightforward, small-scale protection measures.

It is possible that, as has been the case in other disciplines, specialist providers of ground gas CQA will emerge and operate either as independent subcontractors or members of site auditors' specialist support teams.

A7.2.2 CQA requirements

CQA plan

The CQA plan should outline the installation and testing process for the ground gas protection system, and specify the roles and responsibilities of all those participating in the process, including the site owner or manager, the head contractor, the suppliers and installers, the independent consultant(s) and the site auditor.

The process should then be broken down into separable units, hold points and release mechanisms should be identified, and specific inspection and test plans (ITP) should be prepared. Each ITP should explain, justify and document the test procedures, the qualified and experienced professionals required to complete them, the test frequency, the acceptance criteria and the certification mechanism. Necessary records, including measurements and photographic evidence, should be identified. Appropriate forms should be developed for each inspection or test task, with required signatories and necessary attachments identified. Matters to be addressed include the following.

Recording materials delivered to the site

- Supplier
- Means and date of delivery, and record of the attached delivery note
- Batch or roll numbers
- Inspection frequency, and record of the number of samples required for bulk materials
- Condition on receipt, noting any damage
- Compliance with specifications
- Photographic record of damage or non-compliance
- Confirmation of acceptance or rejection

Sub-grade preparation and inspection

- Details of inspection required
- Compliance with specifications
- Photographs
- Corrections required

Venting system installation

- Thickness and condition of granular drainage media
- Number and location of inspection points required
- Continuity and condition of modular drainage system
- Size, layout and joints of pipework or low-profile drainage, in accordance with the design
- Appropriate temporary protection
- Any modifications to manage obstructions
- Installation of monitoring systems, and continuity and protection of monitoring lines

Membrane installation

- Procedure for installing the protective underlay
- Record of protective underlay installation
- Membrane installation procedure
- Membrane or base fabric condition following installation
- Record of installers or sprayers
- Details of what is required and records to be kept for visual and mechanical inspections
- Photographs of detailing, penetrations and joins
- Edge anchoring and/or sealing procedures, where required
- Thickness check – frequency of sampling and measurements required
- Thickness records – roll basis for geofabric or destructive sampling for spray-applied membranes with photographs of locations and calliper reading
- Documentation of defects

Integrity testing

- Procedures required for tracer gas testing or dielectric porosity testing of loose-laid membrane
- Tracer gas to be used
- Required instrumentation and operators identified
- Instrument records
- Procedure required for smoke testing spray-applied membrane
- Photograph or video of smoke test
- Documentation of defects
- Documentation of corrective action taken
- Re-testing records
- Application of protective barrier

Post-steel installation inspection

- Procedure required for post-steel installation smoke test
- Documentation of damage
- Documentation of corrective action

Post–concrete installation inspection

- Inspection of cured slab surface – cracking and general condition
- Penetrations – effectively cast in
- Record of any post-pour penetrations and their condition
- Frequency and duration of inspections – may be extended for post-tensioned slabs
- Record of crack development
- Record of sealing cracks or around penetrations – including sealant used, application times and post-sealing inspections

Above-ground pipework, risers and cowls

- Documentation of installation and any variations from design
- Photographs
- Monitoring access
- Installation of all inlets with correct dimensions and appropriate protection measures
- Installation of all cowls and visual observation of cowl rotation

Fans and other mechanical systems

- Check plating of units installed against specification
- Record of any differences
- Documentation of electrical installation and sign-off by registered electrician
- Switchboards and metering
- Functional testing

Post-installation monitoring

- Procedures required for all monitoring
- Test locations specified
- Monitoring period
- Required number of events
- Required instrumentation and operators specified
- Accessibility of inlets
- Outlets have rotating cowls and operational fans
- Accessibility and integrity of sampling locations – checked and corrected if necessary
- Sub-membrane sampling tubing – gas sampling and/or on-site measurement
- Flow and concentration of risers
- Outlets (if required for environmental monitoring) – concentration
- Building ventilation systems – installed and operating to specification
- Acceptance criteria specified
- Completion of the required number of monitoring sessions over the required period, with performance in accordance with specifications

CQA implementation

As indicated in Section A7.1, the site auditor should review and approve the CQA plan as part of the design verification process.

Once approved, the ground gas protection system must be installed in accordance with the design, and the CQA implemented in accordance with the plan. Any changes and the reasons for them should be documented and, where possible, agreed to in advance by the site auditor. This process requires a high degree of cooperation between the installer and the design and CQA consultant(s), and timely coordination with the site auditor so that they can provide the audit oversight required.

CQA reporting

Once installation and initial testing is complete, the independent consultant should prepare a detailed construction and CQA report that documents the construction process and summarises all the required CQA information. It should incorporate an assessment of the individual component and overall system integrity and be signed by the consultant. The report should be provided to the site auditor for review.

An EMP for the site, prepared in accordance with Appendix 8 of these guidelines, should be provided at the same time.

System verification

The site auditor is responsible for reviewing construction records (including CQC documentation and the CQA report), post-construction validation testing and the EMP, in accordance with the site auditor guidelines. If satisfied that the ground gas protection system has been installed in accordance with the design and is functioning effectively, and that – subject to implementation of the EMP – the site is suitable for the proposed use, the site auditor may verify the installation by issuing a site audit report and site audit statement.

Appendix 8

Further guidance on environmental management plans

A8.1 General comments

The environmental management plan generally should:

- incorporate a mechanism to monitor and report on compliance to an appropriate authority on a regular basis
- not unduly focus on the investigations and remedial works that have been completed – rather, the management plan should briefly describe that work as well as detail the works that must be undertaken to ensure the identified risks continue to be appropriately addressed. It should provide the necessary information to enable such works to be conducted
- be actively instructional (rather than being a passive document)
- be prepared in consultation with the people who will implement it
- detail how the land is to be managed and, if installed, how mitigation systems are to be monitored (for example, pressure, airflow and gas concentration, with associated criteria) and maintained
- be prepared in a manner that is consistent with the life of the development. For example, if the life of the development is 30 years while the life of a gas monitoring probe is only 10 years, it should specify that the gas monitoring probes are to be replaced every 10 years
- allow for staff turnover. Five years after preparing the management plan, it is likely that no-one with first-hand knowledge of the project will still be implementing the plan or be available to clarify any issues that arise
- not expect more from the people implementing the plan than can be provided by those who prepared the plan
- allow for changing circumstances – and, in the event that the plan requires amending in the future, specify proposed changes and the people (for example, a site auditor) who must review them
- be written in a style and format that assists, rather than hinders, the people implementing it. The document should be clear in its direction and requirements, and without ambiguity (for example, due to any differences of opinion between the consultant and the site auditor)
- be reasonable (that is, it should not stipulate requirements that are not practically achievable)
- be consistent with the underlying commissioning report(s). In particular, the mitigation systems should be operated in the same manner as they were when commissioned
- provide assessment criteria and detail the actions to be taken if a trigger level is exceeded
- address any conditions or limitations that were included by the consultant and/or the site auditor within their commissioning report or site audit report
- be capable of being incorporated into the landowner's management systems
- be prepared by the consultant who conducted the works. However, that consultant should appreciate that the management plan will be owned and implemented by others
- discuss foreseeable future works at the property. For example
 - if a floor slab that forms a part of the mitigation system has to be penetrated, how such penetrations must be sealed
 - if significant works are contemplated, a requirement to engage an appropriately experienced consultant to assess whether the works can be undertaken without impacting the gas mitigation systems, and to then supervise those works and update the management plan accordingly

- be written such that only relevant information is provided within a given section. For example the person conducting routine monitoring needs to know how the systems function, why monitoring is being conducted, where to monitor, what to monitor for, the assessment criteria, how to assess the monitoring results, and the actions they should take if a trigger level is exceeded, but they don't necessarily need to know the manufacturer's specifications for the individual parts of the systems. However, the person responsible for replacing faulty equipment would need such information
the person conducting routine gardening does not need detailed information on how the mitigation systems function, but they do need to be instructed not to excavate below a specified depth, not to plant trees and so on
- be a standalone document. For simple systems, a brief plan may be appropriate. When dealing with more complex active systems, an in-depth plan will be required. For complex active systems, it would not be unreasonable for the management plan to comprise several parts, with each part intended for a different readership, where
 - Part 1 outlines procedures for responding to issues that may arise with the mitigation systems (for example, what to do if a fan stops working or if methane is detected above a specified trigger concentration), and is intended for those who will oversee the operation of the systems, rather than their monitoring and maintenance
 - Part 2 details the routine monitoring requirements (for example, quarterly monitoring of the rate at which air is passing through the mitigation system), and is intended for those who will conduct the monitoring
 - Part 3 provides general information on installing and maintaining the systems (for example, as-built drawings and manufacturer's specifications).

An example of the structure of a management plan for a site with a complex ground gas mitigation system is provided below. However, it is important to note that management plans will reflect the measures installed on a site and, in some cases, may be simpler than shown in this example.

A8.2 Summary table

Generally, pertinent aspects of the management plan should be summarised within tables and charts mounted in a suitable location on the site.

Typically, the information should include:

- a list of 'dos' and 'do not's' (including obvious 'do not's', such as 'do not turn off the extraction fans' and 'do not block any air inlets/outlets to ventilation systems')
- a list of the routine activities to be undertaken, with associated frequencies
- a decision tree flow chart presenting procedures for responding to issues that may arise with a mitigation system (for example, what to do if a fan stops working or if methane is detected above a specified concentration)
- where active ground gas mitigation systems have been installed, drawings illustrating the significant parts of those systems, together with details on how to access the systems and any personal protective equipment (PPE) that may be required when doing so
- details of the people responsible for or associated with implementing the management plan, together with their contact details
- an induction register for the manager responsible for the overall implementation of the management plan.

The summary tables and charts should be readily understood by people who are not familiar with the management plan and/or the property.

The plan should highlight whether the property must be vacated and/or emergency services contacted if ground gas is detected above a specified concentration or if a particular alarm is triggered.

A8.3 Part 1 – Procedures for responding to issues with gas mitigation systems

A8.3.1 Summary table

Copies of the summary tables and charts should be included, as appropriate.

A8.3.2 Introduction

This section should provide the context for the management plan, including relevant background information. It should summarise investigation results and the CSM; briefly describe any ground gas mitigation systems that have been installed and explain the need for them; and present any trigger or action levels.

This section should be written in a concise manner and in a style and format that are suitable for the ongoing management of the land and any gas mitigation systems that have been installed.

A8.3.3 Response actions for gas detections

This section should detail the procedures for responding to ground gas detections and explain why action is necessary.

For example, if methane is detected at a concentration of 2% v/v while conducting routine monitoring within a building that sits above a methane mitigation system with an action level of 1.25% v/v, the presence of methane at a concentration greater than 1.25% v/v indicates that the mitigation system has failed, and that the building must be evacuated and emergency services called.

A8.3.4 Response actions for active systems

This section should detail the procedures for responding to any indications that the active systems are not operating as intended, outlining timeframes for responding and why these actions are necessary.

For example, an alarm is triggered indicating that one of two extraction fans is not operating. The fan is promptly inspected by on-site personnel and cannot be reactivated. The site personnel increase the capacity of the operating fan to compensate for the loss of the non-operational fan, and contact the maintenance contractor. The contractor inspects the non-operational fan and finds a faulty part. The contractor informs the responsible manager that the replacement part can be obtained and fitted within two days. The manager decides that two days is an acceptable time period given that the operating fan is working effectively (there is no reason to install the back-up fan stored on-site). Two days later, the fan is repaired and the system is restored to its normal operating status.

A8.3.5 Response procedure for rectifying holes in the gas barrier

This section should detail the procedures for responding if the gas barrier is compromised, outlining timeframes for responding and why these actions are necessary.

For example, during a routine site inspection of a property, a contractor is found to have drilled through a floor slab that forms a part of the gas mitigation system. The floor slab is promptly sealed as per the specifications that are provided elsewhere in the management plan, and the procedures for ensuring unauthorised penetrations of the floor slab do not occur are reviewed.

A8.3.6 Response procedures where contaminated material is exposed

This section should discuss other contaminated land issues, as appropriate. For example, if the site is also contaminated with asbestos, an asbestos management plan must be implemented if any sub-surface works are conducted.

A8.3.7 Appendices

Typically, appendices include:

- as-built drawings illustrating the mitigation systems that have been installed
- photographs of the monitoring points, including any air inlets and outlets, condensate drainage points and so on
- site environmental inspection sheets.

A8.4 Part 2 – Monitoring of gas mitigation systems

A8.4.1 Summary table

Copies of the summary tables and charts should be included, as appropriate.

A8.4.2 Introduction

This section should detail the mitigation systems that have been installed, why they were installed and why it is necessary that they are maintained.

A8.4.3 Monitoring locations and requirements – airflow and pressure

This section should detail the routine (manual and/or automated) airflow and pressure monitoring that will be conducted and the approved methodology. It should also provide the associated commissioning data, together with a discussion detailing how to assess the monitoring results and the actions that should be taken if a monitoring result is not within a specified range.

A8.4.4 Gas monitoring requirements

This section should detail the routine (manual and/or automated) gas monitoring that will be conducted and how. It should also provide the associated assessment criteria, together with a discussion detailing how to assess the monitoring results and the actions that should be taken if a monitoring result exceeds a specified concentration.

A8.4.5 Condensate collection trap inspection

This section should discuss how to inspect for the presence of condensate within the gas mitigation system and the actions that should be taken if a significant volume of condensate is present.

A8.4.6 Reporting and documentation requirements

This section should discuss the reporting and documentation requirements. In particular, it should discuss the actions that should be taken if a significant issue is identified during a monitoring event, and when they should be taken – for example:

- on detecting methane within the building at a concentration greater than 1.25% v/v, the contractor should immediately inform the responsible manager, who should immediately initiate the building evacuation plan
- having determined that an extraction fan is under-performing, before leaving the site the contractor should inform the responsible manager, who should promptly arrange for the maintenance contractor to inspect the fan.

A8.4.7 Subcontractor requirements

This section should detail the level of experience that is expected of persons conducting monitoring at the site.

A8.4.8 Additional monitoring requirements

This section should discuss other monitoring requirements, such as visually inspecting any air inlets and outlets for blockages, and visually assessing the integrity of any gas membranes.

A8.4.9 Health and safety

This section should discuss any potential health and safety issues (for example, when entering a confined space) and the wearing of appropriate PPE.

A8.4.10 Periodic reviews

This section should discuss any required periodic reviews of the gas mitigation systems – for example:

- independent reviews of the operation of the management plan and reporting to an appropriate authority
- a review to confirm whether a passive ventilation system is still appropriate after a specified period of monitoring, or whether it should be upgraded to an active system
- a review to check whether an active ventilation system can be downgraded to a passive one after a period of, say, 10 years
- a review of whether any of the design parameters have significantly changed since last reviewing a natural ventilation system (such as the construction of a new building, which could impact the required natural ventilation).
- where ventilation is primarily used for other purposes but still forms a part of a gas mitigation system (for example, forced ventilation within an underground car park or air-conditioning within a building), a review of whether ventilation is still operating as intended at the time the gas mitigation system was designed.

Any such reviews should be conducted by an appropriately qualified and experienced professional. If a review recommends significant changes to the gas mitigation system, and the original plan was subject to a site audit or consent condition, the changes should be endorsed by a site auditor.

On completion of the works, the management plan should be updated accordingly.

A8.4.11 Appendices

Typically, appendices include:

- as-built drawings illustrating the mitigation systems that have been installed
- photographs of the monitoring points, including any air inlets and outlets, condensate drainage points, and so on
- drawings illustrating the locations of any automated monitoring systems and associated consoles
- environmental site inspection sheets
- an example of a monitoring report.

A8.5 Part 3 – general requirements, maintenance and intrusive works

A8.5.1 Summary table

Copies of the summary tables and charts should be included, as appropriate.

A8.5.2 Introduction

This section should provide an overview of the systems that have been installed, why they have been installed and why it is necessary that they are maintained.

A8.5.3 Management and enforcement of the management plan

This section should discuss issues such as:

- the measure requiring the management plan (site audit statement, condition of consent etc)
- who is responsible for implementing the management plan
- documentation and logbooks that are to be maintained
- endorsement of any revised management plans by a suitably qualified and experienced professional or, when appropriate, a site auditor
- how the management plan is to be enforced.

A8.5.4 Ongoing maintenance of the gas mitigation systems

This section should outline, within a table, the required maintenance schedules and documentation (for example, an annual calibration certificate); sub-sections should then provide specific details.

It should be noted that passive gas mitigation systems also require periodic inspections and maintenance. For example, if a concrete floor that forms a part of the mitigation system has a movement joint, the joint may require resealing every 10 years.

A8.5.5 Undertaking intrusive works that will potentially disturb the gas mitigation systems

This section should highlight that sub-surface works should be avoided as far as practical. However, in the event that sub-surface works have to be undertaken, it should outline the procedures that should be followed and detail how the mitigation systems should be reinstated.

A8.5.6 Health and safety

This section should discuss any potential health and safety issues (for example, when entering a confined space) and the wearing of appropriate PPE.

A8.5.7 General comments

This section should discuss other issues, such as instructing gardeners not to excavate below a specified depth and not to plant trees.

A8.5.8 Periodic reviews

This section should discuss any required periodic reviews of the gas mitigation systems and their monitoring and maintenance requirements.

A8.5.9 Appendices

Typically, appendices include:

- as-built drawings illustrating the mitigation systems that have been installed
- photographs of the monitoring points, including any air inlets and outlets, condensate drainage points, and so on
- drawings illustrating the locations of any automated monitoring systems and associated consoles
- site environmental inspection sheets and a management plan induction sheet
- instrument information and service requirements.

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