Guidelines for the Assessment and Management of Sites Impacted by Hazardous Ground Gases

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1 Introduction

1.1 The ground gas issue in contaminated land management

Ground gases are frequently encountered during the assessment and remediation processes that occur prior to redevelopment of potentially contaminated sites, and 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.

The consequences of failure to recognise and appropriately manage risks due to ground gases during the assessment and remediation of potentially contaminated land, or during the development of land adjacent to sites impacted by ground gases, may be significant. These consequences may range from construction delays and additional costs, through large legal liabilities to neighbouring landholders, to adverse long-term health impacts or structural damage, injury and death due to gas explosions. These are not hypothetical consequences – all have occurred either in Australia or overseas.

1.2 The reasons for these guidelines

Although there have been a number of incidents involving ground gases in NSW, other Australian states and internationally, both public and professional awareness and understanding of the problem is limited.

At the time of preparation of these guidelines, there is no comprehensive guidance for the assessment and management of ground gases in a contaminated land context in NSW. There is also currently very little formal guidance in other Australian jurisdictions.

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, meteorologic 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 Definitions

The term 'hazardous ground gas' is applied to both gases and vapours[1] that may be present within the pore space of soils and rocks and may impact adversely upon human health and safety or the integrity of structures, and may consequently affect activities such as the construction and management of buildings. Such gases or vapours may be of natural or anthropogenic origin.

These guidelines are part of a series of guidelines made by the NSW EPA dealing with various aspects of the management of contaminated land. Accordingly, their focus is on ground gases in the context of the redevelopment of potentially contaminated land or development adjacent to such land.

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

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

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

A distinction is made between radon, VOCs and mercury vapour, which are generally encountered at trace (part-per-billion to part-per-million) concentrations, and are carcinogens or chronic toxicants at those concentrations, and the other six ground gases in the list, which may be encountered at percentage concentrations at which they are potentially explosive, asphyxiating or acute toxicants. The latter are sometimes called *bulk ground gases*.

Physical, chemical and toxicological properties of common ground gases are listed in Appendix 2 and a summary is provided below.

1.3.1 Bulk ground gases

Methane (CH_4) is a flammable gas that is explosive in the concentration range 5–15% v/v in air (somewhat different ranges may apply in atmospheres with enhanced or reduced oxygen concentrations). It is also potentially an asphyxiant if its presence results in a low oxygen concentration. It is less dense than air.

Carbon dioxide (CO_2) is an asphyxiant and toxic gas that is significantly denser than air.

Carbon monoxide (CO) is an acutely toxic gas that is also flammable and potentially explosive. It has neutral buoyancy in air.

Petroleum vapours at percentage concentrations are flammable, potentially explosive and acutely toxic; lower explosive limits (LEL) 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 under the heading **VOCs**.

Hydrogen is a flammable, potentially explosive gas that is much less dense than air.

Hydrogen sulphide (H_2S) is a flammable and acutely toxic gas that is denser than air. It is highly odorous, and a nuisance, at low concentrations.

1.3.2 Trace ground gases

Radon 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, so that the mass present may be constantly replenished. During the decay of radon 222 to lead, alpha and beta radiation is released by radon 222 and its short-lived daughter products. 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 result in the development of 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 contaminants. 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.

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

Mercury is unique among metallic elements in that it is a liquid at 25°C. It also has a significant vapour pressure; the vapour is colourless, odourless and very toxic. Mercury was previously used in a number of industrial processes, although its use is now being phased out. The unusual physical properties of mercury allow spillages to penetrate deeply into the subsurface; although the number of impacted sites is relatively small, at those sites mercury vapour in soil may be a significant and persistent hazard.

1.4 Scope of these guidelines

Section 2 of these guidelines provides information on the origin, migration and behaviour of hazardous ground gases.

Section 3 sets out recommended approaches, and recommended procedures, for assessment and characterisation of sites that may be impacted by ground gases.

Section 4 focuses on the assessment of risks due to ground gases, while Section 5, which is closely linked to Section 4, outlines options for management and mitigation of those risks.

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

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

The guidelines as a whole have some emphasis on bulk ground gases (ground gases that occur at percentage concentrations), particularly methane. This is because these gases are not dealt with in other guidelines currently made or approved in NSW, and because these gases present the greatest and most widespread risk, i.e. they are commonly encountered at potentially hazardous concentrations in a wide range of cultural and geological settings. However, the guidelines do also address trace ground gases.

These guidelines are not intended to address issues associated with active or recently-closed landfills that are currently managed through the landfill licensing process, i.e. under an Environment Protection Licence (EPL) issued pursuant to the *Protection of the Environment Operations Act 1997* (POEO Act).

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 *British Standard BS 8485:2007* and various Construction Industry Research and Information Association (CIRIA) publications to suit local conditions.

1.5 Legal framework, policy and relationship to other guidelines

These guidelines form part of a set of guideline documents made by the NSW 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 who must deal with land that is impacted, or potentially impacted, by hazardous ground gases. A list of the other guidelines in this series is provided in the reference section of these guidelines.

These guidelines complement the other guidelines made by the NSW EPA, and also a number of national guideline documents that have been approved by the NSW EPA. Those guideline documents are also listed in the bibliography and, where appropriate, specifically referenced in the text.

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 emphasis.

Operational and recently-closed landfill sites are administered by the NSW EPA under the POEO Act. Other guideline documents, e.g. *Environmental Guidelines: Solid Waste Landfills* (NSW EPA 1996 and subsequent editions), apply to currently-licensed landfill sites.

The NSW Department of Planning has published a series of guidelines that address risk assessment for planning and development of hazardous industries. Whilst there is a clear distinction between planning issues related to new developments and the management of legacy sites, there are overlaps in the areas 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 gas

As indicated in Section 1 of these guidelines, ground gases are diverse. Their sources are similarly diverse. Whilst some sources have predominated in the problems due to ground gas experienced in Australia and elsewhere, it is important to recognise the wide range of potential sources that exist, both anthropogenic and natural. Consultants and other users of these guidelines need to be aware of these sources, so that problems can be anticipated.

Table 1 lists sources and origins of ground gas that are relevant in NSW; these sources are discussed in the following sub-sections.

Table 1: Sources and origins of hazardous ground gases

Source	Origin	Typical range of concentration (v/v)		
		Methane	**Carbon dioxide**	**Others**
Anthropogenic sources				
Putrescible waste landfill	Anaerobic microbial decay of putrescible waste	20–65%	15–57%	Several hundred non-methane organic gases, some toxic, typically <1% of total volume
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%	
General uncontrolled fill	Anaerobic microbial decay of timber, organic soils, etc.	0–20%	0–10%	
Reclaimed wetlands, mangrove flats	Anaerobic microbial decay of organic material	10–90%	0–5%	Hydrogen sulphide
Agricultural wastes		60–75%	18–40%	Trace organic gases generally <1%, some odorous, hydrogen sulphide
Sewers		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 (VOC) generally <1%, some odorous. Mercury.
Petroleum fuel sites	Tank and pipe leaks and spills	0–20%	0–10%	Hydrocarbon vapours, BTEX
Dry cleaning, electronics sites	Solvent spills and leaks	0–20%	0–10%	Chlorinated hydrocarbons

Table 1 continues overleaf…

Table 1 continued

Source	Origin	Typical range of concentration (v/v)		
		Methane	Carbon dioxide	Others
***Anthropogenic sources*, continued**				
Foundry sands	Anaerobic microbial decay of waste materials such as binders and fillers	Up to 50%	15–40%	Trace organic gases generally <1%, some odorous
Natural gas pipes	Pipe leaks	90–95%	0–9.5% from methane oxidation	CO 0–5%
Abandoned coal-mine workings	Coal-seam methane	<1–90%	0–6%	CO 0–10%
Stress relief following longwall goafing in active mines		<1–90%	0–6%	CO 0–10%
Coal-seam gas exploration and production		90–95%	0–6%	CO 0–10%
Abandoned wells and oilfield infrastructure	Leaking casing and annular cement seals	90–95%	2–8%	
Natural sources				
Soil	Physical, chemical and biological weathering	<2 ppm	350 ppm	
Swamps and wetlands	Anaerobic microbial decay of organic material	10–90%	0–5%	
Coal measures strata	Coal-seam methane	<1–90%	0–6%	
Carbonate strata	Dissolution of carbonates by acidic groundwater		1–9%	
Natural gas traps	Leakage	90–95%	2–8%	
Granites	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 factors including the composition of waste, the age of the landfill, moisture content and temperature. Typically, the gas contains up to 65% v/v methane and 25–35% v/v carbon dioxide.

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

These include:

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

Whilst 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 PVC in the waste (Smith & Dragun 1984).

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

An active or recently-closed landfill can produce gas 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, flaring or venting by some other means. Compartmentalisation and variable saturation may make effective and uniform control of gas pressures difficult. Landfill gas is a powerful greenhouse gas, as well as being odorous and flammable, so uncontrolled venting to the atmosphere is 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 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 (e.g. dry fill, fully saturated fill, putrescible pockets in hard fill), degradation may be slow and methane generation time greatly extended, albeit at lower rates.

The Australian Greenhouse Office (2008) estimated that 23% of degradable waste remains after 30 years and 11% after 50 years. Thus, 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. Predicted lives of some UK landfills are greater than 1000 years.

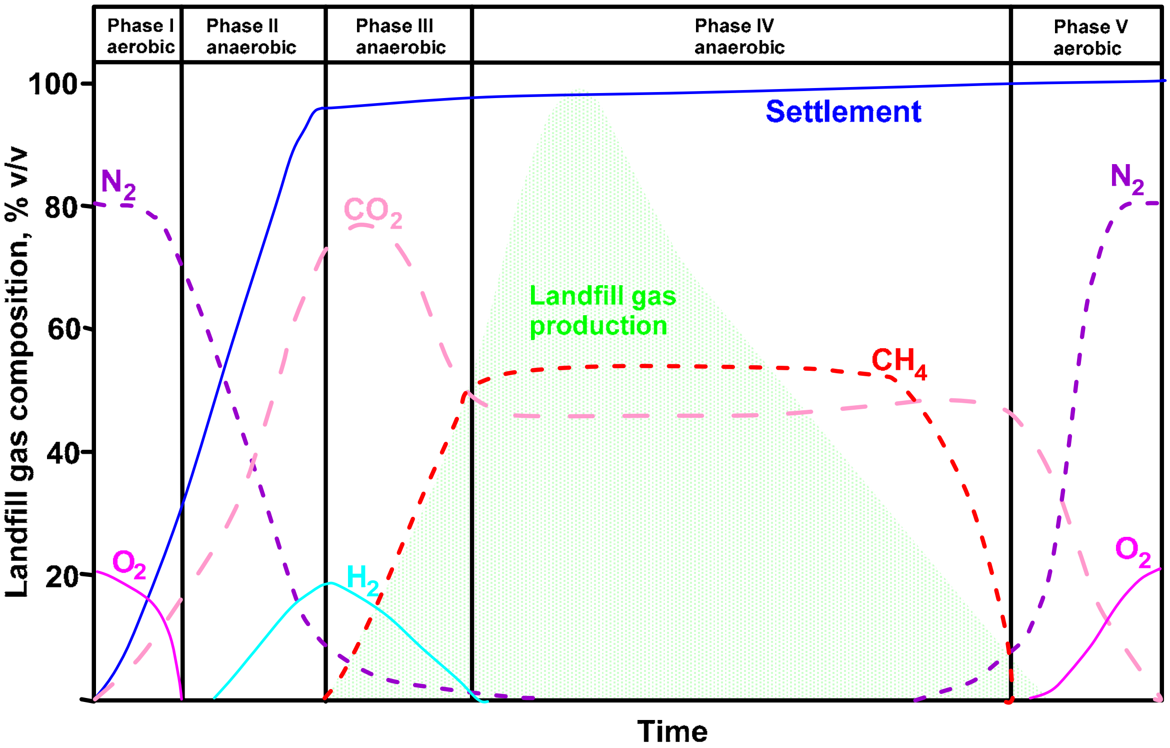

Figure 1: Theoretical stages in landfill maturation

Source: Pohland et al. (1986)

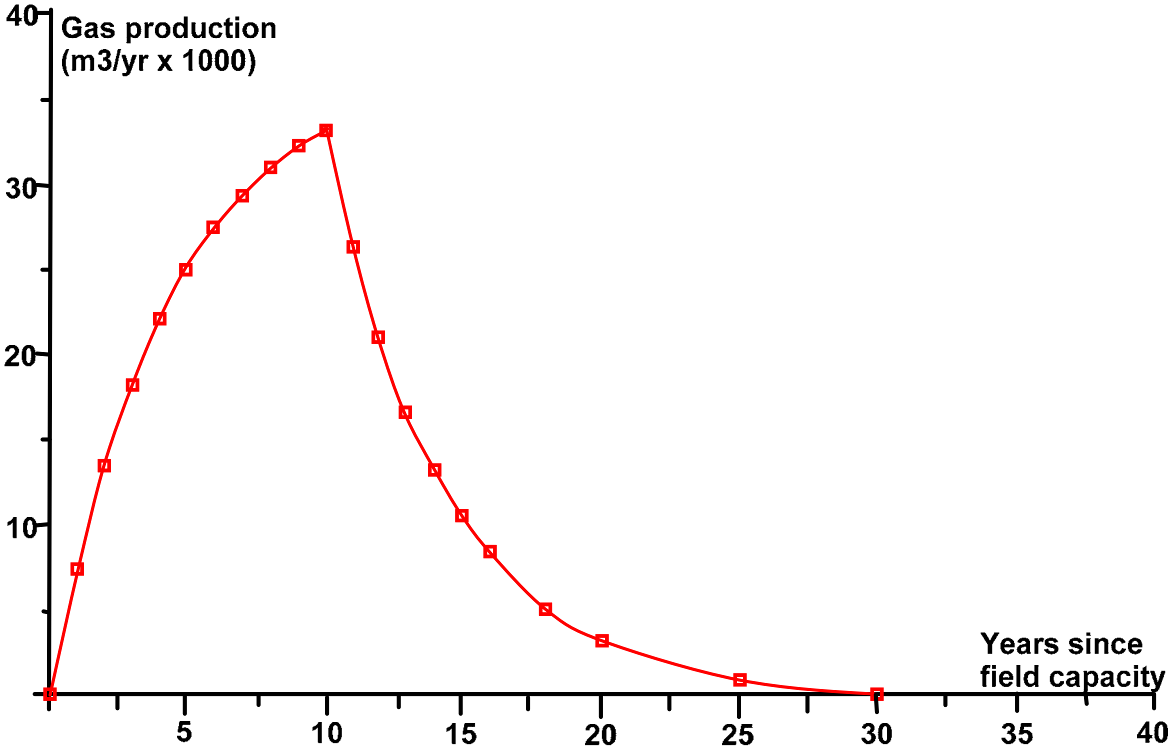

Figure 2: Variation in gas production rate with time

Source: CM Jewell

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.

Thus, inert waste landfills also produce landfill gas, but at lower rates than putrescible waste landfills. However, because conditions for gas generation are not ideal, generation may persist for extended periods. Where waste was deposited below the water table, as in former brick pits, degradation may be very slow, again extending the gas generation life.

2.1.3 General uncontrolled fill

Typically, uncontrolled fill also contains a certain amount of timber, green vegetation and sometimes organic soils, and may generate both methane and carbon dioxide, though generally at low rates.

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 sulphides, and may release hydrogen sulphide.

2.1.5 Organic waste disposal

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

2.1.6 Coal workings

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

Many areas around Newcastle are underlain by abandoned, shallow, bord and pillar workings. Shafts, adits and zones of fractured rock may allow methane migration 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 long wall mines, and has been reported in connection with coal-seam methane 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.

2.1.9 Sources of hydrogen sulphide

Hydrogen sulphide is likely to be formed whenever sulphur 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 sulphide.

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 subsurface. Most known occurrences involve releases of volatile petroleum fuels at service stations and fuel depots, or chlorinated solvents, which are used in a number of industries, most notably dry cleaning. Odorous organosulphur compounds and hydrocarbon vapours may be associated with former gas works 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 in 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, in NSW this does not appear to be the case. Survey work by ARPANSA (1990, 2011) did not identify average indoor air concentrations of radon above the action level of 200 Becquerels per cubic metre (Bq m^{-3}), in any area in NSW, and nationally, less 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. These areas are underlain by rocks of the Lachlan Fold Belt, including numerous granitic plutons.

In the context of the redevelopment of 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

Migration of ground gases from a source to a potential receptor may occur 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 groundwater or a low permeability stratum)
- the water saturation of the soil (because water reduces the pore-space available for gas migration), and
- the pressure gradient.

Barometric pumping can be particularly important in the migration of ground gas into buildings. When there is a rapid drop in barometric pressure, and particularly for large drops, of the order of 20 hPa, there may be a delay of several hours before pressure in the ground responds to the changed condition. This results in a significantly enhanced pressure gradient between the ground and the surface, and between the ground and indoor air spaces.

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 thus 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
- the thickness of the available flow path
- the water saturation of the soil, and
- 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 and 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 increasing pressure, and decreases with increasing temperature, as shown in Figures 3 and 4, overleaf.

For example, methane has a solubility of about 22 mg/L at 25°C and a partial pressure of one atmosphere (101 kPa), and 15 mg/L when the partial pressure is 0.65 atmosphere, as may be the case in a landfill. It is possible for this mechanism to generate high concentrations in soil gas above the water table (partitioning is reversible, so equilibrium soil gas concentration is the same as partial pressure in the source), but mass transport rates are likely to be low.

This mechanism may become more significant when considering geological sources at great depth and high pressure, because gases are much more soluble under these conditions.

Migration dissolved in groundwater may be a significant factor in the lateral migration of VOCs.

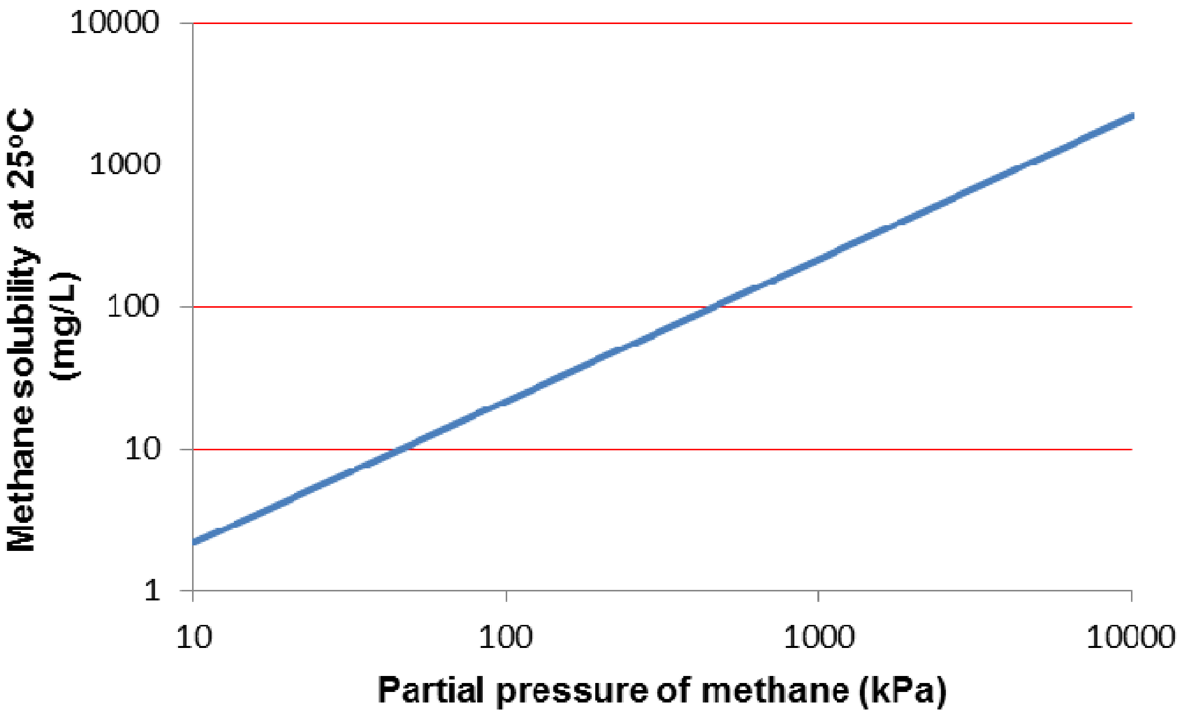

Figure 3: Variation in methane solubility in water with pressure

Source: CM Jewell, based on data from Yamamoto (1976)

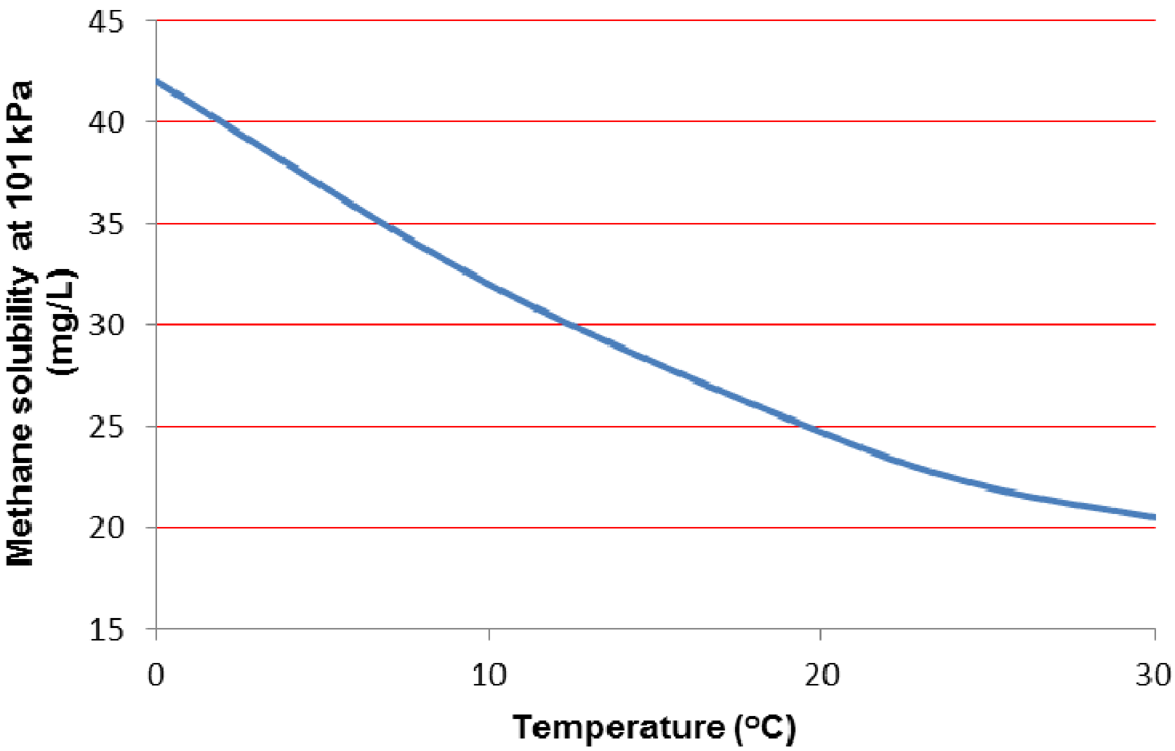

Figure 4: Variation in methane solubility in water with temperature

Source: CM Jewell, based on data from Yamamoto (1976)

2.2.5 Other meteorological factors

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

Rainfall

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

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 may also be harnessed to vent ground gases from buildings.

Temperature

Diurnal temperature variations affect the relative buoyancy of ground gases.

2.2.6 On-site generation and attenuation

Methane and carbon dioxide may also be generated by the decay of organic matter in groundwater contaminated by, for example, landfill leachate or sewage, which 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.

2.2.7 Intrusion into buildings and other structures

Ground gases become most hazardous when they intrude into buildings and structures, such as utility access pits/inspection chambers, where they can accumulate at explosive or toxic concentrations, or form an asphyxiating atmosphere. Clearly, confined spaces, small rooms and service cupboards are of particular concern. A ‘parcel’ of gas that has 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 resegregate.

Ground gas intrusion pathways into buildings are highly dependent upon 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.

Whilst diffusion is often the primary mechanism for ground gas intrusion to buildings, pressure-driven flow may occur due to stack effects, wind-driven pressure gradients and the operation of lifts in shafts.

2.2.8 Comparative ground gas hazards

There are significant differences in the nature of the hazard posed by toxic trace ground gases such as VOCs, and that posed by bulk ground gases such as methane and carbon dioxide. These differences are summarised in Table 2. They determine the priorities for site assessment and characterisation discussed in Section 3.

Table 2: Comparison of VOC hazards with methane and CO_2 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
Risk assessment focused on long-term average concentrations	Risk assessment focused on short-term maximum concentrations and flow rate. Flow rate and concentration are equally important

3 Site assessment and characterisation

Any consideration of risks due to ground gases, however preliminary, needs to be based on an understanding of site conditions. The depth of understanding required will depend upon 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 process should be applied from the outset to identify objectives, plan site investigations, and ensure that data of adequate quality to satisfy the assessment objectives is obtained. A weight of evidence approach is recommended, involving the early development of a conceptual site model, and progressive refinement of that model through compilation of the results of a range of investigations.

3.1 Desk study

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

Historical aerial photography and site photography, site plans, architectural and construction plans, utility service drawings, Google Earth or Spatial Information Exchange imagery, local council records, mine working plans, geological and topographical mapping and the results of previous site investigations are the usual sources for this information.

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

It is important to consider the overall geological setting of the site, including the deep geology; this would normally involve reviewing geological mapping and any data that may be available from previous environmental or geotechnical investigations on the site or adjacent properties.

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 provides easy access to most of the data likely to be required; other data can be obtained on request.

An initial conceptual site model, including a plan, cross-section and written notes concerning potential sources, pathways and receptors should be prepared on the basis of 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 concerning the site has been collated. In addition to allowing observation of current site conditions and management practices, it provides an opportunity to view the surroundings of the site, 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, an indication of gas emission, may be evident.

3.3 Initial conceptual site model

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

The following information must be included in the model. Where necessary, initial estimates can be made and refined later by the addition of site-specific data.

- 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 height of the groundwater capillary fringe
- physical characteristics of the soils (moisture content, bulk density, grain size, total porosity and fraction of organic carbon)
- for potential sources of hazardous ground gas:
  - the type of ground gas anticipated
  - distance to the source
  - depth to the source
  - source age
  - physical and chemical properties of each of the ground gases
- for current or proposed buildings on the site and their use:
  - size and type of construction (slab-on-grade, crawl space, basement)
  - condition of buildings and pavements
  - presence of ventilation or heating/cooling systems and other relevant information which may affect air exchange rate
  - rate of exchange between indoor and outdoor air (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, sewer and stormwater lines)
  - characteristics of any confined space
- 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).

The initial conceptual site model is a critical step in understanding site conditions and potential pathways and linkages. 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 Data Quality Objectives should be established, on the basis of the understanding of the site derived from the conceptual site model, with the broad objective of providing the data required to establish the level of risk that ground gas poses to the existing or proposed future use of the site. Depending upon the robustness of the original conceptual site model, a Level 1 (qualitative) risk assessment may have already been completed, so that the data are required to support a Level 2 risk assessment.

The ground gas investigation may be a stand-alone project, or may be carried out as part of a broader Phase 2 environmental site assessment or geotechnical investigation.

Further, 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:

- confirmation, by intrusive sampling and testing, of geological and hydrogeological conditions, with emphasis on those aspects likely to influence gas generation and migration
- establishment of the lateral and vertical extent of the ground gas source, and the current extent of ground gas migration
- measurement of gas composition and concentration in the source
- assessment of the presence and, if present, concentration of gas in indoor air space and confined spaces such as sumps, drains, culverts and service trenches
- assessment of the continuity (or otherwise) and permeability of potential migration pathways
- provision of any other data necessary to resolve gaps in the conceptual site model
- construction of an adequate number of permanent gas monitoring points to provide coverage of the site and potential pathways
- construction and sampling of groundwater monitoring wells if required
- provision of 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
- assessment of the influence of a full range of weather conditions on gas concentrations and flow rate.

3.4.2 Investigation methodology

Whilst 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, used both for geological investigation and to allow construction of gas and groundwater monitoring wells. For most purposes the term ‘borehole’ may be taken to include relatively shallow drilling through concrete slabs to facilitate the installation of sub-slab gas monitoring points. The location of boreholes will be influenced by access constraints, and is a matter for professional judgement, based on interpretation of the conceptual site model. However, the following points should be considered:

- Where access to the source is possible, boreholes should be drilled in central locations appropriate to assess worst-case conditions, and peripheral locations to confirm the extent of the source.
- Boreholes should be drilled on site boundaries, or offset if necessary, to assess potential migration pathways, and at least some of these should extend to the full known depth of the source (obviously excluding mines and deep geological sources). Where site development / redevelopment is proposed, the depth of investigation should also take into account the actual or proposed construction methods, such as piling.
- Shallow boreholes should be drilled close to occupied buildings to which direct access is not possible in order to assess potential exposure-point concentrations, recognising that concentrations beneath large slabs may be higher than those beneath open areas.
- When access is practicable, for example on an industrial site, boreholes may be drilled within buildings.

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

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

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, because this material is suitable for most installations, readily available from several suppliers in NSW, and widely used for constructing groundwater monitoring wells. Screen sections have 0.4-millimetre factory-cut slots as standard, although other dimensions are available. Although smaller diameter pipe may be necessary or advantageous for gas monitoring in some circumstances, and stainless steel implants on 6-millimetre PE or Teflon tubing are often used for sub-slab gas monitoring, for most outdoor installations there is no reason not to standardise on 50-millimetre diameter pipe.

Screens should be placed with careful forethought, across the permeable horizons of interest, and be appropriately gravel-packed. Where vertical stratification and multiple pathways are likely, multiple wells screened at different depths or multi-port wells should be installed. For both gas and groundwater monitoring wells it is extremely important to ensure that sound bentonite-pellet or grout seals are placed in the annulus between the standpipe and the borehole wall, and that if pellets are used they are 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 recent review of the performance of different types of seal, which provides support for 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 measurement instrument.

Generally, the primary function of a well will be either gas or groundwater monitoring and the well will be designed accordingly. Dual-purpose wells are possible, provided that neither function is compromised. In particular, screen placement should be appropriate to permit both water and gas entry to the well, over the full range of water levels.

3.4.4 Surface emission measurements

Gas emissions may be measured at the ground surface, using a walkover approach and a range of portable measuring equipment. This method is frequently used to assess the integrity of capping on both active and disused landfills. The measurements may be affected by meteorological conditions, soil moisture or oxidation within the soil profile. They are not generally useful for ground gas investigations, but may be appropriate in particular circumstances, for example investigations of vegetation dieback, or of VOC emissions on former landfill sites that have been redeveloped for recreational use.

Surface emissions may also be measured using a flux chamber. Static or dynamic chambers may be used, each has advantages and disadvantages. Flux chamber measurements are most useful when applied in conjunction with borehole methods to assess trace 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 and barometric pressure fluctuations. More detailed information is provided in Davis et al. (2009b) and in Appendix 4.

3.4.5 Gas sampling and measurement techniques

Depending on the gas being sampled, measurements may be taken using field instrumentation, or samples may be obtained using sorbent tubes or summa canisters and submitted for laboratory analysis, with application of standard QA/QC protocols and assessment of data quality indicators.

Field instrumentation is usually used to measure bulk ground gas concentrations, pressure, and borehole flow rates. Initial, maximum and steady concentrations, pressure and flow rate are recorded, or equipment recording at specified intervals to a data logger may be used.

More detailed guidance on gas monitoring, field measurement equipment and sampling is provided in Appendix 4.

Dissolved-phase VOC concentrations in groundwater may be used as an input to risk assessment for trace ground gases, as described in Section 4.4.4.

3.4.6 Duration of gas monitoring

The minimum requirements to assess a gas screening value and characteristic gas situation (as described in Section 4.3.4) are measured flow rates and hazardous gas concentrations from an appropriate number of monitoring locations over an appropriate number of monitoring rounds, which should include measurements taken during falling atmospheric pressure (BS 8485:2007). Selection of the appropriate numbers is a site-specific decision, depending on the sensitivity of the site use, the ground gases of concern and the generation potential of the gas source. It is not intended that these guidelines be prescriptive in this respect; professional judgement based on a sound conceptual site model is required. 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 C665 recommends 6–12 monitoring events extending over 3–12 months (CIRIA 2007). However, 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.

Continuous-monitoring equipment for measurement of gas concentration is available (Appendix 4); use of this type of equipment may enable the number of monitoring events and the overall length of the monitoring period to be reduced, compared with an entirely event-based monitoring program.

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 data set for the nearest Bureau of Meteorology site with continuous pressure recording.

For trace ground gases, average concentrations are more important than short-term peak concentrations, and a shorter period of monitoring may suffice provided a reasonable range of meteorological conditions is captured.

3.5 Refined conceptual site model

Following site investigation, the conceptual site model should be refined to incorporate the results of the investigation. It is possible, indeed likely, that some initial assumptions may need to be changed on the basis of the data acquired. As with the initial conceptual site model, 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 for impact by hazardous ground gases should be based on progressive refinement of the conceptual site model, consideration and evaluation of all the available lines of evidence, and application of the multi-level risk assessment approach outlined in Section 4. This approach is preferable to simple comparison with assessment criteria.

However, because 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, and because there are established indoor air criteria for radon, these criteria are listed in the following sections.

3.6.2 Assessment criteria – sites subject to an EPL

The NSW EPA (1996) *Environmental Guidelines: Solid Waste Landfills* apply to landfill sites regulated under the POEO Act. The *Environmental Guidelines: Solid Waste Landfills* are concerned with best practice design, construction, operation and closure of an active landfill site, and gas management is regulated within that context.

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

The following criteria are provided within the *Environmental Guidelines: Solid Waste Landfills*:

Subsurface monitoring criterion (benchmark technique 16)

- *Notification to EPA within 24 hours and increase in monitoring frequency: >1.25% v/v* CH_4

Surface emission criterion (benchmark technique 17)

- *Threshold concentration for closer investigation and corrective action: 0.05% v/v* CH_4

Gas accumulation criterion (benchmark technique 18)

- *Daily testing until controlled: >1.25% v/v CH_4*

Remediation of uncontrolled gas emissions (benchmark technique 19)

- *Notification to EPA within 24 hours: >1.25% v/v CH_4 in surface, subsurface or building monitoring*

Criteria to show that the landfill is stable and non-polluting, post-closure (benchmark technique 29)

- *Gas concentrations in all perimeter gas wells: <1% v/v CH_4 and <1.5% v/v CO_2 for a period of 24 months*

Section148 of the POEO Act also imposes a general obligation to immediately report to the NSW EPA, and other relevant authorities, pollution incidents causing or threatening material harm to the environment. Further details are provided in Section 6.2 of these guidelines.

3.6.3 Other criteria

The action level for radon 222 in indoor air in residential buildings is 200 Bq m^{-3}. In workplaces the action level is 1000 Bq m^{-3}. ARPANSA (2002a and 2002b) indicates that intervention is required if radiation levels are consistently above these values.

Appendix 2 includes toxicity data for both bulk and trace ground gases. The currency of toxicological data should be checked before it is used.

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

4 Risk assessment framework

Risk assessment is a fundamental part of contaminated land assessment, engineering design, and the delivery of public utilities such as water and power. It is therefore rational that risk assessment (and subsequent management) must underlie any process for the assessment and management of sites impacted by hazardous ground gases.

The purpose of risk assessment is to aid professional judgement and to assist 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 quantitative manner.

A qualitative approach matrix is commonly used, for example, in the assessment of workplace risks.

A quantitative human health risk assessment process is commonly applied to the assessment of chronic toxicity risks due to chemical contaminants in contaminated 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 consequence and then focussing on the calculation of the probability of that consequence occurring, for example (in the case of non-threshold cancer risk) 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.

The components of the risk analysis and assessment process are illustrated in Figure 5.

It can be seen that Figure 5 incorporates a feed-back loop. The first pass through the risk analysis process is a *maximal* risk assessment. Subsequent passes assess the *residual* risk following implementation of mitigation or management measures.

Whilst 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- or fully-quantitative assessment.

Whether dealing with bulk or trace ground gases, use of a weight of evidence approach based on development and progressive refinement of a conceptual site model is likely to provide the most reliable outcome.

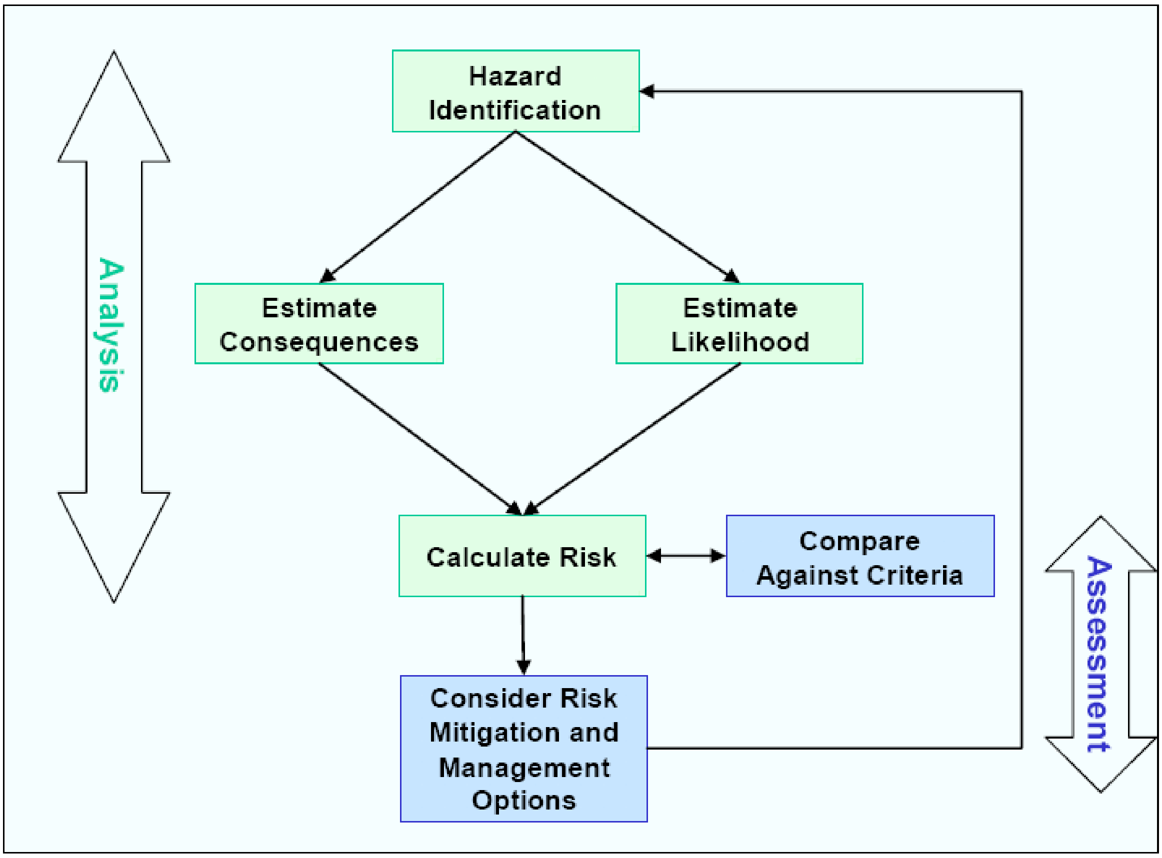

Figure 5: Risk analysis and assessment process

Source: NSW Department of Planning (2011)

4.2 Guidance documents

The following Australian and overseas-sourced guidance documents provide a framework for assessment of risks due to ground gases.

AS/NZS ISO 31000:2009 *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 from which to develop a site-specific risk assessment approach.

The NSW Department of Planning and Infrastructure developed guidelines for hazardous development that are relevant to risk assessment and risk management on sites impacted by bulk gases. In particular, the ***Assessment Guideline – Multi-level Risk Assessment*** (DOP 2011), ***Hazardous Industry Planning Advisory Paper No. 3 – Risk Assessment*** (DOP (HIPAP 3) 2011) and ***Hazardous Industry Planning Advisory Paper No 6 – Hazard Analysis*** (DOP (HIPAP 6) 2011) are particularly relevant.

It is worth noting that whilst those guidelines are intended to be applied during the planning process and specifically to assess off-site risks, the methodology outlined therein can also be appropriately applied to assessment of on-site risk due to ground gases. This is because of the long-standing NSW government policy that community risk assessment procedures should be used in contaminated land risk assessment unless exceptional circumstances apply.

The most comprehensive and relevant guidance for risk assessment in the specific context of ground gases can be found within the CIRIA document ***Assessing Risks Posed by Hazardous Ground Gases to Buildings*** (CIRIA C665 2007). This document sets out detailed, practical procedures for the assessment of risk due to bulk ground gases, and has been used extensively in the preparation of this guideline.

enHealth (2002, revised 2012) has published ***Environmental Health Risk Assessment – Guidelines for Assessing Human Health Risks from Environmental Hazards,*** which provides an Australian guidance framework for assessment of health risks due to chemical toxicants. This document includes default values for exposure assessments and guidance on the evaluation of sources of toxicological information, and is specifically relevant to the quantitative assessment of chronic health risks due to trace ground gases.

Schedule B4 of the ***National Environment Protection (Assessment of Site Contamination) Measure*** (Draft Variation, NEPM 2011) is complementary to the enHealth document and provides detailed guidance concerning both qualitative and quantitative assessment of human health risks due to chronic exposure to chemical toxicants.

4.3 Multi-level risk assessment – bulk ground gases

The *Assessment Guideline – Multi-Level Risk Assessment* (DOP 2011) 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* (DOP 2011) states that the results of the screening step are used to assess whether it is actually 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), with results of a review at the completion of each stage determining the need to proceed to the subsequent stage.

In this approach, risk classification and prioritisation is undertaken following a Level 1 assessment, to permit prioritisation of 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 to allow relative risk levels to be assigned, and mitigation measures to be specified for lower levels of risk. Level 3 remains as a fully quantitative risk analysis, but is triggered when Level 2 indicates higher levels of risk.

This approach is consistent with both the CIRIA (C665) guidance and the enHealth / NEPM guidance.

4.3.1 Preliminary screening

Preliminary screening should be carried out using a simple risk model developed from the initial conceptual site model 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, then 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, then there should be no risk, so that further risk assessment will be unnecessary, and no action to manage bulk ground gas risk will be 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, then the risk assessment should proceed to Level 1 (see Section 4.3.2).

In providing an answer to Question 3 and thus 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 conceptual site model) and the strength of the source. This process requires professional judgement, and the reasoning underlying the judgement must be documented. It would not be 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 hazard identification and assessment of probability. For bulk ground gases, it involves reviewing the conceptual site model and its underlying data, reformulating the risk model and then following the steps shown in Figure 5.

Data review and risk model refinement

It is necessary to carry out a further review of 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 source(s) be adequately defined for the purpose of the model?
- Does the risk model include all credible pathways / linkages?

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

Hazard identification

This step involves the systematic identification of hazardous events or scenarios (e.g. 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.

Generic procedures for hazard identification are set out in the NSW Department of Planning Guidelines (HIPAP 3); when dealing specifically with bulk ground gases, the range of hazards that may arise is more restricted, and some simplification of these procedures is appropriate.

Consequences estimation

This step relates to the assessment of the effects of the hazardous events identified in the previous step. Whilst models are available to assist the estimation of the effect of such incidents 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 10–100 fatalities.

In a qualitative risk assessment consequence may be divided into broad categories. Typically four categories are used, described as Minor, Mild, Medium and Severe, as illustrated and defined in Table 3. The 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 further discussed under *Risk communication* below. However, in the context of 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 on the basis of professional judgement and the particular requirements of involved parties, who may place greater emphasis on aspects such as business disruption or reputational damage. Thus, the definitions set out in Table 3 may be modified on a site-specific basis, provided that the modifications are clearly stated and justified.

Table 3: Classification of consequence

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 building 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, bruises requiring first-aid treatment Cosmetic damage to buildings or pavement Damage to landscaping Minor damage to vehicles

Likelihood estimation

This step involves the derivation of 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 4.

Table 4: 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 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. Thus 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, and therefore unlikely that the stated consequence will occur.

With reference to Table 4, 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 likelihood classification, consideration should be given to the strength of the source (Section 2.1) and the length and continuity of the linkage (Section 2.2), and 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 and conveniently carried out using a matrix, as shown in Table 5.

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, so that the process is transparent and amenable to review.

Table 5: 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 concerning the communication of risk:

> *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 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. Level 1 risk assessment also provides an opportunity to screen out those cases where although a potential source or potentially complete pathway are present, 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 no viable pathways, then there is no need to proceed to 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 as described in Section 3 of these guidelines, followed by a Level 2 risk assessment as described in Section 4.3.4 below. This alternative involves a more limited site assessment, followed by implementation of basic gas protection measures; however, the opportunity to establish that there is no need for any gas protection measures at all is foregone.

Card and Wilson (2011) suggested such an alternative approach to assessment of low-risk sites in the UK. The approach outlined in these guidelines uses some aspects of the Card and Wilson method, but has been modified to reflect Australian environmental conditions, and its application has been restricted to a narrower range of appropriate circumstances. This reflects the current lack of documented comparative applications in Australia.

This alternative will often appear attractive when dealing with sites with assessed low risks of ground gas impact, 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 alternative approach may be applied are currently limited to those where:

- a Level 1 risk assessment has identified a low level of risk
- the conceptual site model and risk model are sound and are 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 or off site) are limited to natural soils with measured low organic carbon content and low hydrogen sulphide risk (specifically excluding reclaimed coastal or estuarine swamps and mangrove flats), or to shallow (<3 metres average depth and a maximum depth at any location of 5 metres) general fill (excluding waste landfill) with minimal timber and other organic matter. The limiting total organic carbon concentration is 3%
- 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 or not 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 A5.2 in Appendix 5 may be used. Further information is provided at the end of Section 4.3.4.

4.3.4 Risk analysis and assessment – Level 2

As indicated previously, 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 this guideline. 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. This approach also follows the process shown in Figure 5.

Data review and risk model refinement

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

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

Determine gas screening value

The Wilson and Card method uses both gas concentrations and borehole flow rates to define a characteristic situation for a site based on the limiting borehole gas volume flow for methane and carbon dioxide. CIRIA C665 uses the term *gas screening value* (GSV) for the limiting borehole gas volume flow, whereas BS 8485:2007 uses the equivalent term *site characteristic hazardous gas flow rate*. GSV is used in this guideline. GSV has units of litres of gas per hour (L/hr).

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

For example, if monitoring data for a site indicated a maximum flow rate of 3.5 L/hr and a maximum methane concentration of 20%, the site would have a GSV of 0.7 L/hr (20/100 x 3.5).

The calculation is carried out for both methane and carbon dioxide, and the worst case value adopted.

Determine characteristic gas situation (CS)

The characteristic gas situation is determined from the gas screening value using Table 6.

Where characteristic gas situation 1 is determined, no further action is required.

Where characteristic gas situation 2 or 3 is determined, gas protection measures are required. Appropriate gas protection measures for the specific site should be selected as outlined in Section 5 of this guideline.

Where characteristic gas situation 4 is determined, 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 to be necessary, the reasons for this decision should be documented, and appropriate gas protection measures for the specific site should then be selected as outlined in Section 5 of this guideline.

Where characteristic gas situation 5 or 6 is determined, 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 assess the residual risk following implementation of those measures.

Table 6: Modified Wilson and Card classification

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

Notes:

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

Application of the alternative process for low-risk sites outlined in Section 4.3.3 will allow, where appropriate, characteristic gas situation 2 (only) to be assumed on the basis of an abbreviated assessment. This may occur in cases where further site investigation and a Level 2 risk assessment could have demonstrated characteristic gas situation 1. The justification for any consequent over-design of protection measures is the net cost saving achieved by avoiding the additional monitoring required to support a Level 2 risk assessment. Adoption of 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.

Quantitative risk analysis is only required to resolve bulk ground gas problems where the characteristic gas situation is 5 or 6, but 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 the assignment of probabilities to rare events, and 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, which improves understanding of the components of the hazard and permits more effective preventive measures to be developed, than from improved estimates of likelihood.

Quantitative risk analysis is a complex subject, and a full treatment is beyond the scope of this guideline. 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 some relevant examples of the use of quantitative risk assessment for ground gases.

4.4 Multi-level risk assessment – trace ground gases

The NSW DECCW *Vapour Intrusion: Technical Practice Note* (2010) provides outline guidance on risk assessment for trace ground gases and includes a set of references for more detailed guidance. It is intended that these guidelines complement the technical practice note by setting 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 risk analysis of trace ground gases. However, due to the limited data available both in Australia and internationally, there is no basis for Level 2 risk assessment for mercury and SVOCs.

4.4.1 Preliminary screening

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

As with bulk ground gases, the screening process should provide answers to the 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 trace ground gas?
3. 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 gas migration is driven primarily by diffusion, not advection, so the credible length of pathways is shorter.

4.4.2 Risk analysis and assessment – Level 1

As indicated previously, Level 1 requires an essentially qualitative approach involving review of the conceptual site model and its underlying data, reformulating the risk model, and then following the steps shown in Figure 5.

Data review and risk model refinement

As with bulk ground gases, answers are required to the following questions:

- Is the information reliable and representative?
- Can all potential sources of trace ground gas be identified?
- Can the extent of the source(s) be adequately defined for the purpose of the model?
- Does the risk model include all credible pathways / linkages?

Hazard identification and evaluation

In the context of trace ground gases, hazard identification involves the recognition of 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 (e.g. volatile petroleum hydrocarbons, chlorinated aliphatic hydrocarbons) or on the basis of specific compounds and concentration ranges (e.g. benzene, PCE, mercury).

Exposure estimation

At Level 1 this involves basic assessment of likely pathway continuity, based on available knowledge of site geology, and building construction and ventilation, leading to 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 some screening-out of potential source-receptor linkages may be possible at this stage. For example, in the case of volatile petroleum hydrocarbons, lateral source-receptor distances greater than about 30 metres may indicate that a diffusion linkage is unlikely, and further vapour assessment is not required (Davis et al. 2009a, USEPA 2002a and ASTM 2005, 2010a), as referenced in the technical practice note. Similarly, a deep water table (greater than seven metres below the receptor) may indicate that diffusive transport of petroleum hydrocarbon vapours from a groundwater source is very unlikely (Wright 2011).

Such screening judgements should not be made without an adequate understanding of site geology and infrastructure, because convective transport along high-permeability 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 this guideline.

Level 2 assessment involves the comparison of 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 application of 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.

In some situations it is possible to carry out sampling and subsequent laboratory analysis of indoor air, and thus 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 be representative of average (time and space) exposure point concentrations.

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

Data review and risk model refinement

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

- Are the data reliable and representative?
- Is there sufficient coverage of the site and source area(s), 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 source(s) 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 / linkages? In particular, is there a possibility that preferred pathways (service trenches or ducts, lift shafts, sumps, wet basements, etc.) are present?

If the answers to any of these questions are negative, the conceptual site model requires improvement.

Estimate indoor air concentration

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

- USEPA (2002a) utilised 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 85–95 percentile values for attenuation factors calculated for paired measurements in a relatively small dataset. They are conservative, but have been widely used over the past 10 years.
- Since 2002, USEPA has developed an expanded vapour intrusion database. The current version (USEPA 2012a – June 2012) has data for 913 buildings, and includes 2929 paired measurements. Eighty-five per cent (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) provides an analysis of attenuation factors for chlorinated hydrocarbons derived from data in the USEPA vapour intrusion database as of 2010. For 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 vinyl chloride (CE) is 0.003, and the 95th percentile is 0.01.
- The Oregon Department of Environmental Quality (ODEQ 2010) also analysed the data in the USEPA vapour intrusion database. That organisation concluded that the data justified an attenuation factor between sub-slab and indoor air of 0.005 for chlorinated hydrocarbons in residential buildings, and that analysis of the limited data for commercial buildings, plus consideration of likely higher ventilation rates in these buildings, justified adoption of 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 for 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 0.003 for residential settings and 0.00003 to 0.0004 for commercial settings.
- As indicated by Davis et al. (2009a), Health Canada (2010) and others, there is significant potential for petroleum hydrocarbons and CE 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 other paved areas.

Therefore it is recommended that:

- where sub-slab gas data are available, an attenuation factor to indoor air of 0.005 should be applied for both petroleum hydrocarbons and chlorinated hydrocarbons
- for petroleum hydrocarbons and CE, where the available data are for soil gas beneath a building at a depth greater than two metres, or soil gas concentrations are calculated from groundwater concentration data, and where it can be demonstrated by measurement that oxygen is present in the soil profile or slab dimensions are less than 15 metres x 15 metres, then an additional biodegradation attenuation factor of 0.1 may be applied.

These attenuation factors should be applied for both residential and commercial buildings unless site-specific information indicates that they are inappropriate, in which case a Level 3 analysis should be carried out.

Compare estimated indoor air concentrations with screening values

The estimated indoor air concentration should be compared with appropriate screening values. For the contaminants of most common concern (BTEX and chlorinated aliphatic hydrocarbons) the appropriate guidelines for Australia are the World Health Organisation's *Guidelines for Air Qua*lity (2000a) and *Air Quality Guidelines for Europe* (2000b), which provide values for benzene, toluene, PCE, TCE and CE. For other contaminants, screening values can be sourced from Section 6 of the technical practice note (NSW DECCW 2010) or by using the hierarchy for toxicological data provided in the NEPM (2011).

When the conceptual risk model is adequate and estimated indoor air concentrations are negligible in comparison to guideline values, no further assessment of risks 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 trace ground gases requires the use of mathematical models to give a numerical estimate of risk. To be worthwhile, such modelling requires good data. A sound conceptual site model / 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 is essential.

Measured concentrations of the contaminants of concern in sub-slab gas, soil gas beneath the building, or groundwater are required. It is not always possible to measure indoor air concentrations. When such data are available, they should be used to complement the results of vapour intrusion modelling.

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

As discussed in the technical practice note, the Johnson and Ettinger (1991) model, in numerous forms and within various public-domain and proprietary packages, is most widely used for modelling vapour intrusion to buildings.

The Johnson and Ettinger model is essentially a tool for carrying out part of an exposure assessment. However, many of the packages incorporate access to databases containing both the human exposure parameters necessary to complete the exposure assessment, and the toxicological data required for hazard assessment. Provided these databases are appropriately modified so they incorporate the values recommended for Australian use (as recommended in enHealth 2002 and Schedule B4 of the NEPM), they can be used to combine the hazard and exposure assessments, and generate a full quantitative human-health risk assessment.

Appendix 5 provides an outline of the human health risk assessment process. In the final step in 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, which represents the sum of the hazard quotients for all threshold chemicals of concern. A hazard index less than one is indicative of acceptable risk, and as the hazard index rises above one, 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 considered acceptable, while risks between 10^{-5} and 10^{-4} require further assessment, monitoring and / or management action. Risks greater than 10^{-4} are unacceptable.

Figure 6, overleaf, 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.

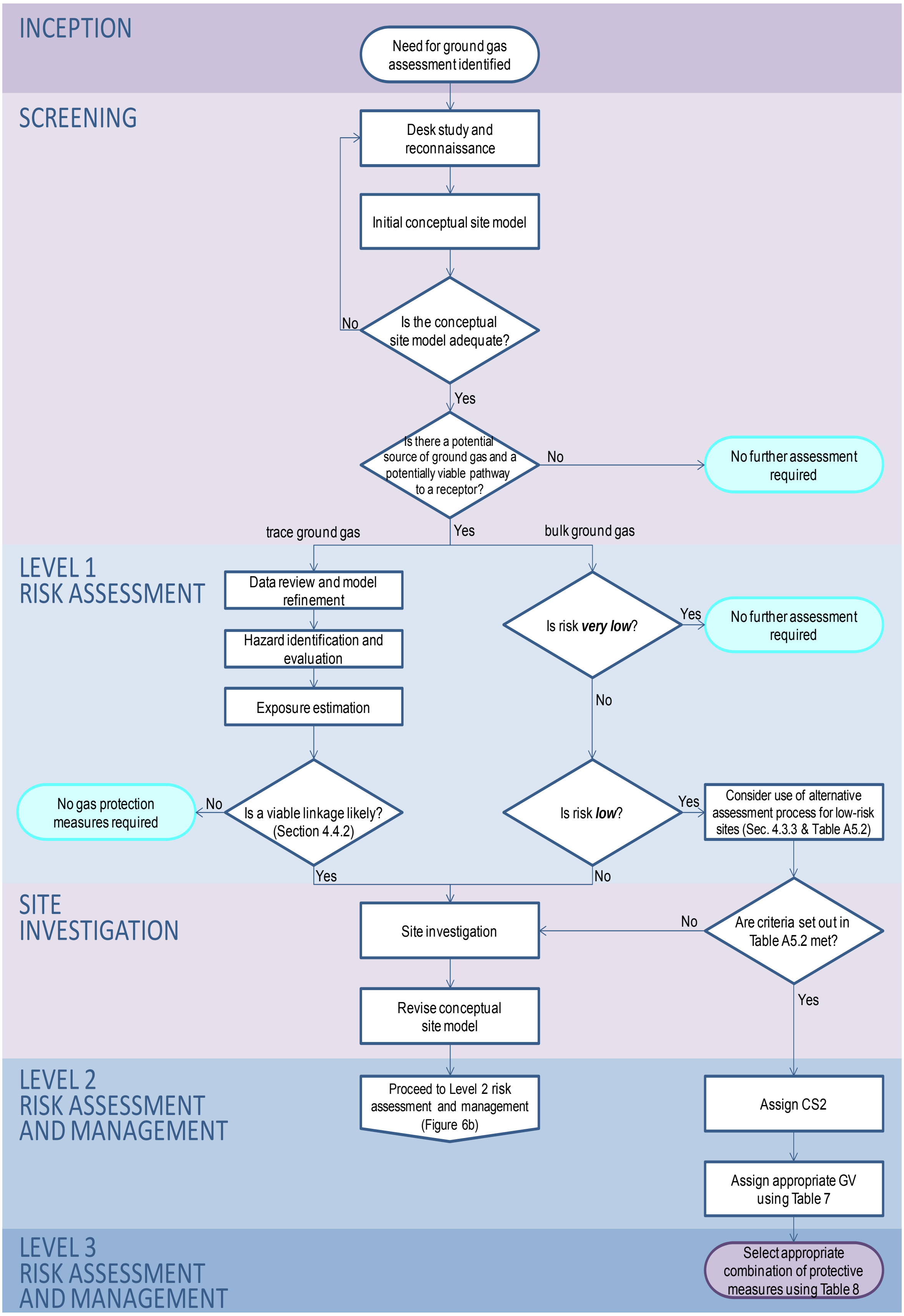

Figure 6a: Summary of risk assessment and management process – Part 1

Source: CM Jewell

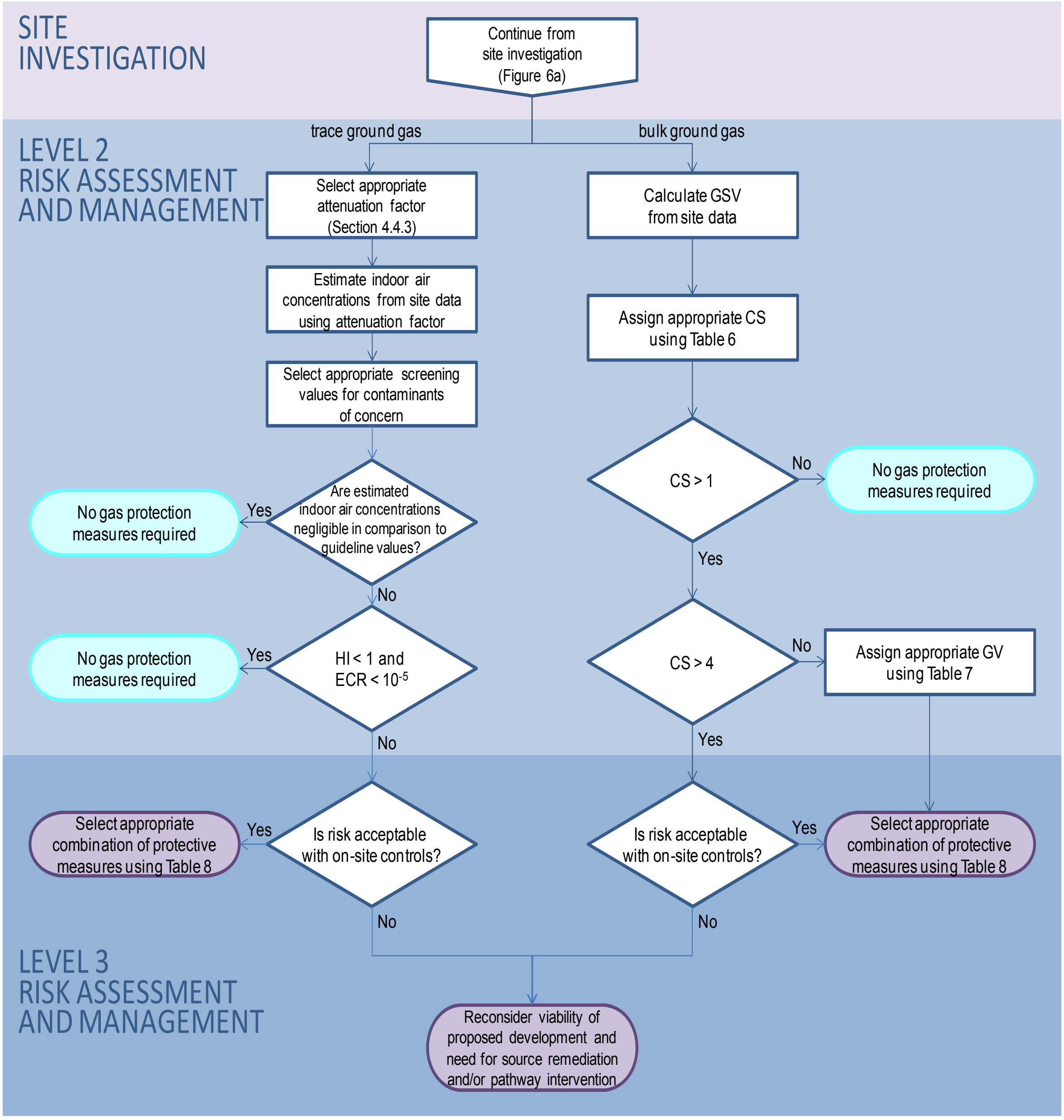

Figure 6b: Summary of risk assessment and management process – Part 2

Source: CM Jewell

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 Environment Protection Licence (EPL) issued under the POEO Act. Such regulation continues until stabilisation criteria have been met. Whilst a landfill site is regulated under an EPL, the terms of the EPL will always take precedence over these guidelines, but these guidelines may nevertheless contain information that is useful in developing site-specific management measures.

Although it is a NSW EPA objective that an EPL remains in force until stabilisation has been achieved, due to heterogeneous ground conditions, ground gas problems 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 2007 and any conditions of consent imposed under the *Environmental Planning and Assessment Act 1979* (EP&A Act). However, these documents commonly contain either no conditions or very general conditions in relation to ground gas migration. These guidelines should be adopted in the absence of specifically applicable conditions.

Active and closed coal mines are regulated under the *Mines Act 1992*, the Mining Regulation 2010, the *Coal Mine Health and Safety Act 2002* and the Coal Mine Health and Safety Regulation 2006, which are administered by the NSW Department of Trade and Investment, Regional Infrastructure and Services (Resources and Energy Division). The draft code of practice for mine closure (Safe Work Australia 2011) recognises the importance of gas issues within mines, but not as ground gases. However, these guidelines may still be useful where a closed mine is a potential gas source.

5.2 Approaches to site management

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

Gas protection measures may include:

- passive measures to prevent or restrict gas migration or accumulation
- active control measures
- management and/or monitoring.

These measures are described briefly in this section, with more detail provided in Appendix 6. Passive measures do not require human intervention (other than periodic inspection and maintenance) once installed. Examples are 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 restrictions on building use, monitoring systems and alarms.

The choice of the most appropriate measures for a particular site must be a site-specific decision, made by a qualified person on the basis of the ground gas regime revealed by site investigations, the nature of development on the site, and the assessed risks. It is recommended that the level of protection required for a site be determined on the basis of the characteristic gas situation, as defined in Table 6. A methodology for determining the level of protection is provided in Section 5.3 of these guidelines, but appropriate professional judgement is also required.

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.

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 include:

- full or partial removal of the gas source
- gas-proof membranes or other barriers installed beneath buildings to prevent vertical gas migration into the building
- passive venting systems installed beneath buildings or incorporated into the design of ground and sub-ground floor (e.g. undercrofts)
- upgrading and sealing joints and penetrations in reinforced floor slabs (generally in conjunction with other measures)
- vertical barriers installed along site boundaries or outside building footprints to prevent lateral gas migration
- vertical subsurface venting systems to prevent lateral gas migration.

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 and this 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 by temporary soil vapour extraction, venting or air sparging systems.

Membranes

Gas-proof membranes installed beneath buildings may be utilised as stand-alone systems or in conjunction with sub-slab venting systems. Membranes may be installed beneath or on top of slabs, and cushion fabrics are usually used to support and/or protect the membrane. The most commonly utilised membranes for gas protection of buildings are high-density polyethylene (seams welded in-situ), linear low-density polyethylene (taped seams) and spray-on bitumastic membranes (seamless). Depending on the application, gas-proof membranes may also function as waterproof membranes.

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

Passive venting

Passive venting systems may involve sub-floor void spaces or drainage systems such as perforated pipes or modular drainage surrounded by gravel blankets. Open voids are superior because of the much higher air and gas flows that can be achieved, and because they are less prone to blockage and water-locking. Examples of sub-slab voids are shown in Figures 7 and 8.

Figure 7: Use of polypropylene formers to create a sub-slab void

Photograph: CM Jewell & Associates Pty Ltd

Upgraded slabs

High-quality reinforced slabs such as post-tensioned slabs (which have high resistance to cracking) can be effective barriers to gas migration provided all joints and penetrations are adequately sealed. Such slabs may be a component of a combined gas protection system utilised in conjunction with, for example, vented sub-slab void-space.

Figure 8: Large vented sub-slab void

Photograph: CM Jewell & Associates Pty Ltd

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 of the types of vertical barrier or cut-off wall 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 water table, taking water table 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 either may be 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 detailed design will depend upon 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.

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, and generally a higher carbon footprint than passive systems.

Active protection measures may include:

- sub-slab depressurisation systems
- active venting systems utilising 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 utilise fans or blowers to maintain pressure in a sub-slab void or blanket below the pressure in 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 utilising 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 air flow 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 utilise 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, or in well systems, they may be design alternatives that 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

If the pressure inside a building (or, for example, a basement car-park) can be maintained above the highest ground-gas pressure, ground gas cannot migrate into the building.

Such systems are most readily incorporated into the design of new, air conditioned buildings, but retrofit 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 a building in which a gas-proof membrane is installed beneath a floor slab, it is possible to over-pressurise the sub-slab (sub membrane) area to prevent ground gas migration into this space. Such systems require careful design, perimeter gas-collection systems and monitoring systems to ensure that adverse impacts on adjacent buildings do not occur.

5.2.3 Management controls

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

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

Restrictions on land use and building design or use would in most cases 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, it may be made subject to regulation under the CLM Act.

Safe work procedures and practice may be utilised to manage risks due to ground gases that may be present in confined spaces such as inspection chambers, tunnels and service ducts.

Monitoring systems and alarms may be used to supplement other protection measures for ground gases, in particular to demonstrate that those measures are working as designed, and to provide warning in the event of system failure. 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 retrofit of other gas protection measures has proved impracticable. The use of monitoring and alarms in these circumstances should be based on the outcome of a risk assessment.

Management plans should be prepared in most cases when gas protection measures have been implemented, even when the measures are passive, in order 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 constructing new slab penetrations that damage a gas-proof membrane.

Where active systems are installed, management plans are essential to document inspection, maintenance, monitoring and contingency procedures, and to ensure that 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 7 for further discussion of management plans.

5.3 Choosing the right approach for the site

As indicated previously, and repeated here for emphasis, the choice of the most appropriate measures for a particular site must be a site-specific decision, made by a qualified person on the basis of 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 use a number of measures in combination 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, preparation of a management plan is essential, but the difficulty of ensuring compliance with such plans in the long term should not be underestimated.

It is recommended that the level of protection required for a site be determined using the following approach, which has been adapted for conditions in NSW from the procedures outlined in British Standard 8485:2007.

5.3.1 Obtaining a guidance value

Using the characteristic gas situation obtained from Table 6 and the nature of the existing buildings or proposed development on the site, obtain an appropriate guidance value from Table 7.

Table 7: Guidance values for gas protection

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

(a) If maximum measured methane concentration exceeds 20%, increase to CS3.
(b) Residential development not recommended at CS4 and above without pathway intervention and high level of management.
(c) Consideration of evacuation issues and social risks required.

5.3.2 Evaluating protection measures

When a guidance value has been obtained from Table 7, proposed gas protection measures and combinations of measures may be evaluated using the scores listed in Table 8. A combination of protection measures appropriate for site conditions should be selected such that the combined score equals or exceeds the required guidance value.

It is important that use of Tables 6, 7 and 8 be based on a sound conceptual site model and reasoned professional judgement.

Table 8: Scores for protection measures

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

[a] Building Code of Australia

5.4 VOC and mercury vapours

Installation of measures to protect existing or new buildings against vapour intrusion should be considered when:

- the building is located (or proposed to be located) above or close to a source area or groundwater plume that cannot practicably 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 two, or a carcinogenic risk for non-threshold chemicals of greater than 10^{-5}, or
- for a proposed building, credible changes to the groundwater flow regime could result in the acceptable risk levels being exceeded, and it is rational to incorporate protection measures into the original building construction.

Although Tables 7 and 8 were developed to assess protection requirements for bulk ground gases, the protection measures listed in Table 8 will be effective in the management of vapour intrusion into buildings provided the chemical resistance of materials is considered. 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 30 years (commercial / industrial land use) to 70 years (residential land use).
- In most cases remediation of the vapour source to the extent practicable will be required by the NSW EPA, and thus the source concentration should decrease with time. This should be considered in the selection of protection measures.

Taking these factors into account, together with the need for some redundancy, it is considered that when protective measures against vapour intrusion are required, a level of protection equivalent to that specified for CS3 (Tables 7 and 8) will generally be appropriate.

Long-term management plans will usually be required.

5.5 Radon

In NSW, it is likely that any need for intervention measures to reduce radon concentrations will be assessed on the basis of persistent exceedence of the guideline levels 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 management of other ground gases will be effective in the management of radon intrusion; the key consideration will usually be the practicability of retrofitting measures to an existing building. However, it is possible that if a problem is demonstrated in a particular area due to a local geological source, 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 m^{-3} (equivalent to the UK action level) by a factor of two or less, improved ventilation of the building and use of a silicone or mastic sealant and/or 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 m^{-3} by a factor of up to four, a level of protection equivalent to that required for CS2 (Tables 7 and 8) is appropriate. This should provide protection similar to (or somewhat better than) the *Full Protection* level of BRE (2007).

Some specific measures not listed in Table 8, for example the use of vented sumps and building over-pressurisation (Section 5.2.2), should also be considered.

5.6 Review and validation of protection measures

It is important that the selection and implementation of protection measures be validated and reviewed. In NSW this will generally be carried out through the planning construction certification process.

Where management plans are specified, it is important that these are enforceable, and mechanisms for regular independent review and reporting of their implementation and effectiveness are also specified.

6 Interfaces with government and other agencies

6.1 Interface with the planning process

Under the requirements of Clause 7 of State Environment Planning Policy No. 55 (SEPP55), consent authorities must consider whether land is contaminated before consenting to the carrying out of any development on that land. Ground gases at concentrations that present a risk of harm to human health fall within the definition of contamination set out in section 5 of the CLM Act.

Thus in general, consent authorities should consider whether land that falls within the ambit of Clause 7 of SEPP55 may have been impacted by ground gases. These guidelines should assist with that consideration.

6.2 Interface with 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, potential loss or property damage exceeding $10,000. Therefore, in many circumstances detections of ground gas will meet the criteria for notification.

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) the WorkCover Authority

f) Fire and Rescue NSW.

The *appropriate regulatory authority* is dependent upon the circumstances of the site, as described under section 6 of the POEO Act.

Detections of ground gases that may be indicative of 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. Similarly, sites that are the source of ground gases that are migrating across site boundaries are likely to require notification.

A decision process for use by site owners or responsible persons considering reporting contamination under section 60 is provided in Figure 1 of the *Guidelines on the duty to report contamination under the Contaminated Land Management Act 1997* (NSW DECCW 2009). In applying this process to potential contamination by ground gases, Step 1 of the process may be considered equivalent to the preliminary screening processes outlined in Sections 4.3.1 and 4.4.1 of these guidelines. If it is necessary to proceed to Steps 2 and 3 of the process, the risk assessment procedures described in Sections 4.3.3 to 4.3.5 (bulk ground gases) and Sections 4.4.3 to 4.4.5 (trace ground gases) should be applied.

Contamination by ground gases is covered in Section 2.4 of the *Guidelines on the duty to report contamination under the Contaminated Land Management Act 1997* (NSW DECCW 2009). Consistent with the approach to notification triggers adopted in Section 2.3 of those guidelines, where notification triggers are set to the relevant investigation levels for soil and groundwater, notification is required where a risk level of moderate or higher is assessed for bulk ground gases (characteristic gas situation 3 or above), or the estimated indoor air concentration exceeds the relevant guideline values for trace ground gases.

6.4 Interface with the NSW Site Auditor Scheme

Some sites that are impacted or potentially impacted by ground gases will be subject to a site audit, 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 approval issued by the NSW EPA under Part 3 of the CLM Act.

Site auditors may use these guidelines to assist with a determination as to whether gas protection measures are required, what gas protection measures are appropriate for a particular site, and whether they have been adequately constructed.

Where gas protection measures are required, appropriate staging of the site audit and other certification requirements is necessary because implementation of gas protection measures is 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 not until the final stages of the construction process.

Because gas protection measures (whether active or passive) must be maintained in operation in order to provide continuing management of the risks associated with ground gases, it will generally be appropriate for site auditors to use Section B, rather than Section A, of the site audit statement form.

6.5 Long-term management plans

Because 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 is particularly important, and these aspects thus require particular care from site owners, site auditors and local authorities. Mechanisms for regular independent review and reporting of the implementation and effectiveness of management plans should be developed. An annual review or audit by a qualified independent expert that includes a report to be provided to the appropriate planning or regulatory authority will generally be necessary.

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 Fire Commissioner in the annual fire safety statement.

Management plans should also contain provisions for notification of the appropriate authorities, which may include the NSW EPA and the emergency services, in the event that gas concentrations above the levels specified in the plan are measured during post-implementation monitoring.

Where there is a requirement for the appropriateness of a long-term management plan to be certified by a site auditor, this should be done using Section B of the site audit statement form.

A framework for development of long-term management plans for sites impacted by ground gases is provided in Appendix 7.

6.6 Emergency notifications

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

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

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

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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	Transportation of a substance (including contaminants) by the flow of a fluid such as water or air
Aerobic	A process that proceeds in the presence of oxygen
Anaerobic	A process that proceeds 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 concentration of chemical species present in a fluid, generally with flow or with time, for example the decrease in concentration of pollutants in groundwater as a result of biological activity, or as a result of adsorption onto the aquifer matrix
Bentonite	A clay composed mainly of the clay mineral montmorillonite. It swells to many times its dry volume when in contact with water
Biochemical (biological) oxygen demand (BOD)	An empirical measurement 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 provide an indication of organic contamination
Borehole	A hole drilled in the ground in order to obtain samples of soil or rock. Permanent groundwater and gas monitoring wells can be installed in a borehole. Also used as a means of venting or withdrawing gas, or draining or pumping water
Borehole flow rate	Volume of gas per unit time which is escaping from the borehole or standpipe (regardless of composition), usually measured in L/hr
Brownfield sites	A term generally used to describe previously developed land which may or may not be contaminated
Bulk ground gas	Major component of ground gas, typically present at percentage concentrations
Catalyst	A substance which speeds up a chemical reaction without itself undergoing any permanent change
Characteristic gas situation (CS)	A risk classification determined by the gas screening value and additional factors

Chemical oxygen demand (COD)	A measure of the potential for a polluting liquid to remove oxygen from the receiving water by 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 site model (CSM)	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	Confined groundwater is held in an aquifer at a pressure greater than hydrostatic by the presence of an overlying confining bed (aquitard). This bed must have a distinctly lower hydraulic conductivity than the aquifer
Contaminant	Any physical, chemical, biological or radiological substance or matter in water or soil that is not normally present
Convection	Mass transfer of a gas or liquid due to the combined effects of both 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 wastes deposited in landfills
Critical pressure	Pressure above which a solid or liquid cannot be converted to a gas by increasing the temperature
Critical temperature	Temperature above which a gas cannot be converted to a liquid by the application of pressure alone
Degradable material	Any material that can biodegrade to produce ground gas (see also *putrescible material*)
Development	Works of construction, which may be buildings or civil engineering structures above or below ground, including ancillary works, installations and open spaces associated with the structures
Diffusion	Movement 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
Explosion	A sudden increase in volume and release of energy in a violent manner, usually 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 this guideline, to provide for the possibility of gas flows greater than those assumed and for uncertainties in monitoring and modelling of 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)
Fractures	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 indefinite expansion to occupy with almost complete uniformity the whole of any container. At a given temperature, a gas is distinguished from a vapour because it cannot be liquefied by the application of pressure alone (e.g. methane at temperatures above its critical temperature, -83°C)
Gas flow rate	Volume of gas moving through a permeable medium or issuing from a monitoring well per unit of time
Gas generation rate	Rate at which a source degrades to produce methane or carbon dioxide gas. Measured as a volume of gas produced per unit mass or volume of substrate per unit time
Gas screening value (GSV)	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 vapours
Ground gases	A general term to include all gases (i.e. including methane, VOCs or vapours) occurring or generated within the ground
Groundwater	Groundwater is the water in the subsurface zone. It comprises both unsaturated (vadose) zone groundwater and saturated (phreatic) zone groundwater; synonymous with ground water (US usage)
Groundwater table (water table)	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
Halogenated (volatile) organic compounds (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
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) and dynamic viscosity (μ) of water, and the degree of saturation, where $K_{(sat)} = k\rho g/\mu$., and is measured as the flow per unit cross-sectional area under unit hydraulic gradient. It has the dimensions of length over time [LT^{-1}] and SI units $m.s^{-1}$
Hydraulic gradient	The change in static head per unit of distance in a given direction. If not specified, the direction generally is 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 this guideline it includes contaminants such as fuels, oils, chlorinated solvents, hydrocarbons, etc.

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 the removal or addition of electrons
Intrinsically safe	Of an instrument (or equipment) which 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	Variable mixture of gases generated by decaying organic matter within a landfill site. Principal components are methane and carbon dioxide but it can contain may 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 lower limit of explosivity that is the minimum percentage by volume of a mixture of gas in air which will propagate a flame in a confined space, at normal atmospheric temperature and pressure
Mass concentration (gaseous)	Mass of a particular gaseous constituent in a given volume of gas mixture. Typically denoted in units of mg/m^3 or $\mu g/m^3$
Methanogenic	Methane producing
Monitoring well	A well installed into the ground (commonly in a borehole but can be driven into the ground) to monitor groundwater or ground gas
Oxidation	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	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 water table. Perched groundwater is held up by a confining bed whose hydraulic conductivity is so low that water percolating downwards through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure. Perched groundwater is a common, though not a necessary, feature of recharge areas
Permeability (k)	The permeability of a rock or soil is a measure of the ease with which fluids can flow through it. The intrinsic permeability is independent of the properties of the fluid but the term is sometimes used as a synonym of hydraulic conductivity (K). However, $K = k\rho g/\mu$. Common unit is the Darcy. Dimensions are $[L^2]$ and SI units m^2

pH	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 increasing alkalinity and decreasing with acidity. Originally stood for the words potential of hydrogen
Piezometric surface	See Potentiometric surface, which is the preferred term
Porosity (φ or ή)	The porosity of a rock or soil is its property of containing voids (spaces in the material not occupied by solid matter) and may be expressed quantitatively as the ratio of the volume of the voids to its total volume. 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, thus by their high specific retention rather than by differences in total porosity. Porosity is dimensionless
Potentiometric surface	A potentiometric surface is an imaginary surface defined by the potentials at all points on a given plane in an aquifer. Where the hydraulic gradient perpendicular to the aquifer is much less than the hydraulic gradient along the aquifer it is reasonable to apply the concept of potentiometric surface to the aquifer as a whole. Potentiometric surface is a synonym of piezometric surface, and is the preferred term
Putrescible material (putrescible waste)	Material (generally organic material) that can biodegrade in a landfill to produce ground gas and leachate components
Receptor	Environment, property, humans, animals or anything else that could be affected by a hazard
Reduction	Removal of oxygen, addition of hydrogen or addition of electrons during a chemical reaction
Risk	Probability that harm will occur as a result of exposure to a hazard
Solubility	The mass of the dissolved solid or gas which will saturate a unit volume of a solvent under stated conditions
Surface emission rate	Rate at which gas is emitted from a unit area of the ground surface, i.e. a volume of gas per unit time per unit area, typically measured in $L/m^2/h$
Trace ground gas	Minor constituent of ground gas, typically present at ppm or ppb concentration
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 equal to the summation of the hydraulic conductivities across a unit width of the saturated part of the aquifer perpendicular to the flow paths. Dimensions are $[L^2T^{-1}]$ and SI units $m^2.s^{-1}$
Unified Soil Classification System (USCS)	A soil classification system used in engineering and geology to describe the texture and grain size of a soil; can be carried out by either field examination or laboratory testing

Upper explosive limit (UEL)	The upper limit of explosivity that is the maximum percentage by volume of a mixture of gas in air, at normal atmospheric temperature and pressure, which will propagate flame in a confined space. However, if the UEL is exceeded there could still be a risk of explosion due to dilution of the gas
Vadose zone	The zone containing water under pressure less than that of the atmosphere, 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 water table
Vapour	At a given temperature, a vapour is distinguished from a gas because it can be liquefied by the application of 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 as 'thickness', or resistance to flow. Viscosity describes a fluid's internal resistance to flow and may be thought of as a measure of fluid friction. Dimensions are $[ML^{-1}T^{-1}]$. The SI physical unit of dynamic viscosity is the Pascal-second (Pa·s), which is identical to 1 $kg \cdot m^{-1} \cdot s^{-1}$
Void space	The space between solid particles, occupied by a gas
Volatile organic compounds (VOCs)	A 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
Volatilisation	Process whereby a liquid contaminant is converted into vapour
Volumetric concentration	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

Properties of some hazardous bulk ground gases							
Name	**Methane**	**Carbon dioxide**	**Hydrogen sulphide**	**Carbon monoxide**	**Ammonia**	**Hydrogen**	**Hydrogen cyanide**
Formula	CH_4	CO_2	H_2S	**CO**	NH_3	H_2	**HCN**
CAS no.	**74-82-8**	**124-38-9**	**7783-06-4**	**630-08-0**	**7664-41-7**	**1333-74-0**	**74-90-8**
Physical and chemical properties							
Hazard	Flammable, explosive, asphyxiating	Asphyxiating, toxic	Toxic, flammable, explosive	Toxic, flammable, explosive	Toxic, corrosive	Flammable, explosive, asphyxiating	Toxic, flammable
Description	Colourless, odourless and flammable gas. Important greenhouse gas	Colourless, odourless and toxic gas. Important greenhouse gas	Colourless, flammable and toxic gas. Rotten eggs odour at low concentrations <1 ppm, but odourless at concentrations > about 50 ppm due to anaesthesia of olfactory sense	Colourless, toxic, odourless and flammable	Colourless, toxic gas with characteristic, irritating pungent odour. Burns in oxygen	Colourless, odourless and flammable gas	Colourless, toxic gas, faint bitter almond like odour. Explosive in air
Formation	Anaerobic degradation of organic material (biogenic) High-temperature / pressure transformation of organic material (thermogenic)	Aerobic and anaerobic degradation of organic material, action of acidic water in carbonate rocks and respiration of soil bacteria	Reduction of sulphate by bacteria in the presence of organic matter in anaerobic environments (landfills, swamps, sewers, confined groundwater). Other anaerobic bacteria produce H_2S by digesting amino acids containing sulphate. Commonly present in volcanic gases and geothermal waters	Incomplete combustion of organic materials, including methane. In landfill waste can also be produced by the reduction of carbon dioxide by nascent hydrogen	Fixation of atmospheric nitrogen by soil enzymes. Also from degradation of amino acids in waste by soil bacteria. Gas-works wastes	Fermentation. Chemical reaction between water and metals in the ground	Degradation of cyanohydrins in vegetables and fruits. Degradation of plastics containing nitrogen. Can be synthesised by the reaction of methane and ammonia. Action of acid on organic cyanide salts
Molecular weight (g/mol)	16	44	34	28	17	2	27
Density (kg/m^3) @ STP	0.71	1.98	1.53	1.25	0.68	0.085	0.687
Buoyancy in air	+ve	-ve	-ve	-ve (near-neutral)	+ve	+ve	+ve
Solubility in water @ STP (mg/L)	25	1450	4100	21.4	899,000	1.62 (@21°C)	Completely miscible

Properties of some hazardous bulk ground gases, continued							
Name	**Methane**	**Carbon dioxide**	**Hydrogen sulphide**	**Carbon monoxide**	**Ammonia**	**Hydrogen**	**Hydrogen cyanide**
Formula	**CH_4**	**CO_2**	**H_2S**	**CO**	**NH_3**	**H_2**	**HCN**
CAS no.	**74-82-8**	**124-38-9**	**7783-06-4**	**630-08-0**	**7664-41-7**	**1333-74-0**	**74-90-8**
***Physical and chemical properties*, continued**							
Viscosity (Ns/m^2)	1.03×10^{-5}	1.4×10^{-5}	1.0×10^{-5}	1.66×10^{-5}	9.8×10^{-6}	8.7×10^{-6}	1.0×10^{-5}
Diffusion coefficient in air (m^2/s) (@STP)	1.5×10^{-5} m^2/s	1.39×10^{-5}	1.76×10^{-5}	1.96×10^{-5} (@9°C)	1.98×10^{-5}	6.1×10^{-5}	1.73×10^{-5}
Approximate odour threshold (ppm v/v)			0.0005		0.04		0.6
Hazardous properties							
Lower explosive or flammable limit (% v/v in air)	5	Non-combustible	4.5	12.5	Non-combustible	4	5.6
Upper explosive or flammable limit (% v/v in air)[1]	15	Non-combustible	45.5	74.2	Non-combustible	74	40
Toxicity	Not toxic (but can cause asphyxiation by displacing oxygen)	Headaches and shortness of breath at 3% v/v becoming severe at 5% v/v. Loss of consciousness at 10%, fatal at 22%	At 20–150 ppm watering eyes, blurred vision, shortness of breath, sore throat. At 400–500 ppm pulmonary oedema, headache, dizziness, coma, asphyxiation	Symptoms of mild poisoning include: headaches and flu-like effects. Greater exposure can lead to loss of consciousness and death	Irritant to skin, eyes, throat, coughing, burns, lung damage, death	Non-toxic (but can cause asphyxiation by displacing oxygen)	Highly toxic by inhalation and skin contact resulting in nausea and death
Workplace exposure standards (Safe Work Australia HSIS)	None	TWA: 5000 ppm STEL: 30,000 ppm	TWA: 10 ppm STEL: 15 ppm	TWA: 30 ppm	TWA: 25 ppm	None	TWA: 10 ppm / 11 mg/m^3
Environmental guideline levels for air (WHO 2000a and 2000b)			7 $\mu g/m^3$ (aesthetic) 150 $\mu g/m^3$ (health)	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			3 $\mu g/m^3$
Notes	Explosive limit changes when oxygen concentration reduces. When CO_2 concentration reaches 24.5% v/v methane is non-flammable. Oxidises to CO_2 by bacterial action		After short period of exposure the gas paralyses the sense of smell				Like hydrogen sulphide short exposure can result in loss of smell

Properties of some hazardous trace ground gases / vapours								
Name	**Benzene**	**Toluene**	**Xylene (mixed isomers)**	**Naphthalene**	**Tetrachloroethene (PCE)**	**Trichloroethene (TCE)**	**Chloroethene (CE)**	**Mercury**
Formula	C_6H_6	C_7H_8	C_8H_{10}	$C_{10}H_8$	C_2Cl_4	C_2HCl_3	C_2H_3Cl	Hg
CAS no.	**71-43-2**	**108-88-3**	**1330-20-7**	**91-20-3**	**127-18-4**	**79-01-6**	**75-01-4**	**7439-97-6**
Physical and chemical properties								
Hazard	Flammable, toxic	Flammable, toxic	Flammable, toxic	Flammable, toxic	Toxic	Toxic	Flammable, toxic	Toxic
Description	Volatile, colourless liquid, sweet odour	Volatile, colourless liquid, sweet odour	Volatile, colourless liquid, sweet odour	Crystalline, aromatic, white, solid hydrocarbon. Odour of mothballs	Volatile, colourless liquid with mildly sweet odour. Also known as tetrachloro-ethylene, PERC, perchloro-ethylene and PCE	Colourless, volatile liquid with sweet odour like chloroform. Also known as trichloroethylene, ethylene trichloride, TCE and trilene	Colourless gas with slightly sweet odour Also known as vinyl chloride and CE	Silvery liquid metal partitioning to colourless, odourless vapour
Common sources	Fuel spills are main source in ground. Also present in cigarette smoke	Fuel spills are main source in ground	Fuel spills are main source in ground	Fuel spills, gas works	Chemical spills: used widely in dry cleaning and degreasing	Chemical spills: used widely in cleaning and degreasing, degradation of PCE	Degradation of PVC and related polymers and certain chlorinated solvents (PCE/TCE)	Spills and leaks from industrial processes, electrical equipment and medical / scientific instruments
Molecular weight (g/mol)	78.1	92.4	106.2	128.2	165.8	131.4	62.5	200.6
Boiling point (°C)	80	111	139	218	121	87.2	-13.9	357
Vapour pressure @ 25°C (mmHg)	94.8	28.4	7.99	0.085	18.5	69	2980	1.96×10^{-3}
Solubility in water @ STP (mg/L)	1750	515	198	31	200	1000	2700	0.06
Liquid viscosity @ 25°C (Ns/m^2)	6.52×10^{-4}	5.9×10^{-4}	N/A	N/A	8.9×10^{-4}	5.3×10^{-4}	N/A	1.526×10^{-3}
Vapour viscosity @ 25°C (Ns/m^2)	7.5×10^{-6}	7.0×10^{-6}						1.7×10^{-5}
Diffusion coefficient in air (cm^2/s)	0.088	0.085	0.072	0.059	0.072	0.082	0.106	0.0307
Sorption coefficient Log K_{OC} (log L/kg)	1.77	2.13	2.38	3.30	2.19	2.10	1.75	–
Henry's law constant (dimensionless)	0.2289	0.2600	0.2900	0.0199	0.7588	0.4136	0.0560	0.467
Approximate odour threshold (ppm v/v)	1.5	8	1	0.3	47 Note: Most people stop noticing odour after a short period	50	4000	

Properties of some hazardous trace ground gases / vapours, continued								
Name	**Benzene**	**Toluene**	**Xylene (mixed isomers)**	**Naphthalene**	**Tetrachloroethene (PCE)**	**Trichloroethene (TCE)**	**Chloroethene (CE)**	**Mercury**
Formula	C_6H_6	C_7H_8	C_8H_{10}	$C_{10}H_8$	C_2Cl_4	C_2HCl_3	C_2H_3Cl	Hg
CAS no.	**71-43-2**	**108-88-3**	**1330-20-7**	**91-20-3**	**127-18-4**	**79-01-6**	**75-01-4**	**7439-97-6**
Hazardous properties								
Lower explosive or flammable limit (% v/v in air)	1.2	1.1	1.1 (paraxylene)	0.9	Not combustible	Not combustible	3.8	Not combustible
Upper explosive or flammable limit (% v/v in air)1	7.1	7.1	6.6 (paraxylene)	5.9	Not combustible	Not combustible	31	Not combustible
Toxicity	Causes drowsiness, dizziness and loss of consciousness, carcinogen	Causes drowsiness, dizziness and loss of consciousness, carcinogen	Causes dizziness, confusion and loss of balance	Causes headaches, confusion, excitement, nausea and vomiting. May be dysuria, haematuria and acute haemolytic reaction	Vapour causes irritation of the eyes, nose and throat. Suppresses central nervous system. High concentrations cause loss of consciousness and death, carcinogen	Vapour causes irritation of the eyes, nose and throat. Suppresses central nervous system. High concentrations cause loss of consciousness and death, carcinogen	Vapour causes dizziness and sleepiness. High concentrations lead to loss of consciousness and death, genotoxic carcinogen	Vapour toxic by inhalation, gastrointestinal, renal and central nervous system effects
Workplace exposure standards (Safe Work Australia HSIS 2011)								
Time weighted average (TWA)	TWA: 3.2	TWA: 191	TWA: 350	TWA: 52	TWA: 340	TWA: 54	TWA: 13	TWA: 0.025
Short term exposure limit (STEL) (mg/m3)		STEL: 574	STEL: 665	STEL: 179	STEL: 1020	STEL:216		
Environmental guideline levels for air (WHO 2000a and 2000b) (µg/m3)	0.17	260	24 hrs 4800 1 year 870		250	2.3	1	1

Note: If concentrations of a hazardous gas are detected above the upper explosive limit there could still be a risk of explosion due to dilution of the gas.

Appendix 3: Trace components of landfill gas

The source of the data in the following table is Environment Agency UK (2004a), and is for a 'typical' UK landfill, being based on data from a large number of sites. Similar, though less comprehensive, data are provided in USEPA (2005).

The probability density function is incorporated in the current version of the GasSim model. LogU denotes LOGUNIFORM and LogT denotes LOGTRIANGULAR.

Concentration distribution of priority trace components in landfill gas

	Concentration (mg/m^3)										
Priority chemical	**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 sulphide	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 disulphide	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 disulphide	<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 sulphide	<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 Section 3 and elsewhere in the body of these guidelines, it is essential that site assessment and monitoring work is planned on the basis of a desk study, site reconnaissance and an adequate conceptual site model. This appendix provides a guidance summary, and links to further up-to-date guidance.

In electronic versions of this document, clicking on blue highlighted text will take you to a master link table, with hyperlinks to internal and external references. In print versions, please refer directly to the master link table at the end of the document.

A4.1 Investigation techniques

Gas monitoring wells constructed in drilled boreholes remain the mainstay of ground gas investigations. However, a number of other techniques are available, and a summary is provided in Table A4.1. Implants (tubing tips), flux chambers and passive sampling devices are most commonly used for trace gas assessment, often in conjunction with monitoring wells.

Table A4.1: Investigation techniques

Technique	Applicability	Advantages	Disadvantages
Driven probe	All gases, shallow soils	Rapid temporary installation for screening surveys, low cost, suitable for restricted spaces	Limited installation depth in most soils, refusal on hard objects, not possible to seal effectively, some types difficult to clean, and only qualitative data
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 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	Easy to install, low-sorption Teflon or LDPE tubing, durable stainless steel tips, multi-level installations possible	Easily blocked by water and sediment, difficult to clean
Flux chamber	All gases, surface emissions or emissions through base of a pit	Direct measurement of surface emissions	Requires considerable skill to set up and operate, strongly influenced by soil moisture and barometric 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, inspection chambers, 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	Interference, strongly influenced by soil moisture 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.

Table A4.2: 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)
	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)
	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 as pre-access screen or as pathway assessment. Drains, services, wall cavities, roof spaces
Surface emission measurement	Closed landfill, filled ground	Carbon dioxide 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

A4.3 Gas monitoring well design and construction

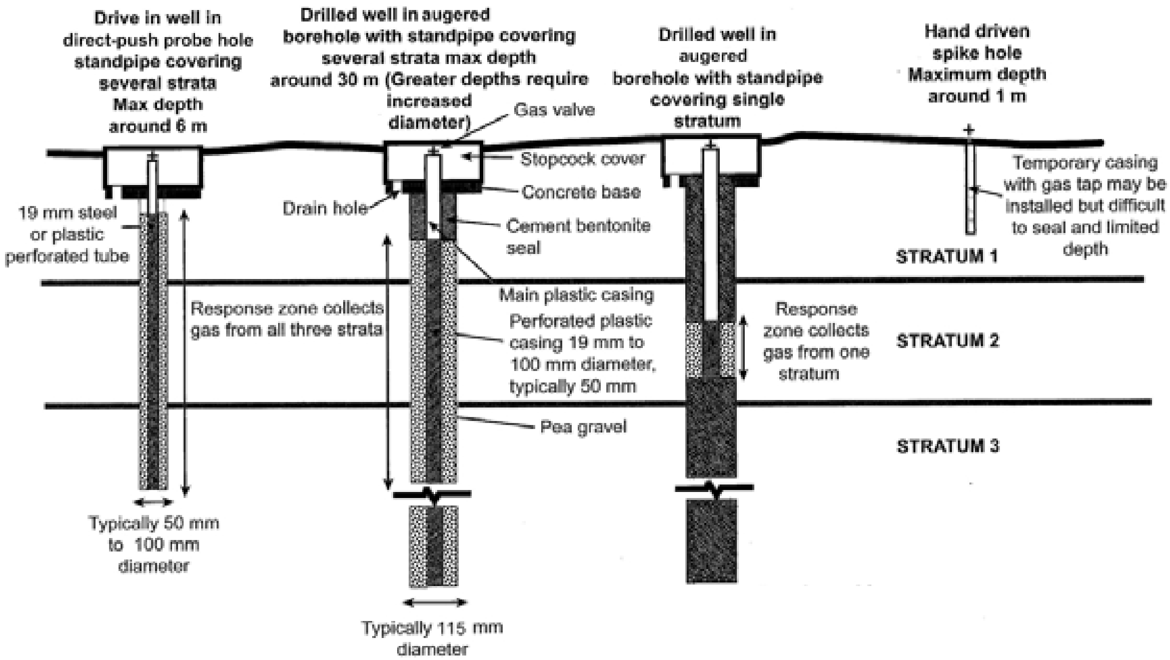

Figure A4.1: Key features required for a gas monitoring well

Modified from Wilson et al. 2009

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

Screens should be placed across permeable horizons of interest and appropriately gravel-packed. Either bentonite-cement or bentonite-pellet seals are placed in the annulus between the standpipe and the borehole wall and the pellets must be hydrated by pouring water into the annulus above the pellets.

Wells are 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 measurement instrument.

A4.4 Ground gas sampling and measurement techniques

Depending on the gas being sampled, measurements may be taken using field instrumentation, or samples may be obtained using sorbent tubes or summa canisters and submitted for laboratory analysis, with application of standard QA/QC 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 concentration, pressure and flow rate are typically recorded.

Measurement methodology

A fairly wide range of equipment that may be used for ground gas monitoring is available on the local and international markets. However, care is required to select the appropriate instrument for a particular task.

The following sections cover the most commonly used field analytical methods – infrared absorption, 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).

The absorption of infrared radiation of 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 (0–100%) and generally good resolution across this range, except at very low concentrations.

IR instruments are affected by water vapour, and other hydrocarbons may interfere with methane measurements.

Electrochemical cells

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

Electrochemical cells are frequently combined with infrared absorption in the same field instrument.

Photo-ionisation detector

Photo-ionisation-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. Depending on the energy of the lamp installed (typically 10.6 eV, but higher-energy options are available), a wide range of compounds can be detected. Typically, the 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.

Flame ionisation detector

Like the PID, a flame ionisation detector (FID) can be used to screen for VOCs as total ionisable gases, with the advantage that the instrument 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.

Gas chromatograph

Portable gas chromatographs (GC) 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.

The following sections provide some examples of field instrumentation that is available in the local purchase and rental markets. The inclusion of an instrument here does not imply any particular endorsement, rather they are included to illustrate the range available. As with other types of equipment, at each price point the major manufacturers and distributors tend to offer instruments that have similar basic capabilities but some unique features.

Examples of infrared absorption / EC instruments

The **Geotech GA2000** is one of the most widely used landfill gas analysers. Though now superseded, there are many still in use, and it is available for rental in the Australian market. It is an infrared absorption instrument (for methane and carbon dioxide), measuring:

- CH_4 – 0–100% v/v or 0–100% LEL
- CO_2 – 0–100% v/v
- O_2 – 0–25% v/v by internal electrochemical sensor
- H_2S – 0–200 ppm by optional internal electrochemical sensor
- CO – 0–500 ppm by internal electrochemical sensor

◄ **Geotech GA2000**
Photo courtesy of Geotech

The **Geotech GA5000** is the successor to the GA2000. It is also an infrared absorption instrument (for methane and carbon dioxide), measuring:

- CH_4 – 0–100% v/v
- CO_2 – 0–100% v/v
- O_2 – 0–25% v/v
- CO – 0–2000 ppm
- H_2S – 0–5000 ppm or 0–10,000 ppm

Geotech GA5000

Photo courtesy of Geotech

The instrument also measures gas flow from a borehole, differential pressure, barometric pressure, optional temperature, and optional GPS position.

The Geotech GEM5000 is a version of this meter, designed specifically for landfill gas extraction work.

The **Salamander Group GasClam®** allows continuous, unstaffed data collection.

GasClam®

Photo courtesy of Salamander Group

The GasClam® gas monitor measures methane and carbon dioxide concentrations by infrared absorption, and oxygen by electrochemical cell as well as borehole pressure, atmospheric pressure and temperature. Optional CO, H_2S (electrochemical) and VOC (PID), plus water depth are available along with a telemetry module for remote, continuous data download.

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

The gas monitor's sampling frequency can be set at user-defined intervals, variable from two minutes to once daily, and can be set to alert. Data is downloaded to a PC or viewed remotely using the optional GPRS telemetry system.

Examples of PID instruments

The **MiniRae 3000** is widely used and available for rental in Australia. It is a direct-reading VOC monitor that can be supplied with 9.8, 10.6 or 11.7 eV ultraviolet lamps. The instrument is normally calibrated to an isobutylene standard in three ranges (0–99 ppm, 100–1999 ppm and 2000–10,000 ppm). It has built-in correction factors for 102 VOC compounds.

MiniRae 3000

Photo courtesy of Active Environmental Solutions

The **Photovac 2020ppbPRO** is an upmarket VOC monitor that can detect a broad range of compounds to very low levels with either a standard 10.6 eV lamp or optional 11.7 eV lamp. The operating concentration range is 10 ppb to 40 ppm isobutylene equivalent with 10 ppb resolution.

Photovac 2020ppbPRO

Photo courtesy of INFICON Inc

Examples of FID instruments

The **Photovac MicroFID II** is intrinsically safe and has an operating range of 0.1 ppm to 50,000 ppm. It detects VOCs, methane and other saturated and unsaturated hydrocarbon gases.

∢ **Photovac MicroFID II**
Photo courtesy of INFICON Inc

Examples of GC instruments

The **Photovac Explorer** is a portable GC in a 400 mm x 270 mm case, which weighs less than 7 kg. It is supplied with a PID with a 10.6 eV (standard) UV lamp, or an optional electron capture detector. Low detection limits are dependent on the compound monitored, but are typically are 5 ppb to 50 ppb.

∢ **Photovac Explorer**
Photo courtesy of INFICON Inc

Table A4.3 provides a summary of ground gas sampling and site measurement methods. In electronic versions of this document, clicking on blue highlighted text will take you to a master link table, with hyperlinks to internal and external references. In print versions, please refer directly to the master link table at the end of the document.

Table A4.3: Ground gas sampling and site measurement methods

Technique	Method	Gases	Applicability
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_2S	
	FID	CH_4; hydrocarbon gases	Screening, where gas composition unknown. Intrinsically safe models are available
	GC	CH_4; CO_2; O_2; H_2; CO; H_2S; hydrocarbon gases	Long-term monitoring where costs of set-up and use of specialist personnel are justified
	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	
	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. Hand-portable 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. Intrinsically safe models are available
Field measurement – trace gases	PID	VOCs; 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_2S 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

Appendix 5: Further guidance on risk assessment

Table A5.1 provides a summary of further guidance for risk assessment. In electronic versions of this document, clicking on blue highlighted text will take you to a master link table providing hyperlinks to internal and external references. In print versions, please refer directly to the master link table at the end of the document.

Table A5.1: Risk assessment

Level	Issue	Requirements
Qualitative assessment	Principles	Basic principles of risk assessment as set out in AS/NZS ISO 31000:2009 *Risk management – principles and guidelines*.
	Multi-level risk assessment	As described in the NSW Department of Planning (2011) *Assessment guideline – multi-level risk assessment*.
	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).
	Characteristic gas situation	Is assessed from the gas screening value and the conceptual site model.
Quantitative assessment – event based (bulk ground gases)	Probability modelling	Quantitative risk assessment in respect of bulk ground gases, if carried out at all, is generally restricted to hazard analysis, and does not extend far into consequence analysis. Detailed guidance with respect to ground gases is provided in CIRIA R152, whilst hazard and consequence analysis in a more general hazardous industry context for NSW is provided in HIDAP 6 (DOP 2011).
	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 which 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 exist 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, as well as being 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 the adequacy of protective equipment and procedures to be assessed. The technique begins with an initiating event and analyses the various event sequences which 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 US. Other models include EPER (France) and LFGGEN (US).

Level	Issue	Requirements
Quantitative assessment – toxicity based	Issue identification	A review of 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 NEPM (1999), hazard identification examines the capacity of an agent to cause adverse health effects in humans and other animals. It is an essentially qualitative description based on the type and quality of the data, complementary information (e.g. structure-activity analysis, genetic toxicity, pharmacokinetics), and the weight of evidence from these various sources. Key issues include: • nature, reliability and consistency of human and animal studies • the available information on the mechanisms of toxic effect, and • the relevance of the animal studies to humans.
	Toxicity assessment	The core task of toxicity assessment is definition of the quantitative dose-response relationships 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: • the relationship between the extrapolation models selected and available information on biological mechanisms • how appropriate data sets were selected from those that show the range of possible potencies both in laboratory animals and humans • the basis for selecting interspecies scaling factors to account for scaling doses from experimental animals to humans • 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 to the assessment of the expected duration of exposure and the exposure durations in the studies forming the basis of the dose-response assessment, and • the potential for differing susceptibilities in population subgroups. In general, chemicals of concern are divided into two groups: threshold chemicals, for which there is a level of exposure below which there is 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.
continues overleaf…	Exposure assessment	As outlined in Schedule B4 of the NEPM (1999), exposure assessment involves the estimation of the magnitude, frequency, extent and duration of exposures in the past, currently, and in the future. It also identifies exposed populations, and particularly sensitive subpopulations, and exposure pathways. The process involves: • analysis of contaminant releases • identification of exposed populations • identification of potential exposure pathways • estimation of exposure concentrations for each pathway, and • estimation of contaminant intakes for each pathway for a range of scenarios. The NEPM is the primary reference for Australian purposes, but enHealth (2002) and USEPA (1991) are also relevant.

Table A5.1 continued

Level	Issue	Requirements
Quantitative assessment – toxicity based, continued	Vapour intrusion models	The Johnson and Ettinger (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 are available. The Farmer model (Farmer et al. 1980) and later developments of this model are also sometimes used in Australia. The USEPA (1996) and ASTM (2010b) models, and derivations, can be used to assess outdoor air concentrations. Modelling of biodegradation will be worthwhile in some circumstances for methane and hydrocarbon vapours, including BTEX.
	Toxicological data sources	enHealth (2002) 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.
	Risk characterisation	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. 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 is indicative of 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 considered acceptable, while risks between 10^{-5} and 10^{-4} require further assessment, monitoring and possible action. Risks greater than 10^{-4} are unacceptable.

Table A5.2: Alternative process for low-risk sites

Requirement	Details	Criteria
Desk study and reconnaissance	As set out in Section 3.1 and 3.2 for all sites	
Initial conceptual model	As set out in Section 3.3	
Screening-level risk assessment	As set out in Section 4.3.1	If no potential source or credible pathway – no further investigation and no gas mitigation measures required. Exit process at this point.
Initial site investigation	Must include site-specific geological data, including logs prepared by a geologist using the USCS	
Refined conceptual site model 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 sulphide 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 very low risk, no further assessment required. May assume CS1 and exit at this point. If moderate risk or above proceed to Level 2 risk assessment. Must be low risk to proceed further with 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 <0.7 and meets other CS2 criteria
	Test pit excavation in all potential source areas (minimum 5 pits per area) with geological description of material encountered, with percentage of each material estimated	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 proportion of total sample	TOC concentration <3%
Review results	Professional review of results	May assume CS2 if all criteria met

Appendix 6: Further guidance on risk mitigation and site management

Table A6.1 provides a summary of further guidance on risk mitigation and site management. In electronic versions of this document, clicking on blue highlighted text will take you to a master link table, with hyperlinks to internal and external references. In print versions, please refer directly to the master link table at the end of the document.

Table A6.1: Risk mitigation and site management

Approach	Method	Requirements
Passive protection – source	Source removal	Excavation and visual / instrumental validation of removal of potential source materials
	In-ground barriers – vertical	Impermeable barriers to prevent the lateral movement of ground gases. Designs may include secant pile walls, slurry walls, sheet-pile walls and vertical membranes. Membrane materials include high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE) and other polymers. Materials selection and detailed design based on adequate conceptual site model (CSM). Construction quality assurance and validation. 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 water table. The potential for redirection of gas flow around the end of the barrier, and effects on drainage and groundwater flow, must be considered. May be used in combination with passive or active venting.
	In-ground barriers – horizontal	Essentially capping systems. Materials selection and detailed design based on adequate CSM. Construction quality assurance and validation. Designs may include compacted clay, geosynthetic-clay, HDPE and LLDPE membranes, spray-on bituminous membranes, concrete and asphalt pavement, and combinations of these materials. Basic requirement is that the barrier be sufficiently impermeable to reduce gas flow to an acceptable level. It is essential to consider the effect of the barrier or cap in lateral diversion of gas that formerly escaped vertically to the atmosphere. Controlled venting, flaring or utilisation of gas may be required to manage this risk. Other key concerns are the effect on drainage, durability, resistance to desiccation and erosion, and resistance to anthropogenic damage and damage caused by tree roots and burrowing animals.
	Passive venting	In this context 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, thus interrupting lateral migration of ground gases. Materials selection and detailed design based on adequate CSM and usually quantitative gas flow model. Construction quality assurance and validation. Basic requirement is that the system provides control over the full depth over which gas migration is likely to occur. Important considerations are the relative importance of advection versus diffusion in gas migration, capture radius of system and components, and the effect of fluctuations in groundwater levels. May be used in combination with vertical barrier.

Approach	Method	Requirements
Passive protection – source, continued	Monitoring	Generally the installation of 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. May be a stand-alone system, but frequently used to supplement other systems such as barriers.
Active protection – source	In-ground venting systems	In this context source-area venting systems, such as landfill gas extraction systems, designed to reduce the pressure and/or concentration in the source area and thus reduce the driving force for gas migration.
	Active venting barriers	In this context vent trenches or borehole systems that force ground gases to vent to the atmosphere through the use of electrically or mechanically-driven fans or pumps, thus interrupting lateral migration of ground gases. Materials selection and detailed design based on adequate CSM and usually quantitative gas flow model. Construction quality assurance and validation. Basic requirement is that the system provides control over the full depth over which gas migration is likely to occur. Important considerations are the capture radius of the system and components, managing the consequences of mechanical failure and the effect of fluctuations in groundwater levels. May be used in combination with vertical barriers and passive venting.
Passive protection – building	Slab design	Concrete floor slabs are often the first and sometimes the only line of defence against ground gas intrusion. Concrete has measureable vapour permeability, if it did not then fresh concrete would never dry, 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, and 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 upon as a component of a gas management system then it is essential that all joints and penetrations be sealed, preferably with water bars, and that an independent inspection is carried out.
continues overleaf…	Spray-on barriers	A number of spray-on bitumastic or asphaltic membranes are available in Australia. Examples are *Liquid Boot* and *Geo-Seal.* These may be applied directly to the upper or lower surface of a slab, but more commonly are applied to a geotextile placed under or over the slab. These membranes may also serve as water barriers. The advantages of spray-on membranes are ease of sealing around penetrations and complex edges, ease of bonding to structural elements, resistance to damage (they are to some extent self-repairing, as the bituminous coating remains plastic). Identified defects can readily be repaired by over-spraying. The main disadvantage is the difficulty of maintaining a constant membrane thickness during on-site application. It is possible to retrofit spray-on membranes to the top surface of existing slabs during major building renovations.

Table A6.1 continued

Approach	Method	Requirements
Passive protection – building, continued	Geomembranes	A number of types of gas-resistant membrane are available. The most commonly used are: • high-density polyethylene (HDPE), with joints welded on site • polypropylene (PP), with joints welded on site • linear low-density polyethylene (LLDPE) • low-density polyethylene (LDPE), with lapped and taped joints • reinforced LDPE composite membrane with aluminium core. Most of these membranes are available in a range of thicknesses; membrane properties are provided in the linked documents. The primary considerations for membrane specification for a particular site are membrane permeability to the gases or vapours of concern, chemical resistance, mechanical strength, tear and puncture resistance, and practicality of installation. The relative importance of these considerations will vary between sites, but resistance to damage during and post installation is always a major consideration. Small punctures or tears will result in a drastic increase in the overall gas transmissivity of the installation.
	Passive venting	Passive venting utilises either void spaces beneath the occupied levels of buildings, or drainage blankets installed beneath floor slabs. The most common types are: • 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 by using void formers • gas drainage layers formed by perforated or slotted pipes or modular drainage systems surrounded by a gravel blanket. The essential feature of passive systems is that gas is removed and externally vented by air-flow through the void or drainage layer that is driven by wind-induced pressure and suction, or wind-driven cowls. The advantage of these systems over active systems is that they are not vulnerable to power, mechanical or maintenance failures[(a)], and thus provide more robust protection. In most circumstances this is likely to be more acceptable to auditors and regulators. 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. (a) Although wind driven cowls are not vulnerable to power outages, they may be affected by mechanical and/or maintenance failures. For example, cowls can be damaged during storm events and bearings can seize over time, preventing the cowl from spinning if maintenance is not undertaken.
	Monitoring / alarms	Installation of automatic alarmed or telemetric gas monitoring systems, within buildings or confined spaces. Typically installed in the smallest rooms and set to alarm at conservative concentrations. May be a stand-alone system, but frequently used to supplement other systems, particularly active venting systems.

Approach	Method	Requirements
Active protection – building	Active venting / sub-slab depressurisation	Void spaces and drainage blankets can be designed to be mechanically vented, providing more effective ventilation over a wider range of weather conditions, or enabling smaller dimensions to be used. Mechanically-vented basements, particularly basement car parks, may be used as a component of a gas management system. 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 long-term management plans that will ensure maintenance of active systems, regardless of changes in personnel or building ownership, for the life of a building. Active ventilation systems may be more acceptable as part of a composite system that has a passive component, such as a barrier.
	Building over-pressurisation	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. The energy efficiency and running costs of such systems are significant considerations.
	Sub-slab over-pressurisation	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, and thus preventing gas migrating from the ground into the void. These systems are usually employed in conjunction with a membrane or other barrier, and are only suitable for some ground conditions, being uneconomic when soil permeability is high. Appropriate system design and monitoring are required to ensure that operation of the system does not result in gas being forced into service trenches or other buildings.

Appendix 7: Further guidance on long-term management plans

A7.1 General comments

The management plan 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 detail the works that are required to be undertaken to ensure that the identified risks continue to be appropriately addressed into the future. It should provide the necessary information to enable such works to be conducted
- be actively instructional (i.e. rather than being a passive document)
- be prepared in consultation with those people who will implement it
- detail how exactly the land is to be managed and if mitigation systems have been installed, how those systems are to be monitored (e.g. pressure, air flow, gas concentration, etc., with associated criteria) and maintained into the future
- 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 whilst the life of a gas monitoring probe is only 10 years, the plan should specify that the gas monitoring probes are to be replaced every 10 years
- allow for the turnover of staff. Five years after preparing the management plan it is likely that nobody with first-hand knowledge of the project would still be implementing the plan, or be available to clarify any issues that arise
- not expect more from those people implementing the plan than can be provided by those people preparing the plan
- allow for changing circumstances, and in the event that the plan requires amending in the future, specify those persons (e.g. a site auditor) who must review and approve any proposed changes to the plan
- be written in a style and format that assists, rather than hinders, those people implementing it. The document should be clear in its direction and requirements, and without ambiguity (e.g. due to differences of opinion that may exist between the consultant and the site auditor)
- be reasonable and not stipulate unachievable requirements
- 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 in the event 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 / site audit report
- be capable of being incorporated into the landowner’s own management systems

- be prepared by the consultant that 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 any such penetrations must be sealed
  - require that, if significant works are contemplated, an appropriately experienced consultant be engaged to assess whether the works can be undertaken without impacting on the gas mitigation systems, and to supervise those works and subsequently 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 to be taken in the event that a trigger level is exceeded. However, that person does not necessarily need to know the manufacturer's specifications for the individual parts of the systems. The person replacing faulty equipment would need such information however.
  - The person conducting routine gardening does not need detailed information about how the mitigation systems function, but they do need to be instructed not to excavate below a specified depth, not to plant trees, etc.
- be a standalone document.

  For basic systems, a simple 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 of several parts, with each part intended for a different readership, where:
  - Part 1 provides response procedures to issues that may arise with the mitigation systems (e.g. what to do if a fan stops working or if methane is detected above a specified trigger concentration), and be intended for those who will oversee the operation of the systems, rather than the monitoring and maintenance of the systems
  - Part 2 details the routine monitoring requirements (e.g. quarterly monitoring of the rate at which air is passing through the mitigation system), and be intended for those who will conduct the monitoring
  - Part 3 provides general information relating to the installation and maintenance of the systems (e.g. 'as built' drawings, manufacturer's specifications).

An example of the structure of a management plan for a site with a complex ground gas mitigation system is provided in Section A7.3. Clearly, the contents of any management plan will reflect the measures actually installed on a site, and in some cases plans may be simpler than shown in this example.

A7.2 Summary tables

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

Typically, the following should be provided:

- a list of DOs and DO NOTs (including obvious DO NOTs such as 'do not turn off the extraction fans' and 'do not block any air inlets/outlets to the systems')
- a list of the routine activities to be undertaken, with associated frequencies
- a decision tree flowchart presenting response procedures to issues that may arise with a mitigation system (e.g. 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 the 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 those responsible or associated with the implementation of the management plan, together with their contact details
- an induction register for the manager who is responsible for the (overall) implementation of the management plan.

The summary tables and charts should be readily useable by those not necessarily familiar with the management plan and/or the property.

If the property must be vacated and/or the emergency services contacted if ground gas is detected above a specified concentration and/or a particular alarm is triggered, this should be highlighted in the plan.

A7.3 Sample structure for a management plan for a site with a complex ground gas mitigation system

PART 1 – Response procedures for issues with the gas mitigation systems

Summary tables

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

Introduction

This section should provide the context for the management plan, providing relevant background information, summarising investigation results and the conceptual site model, explaining the need for and importance of any ground gas mitigation systems that have been installed, and presenting any trigger / action levels.

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

Response actions for gas detections

This section should detail the response procedures to any detections of a ground gas and explain why action is necessary.

For example, if whilst conducting a routine monitoring event within a building that sits above a methane mitigation system methane is detected at a concentration of 2% v/v versus 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 the emergency services called.

Response actions for active systems

This section should detail the response procedures to any indications that the active systems are not operating as intended, and explain why this action is necessary and within what timeframe.

For example, an alarm is triggered indicating that one of the 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-operating fan, and the (on-call) maintenance contractor is contacted. The non-operating fan is inspected by the contractor and found to have 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 (i.e. there is no reason to install the back-up fan that is stored on the site). Two days later the fan is repaired and the system restored to its normal operating status.

Response procedure for rectifying holes in the gas barrier

This section should detail the response procedures if the gas barrier is compromised, and explain why this action is necessary and within what timeframe.

For example, during a routine site inspection of the property it is observed that a contractor has drilled through a floor slab that forms 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 that unauthorised penetrations of the floor slab do not occur, are reviewed.

Response procedures where contaminated material is exposed

This section should discuss other contaminated land issues, as appropriate. For example, the site could also be contaminated with asbestos and an asbestos management plan is required to be implemented in the event that any subsurface works are conducted.

Appendices

Typically, the following information would be provided within appendices:

- 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, etc.
- site environmental inspection sheets.

PART 2 – Monitoring of the gas mitigation systems

Summary tables

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

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.

Monitoring locations and requirements – airflow and pressure

This section should detail the routine (manual and/or automated) airflow and pressure monitoring that is to be conducted and the approved methodology. The associated commissioning data should also be provided, together with a discussion detailing how the monitoring results should be assessed and the action to be taken in the event that a monitoring result is not within a specified range.

Gas monitoring requirements

This section should detail the routine (manual and/or automated) gas monitoring that is to be conducted and how it is to be conducted. The associated assessment criteria should also be provided, together with a discussion detailing how the monitoring results should be assessed and the actions to be taken in the event that a monitoring result exceeds a specified concentration.

Condensate collection trap inspection

This section should discuss issues such as inspecting for the presence of condensate within the gas mitigation system and the actions to be taken in the event that a significant volume of condensate is found to be present.

Reporting and documentation requirements

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

For example:

- Upon detecting methane within the building at a concentration greater than 1.25% v/v the contractor should immediately inform the responsible manager, who should then immediately initiate the building evacuation plan.
- Having determined that an extraction fan is under-performing, prior to leaving the site the contractor should inform the responsible manager, who should then promptly arrange for the fan to be inspected by the (on-call) maintenance contractor.

Sub-contractor requirements

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

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.

Health and safety

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

Periodic reviews

This section should discuss any required periodic reviews of the gas mitigation systems.

For example:

- a requirement for independent review of the operation of the management plan, and reporting to an appropriate authority

- if a passive ventilation system has been installed, after a specified period of monitoring, do the results confirm that a passive ventilation system is (still) appropriate, or should the ventilation system be upgraded to an active system?
- Conversely, where an active ventilation system has been installed, after a period of say 10 years, can the system be downgraded to a passive ventilation system?
- Where a naturally ventilated system has been installed, have any of the design parameters significantly changed since the last review was conducted (e.g. has a new building been constructed which could impact on the required natural ventilation)?
- Where ventilation that is primarily operated for other purposes but which still forms a part of the gas mitigation system (e.g. forced ventilation within an under ground car park, air conditioning within a building etc.), is that ventilation still operating as intended at the time the gas mitigation system was designed.

Any such reviews should be conducted by an appropriately experienced consultant and, if significant changes to the gas mitigation system are recommended, those changes should be endorsed by a suitably qualified person such as a site auditor.

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

Appendices

Typically, the following information would be provided within appendices:

- 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, etc.
- drawings illustrating the locations of any automated monitoring systems and associated consoles
- environmental site inspection sheets
- example of a monitoring report.

PART 3 – General requirements, maintenance and intrusive works

Summary tables

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

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.

Management and enforcement of the management plan

This section should discuss issues such as:

- who is responsible for implementing the management plan
- the documentation and logbooks that are to be maintained
- in the event that the management plan is revised, how those revisions are to be endorsed by a suitably qualified person such as a site auditor
- how the management plan is enforced.

Ongoing maintenance of the gas mitigation systems

This section should outline, within a table, the required maintenance schedules and the documentation that is required (e.g. an annual calibration certificate); subsections 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 forms a part of the mitigation system and if the concrete floor has a movement joint, the joint may require resealing every 10 years.

Undertaking intrusive works that will potentially disturb the gas mitigation systems

This section should highlight that subsurface works should be avoided as far as practical – but in the event that subsurface works have to be undertaken, it should provide an outline of the procedures that should be followed and detail how the mitigation systems should be reinstated.

Health and safety

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

General comments

This section should discuss other issues such instructing the gardener not to excavate below a specified depth and not to plant trees.

Periodic reviews

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

Appendices

Typically, the following information would be provided within appendices:

- management plan induction sheet
- 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, etc.
- drawings illustrating the locations of any automated monitoring systems and associated consoles
- site environmental inspection sheets
- instrument information and service requirements.

MASTER LINK TABLE	
Technique	**External reference / link**
Investigation techniques	
General	www.crccare.com/publications/downloads/CRC-CARE-Tech-Report-13.pdf www.itrcweb.org/documents/VI-1.pdf www.nj.gov/dep/srp/guidance/fspm/pdf/table_of_contents.pdf
Implants	http://geoprobe.com/sites/default/files/pdfs/implants_oper.pdf
Flux chamber	http://pubs.awma.org/gsearch/journal/1992/12/42_12_1583.pdf
Passive devices	www.astm.org/Standards/D7758.htm www.epa.gov/etv/pubs/01_vr_goresorber.pdf www.nj.gov/dep/srp/guidance/fspm/pdf/chapter09.pdf
Ambient (indoor) air sampling	www.mass.gov/dep/cleanup/laws/02-430.pdf www.health.state.mn.us/divs/eh/hazardous/topics/iasampling.pdf
Surface emission measurement	http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=137824 http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/geho0311btol-e-e.pdf http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/geho0311btoo-e-e.pdf
Ground gas sampling and assessment methods	
IR	www.draeger.com/local/DE/de/gds/en/draeger_Review_100_June_2010_Infrared.pdf www.intlsensor.com/pdf/infrared.pdf
EC	www.intlsensor.com/pdf/electrochemical.pdf
PID	www.intlsensor.com/pdf/photoionization.pdf
FID	www.aoti.net/fid.pdf www.shsu.edu/~chm_tgc/primers/FID.html
GC	http://clu-in.org/characterization/technologies/gc.cfm http://clu-in.org/download/char/verstate/gcms/viking.pdf
FTIR	http://clu-in.org/programs/21m2/openpath/op-ftir/ www.imk-ifu.kit.edu/645.php http://webbook.nist.gov/chemistry/quant-ir/quant-ir-paper.pdf http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=164903
Laser/LIDAR	http://clu-in.org/programs/21m2/openpath/lidar/ www.aweimagazine.com/article.php?article_id=176
Mass flow	http://cdm.unfccc.int/filestorage/6/S/P/6SP493C8D8QTI6P2JKH4U9YWVXRMIM/Biogas%20Technology%20%28200 6b%29%3A%20Measurement%20of%20landfill%20gas%20using%20a%20mass%20flow%20meter.pdf?t=NFV8bW RlejBnfDDL7uCs_k2UEZm_jreaCjyT
Summa canisters	http://ndep.nv.gov/fallon/summa.pdf www.calscience.com/PDF/Air_Guide.pdf www.epa.gov/ttnamti1/files/ambient/airtox/to-15r.pdf www.epa.gov/ttnamti1/files/ambient/airtox/TO-15-Supplement.pdf www.epa.gov/region9/qa/pdfs/aircrf.pdf
Sorbent tubes	www.epa.gov/ttnamti1/files/ambient/airtox/to-17r.pdf http://clu-in.org/download/contaminantfocus/vi/Canisters%20v%20Sorbent%20Tubes.pdf www.draeger.com/media/10/01/87/10018750/tubeshandbook_br_9092086_en.pdf
Passive samplers	www.sigmaaldrich.com/content/dam/sigma-aldrich/docs/Supelco/The_Reporter/1/t211003-radiello.pdf www.skcinc.com//instructions/1720.pdf www.epa.gov/etv/pubs/01_vs_goresorber.pdf www.gore.com/en_xx/products/geochemical/environmental/surveys_environmental_modules.html

MASTER LINK TABLE	
Technique	**External reference / link**
Risk assessment	
Principles	www.epa.gov/oswer/riskassessment/ragsa/pdf/rags-vol1-pta_complete.pdf http://infostore.saiglobal.com/store/Details.aspx?ProductID=1378614&gclid=CM7745COy7MCFadMpgodQ3UAdw http://sherq.org/31000.pdf www.health.gov.au/internet/main/publishing.nsf/Content/804F8795BABFB1C7CA256F1900045479/$File/DoHA-EHRA-120910.pdf
Multi-level risk assessment	www.planning.nsw.gov.au/LinkClick.aspx?fileticket=patxHr85P24%3d&tabid=168&language=en-US
Fault trees	www.planning.nsw.gov.au/LinkClick.aspx?fileticket=WXqkxStqe64%3d&tabid=168&language=en-AU
Event trees	
Gas generation models	www.gassim.co.uk/Download.html www.epa.gov/ttn/catc/dir1/landgem-v302-guide.pdf www.epa.gov/ttn/catc/dir1/landgem-v302.xls
Issue Identification	www.health.gov.au/internet/publications/publishing.nsf/Content/ohp-ehra-2004.htm~ohp-ehra-2004-issue.htm~ohp-ehra-2004-issue-1.htm
Hazard identification	www.crccare.com/publications/downloads/CRC-CARE-Tech-Report-10-Part-1.pdf
Exposure assessment	www.health.gov.au/internet/main/publishing.nsf/Content/804F8795BABFB1C7CA256F1900045479/$File/doha-aefg-120910.pdf www.epa.gov/raf/publications/pdfs/GUIDELINES_EXPOSURE_ASSESSMENT.PDF www.epa.gov/ncea/efh/pdfs/efh-complete.pdf
Vapour intrusion models	www.epa.gov/oswer/riskassessment/airmodel/johnson_ettinger.htm www.epa.gov/oswer/riskassessment/airmodel/xls/excel.zip www.bprisc.com/pages/aboutRISC.htm www.crccare.com/publications/downloads/CRC-CARE-Tech-Report-10-Part-4.pdf
Toxicity assessment	www.ephc.gov.au/sites/default/files/ASC_NEPMsch__04_Health_Risk_Assessment_199912.pdf
Toxicological data sources	www.health.gov.au/internet/publications/publishing.nsf/Content/ohp-ehra-2004.htm~ohp-ehra-2004-reports.htm~ohp-ehra-2004-reports-2.htm www.euro.who.int/__data/assets/pdf_file/0005/74732/E71922.pdf http://cfpub.epa.gov/ncea/iris/index.cfm?fuseaction=iris.showSubstanceList
Risk characterisation	www.health.gov.au/internet/publications/publishing.nsf/Content/ohp-ehra-2004.htm~ohp-ehra-2004-risk-char.htm~ohp-ehra-2004-risk-char-1.htm www.epa.gov/spc/pdfs/rchandbk.pdf
Risk mitigation and site management	
General	http://cluin.org/download/contaminantfocus/vi/Engineering%20Issue.pdf www.hillingdon.gov.uk/media/pdf/l/a/BR414.pdf
Mines	www.safeworkaustralia.gov.au/sites/SWA/Legislation/PublicComment/Documents/Mining%20Public%20Comment%202011/Draft%20Model%20Codes%20of%20Practice%20for%20Public%20Comment%2029%20July/MineClosure.pdf
Spray-on barriers	http://remediation.cetco.com/LeftSideNavigation/Products/LiquidBoot/tabid/1356/Default.aspx
Geomembranes	Geomembranes for Gas Protection Table.pdf
Sub-slab depressurisation	www.mass.gov/dep/cleanup/laws/ssd1e.pdf http://cluin.org/download/contaminantfocus/vi/Subsurface%20Depressurization%20Systems%20(Fact%20Sheet).pdf