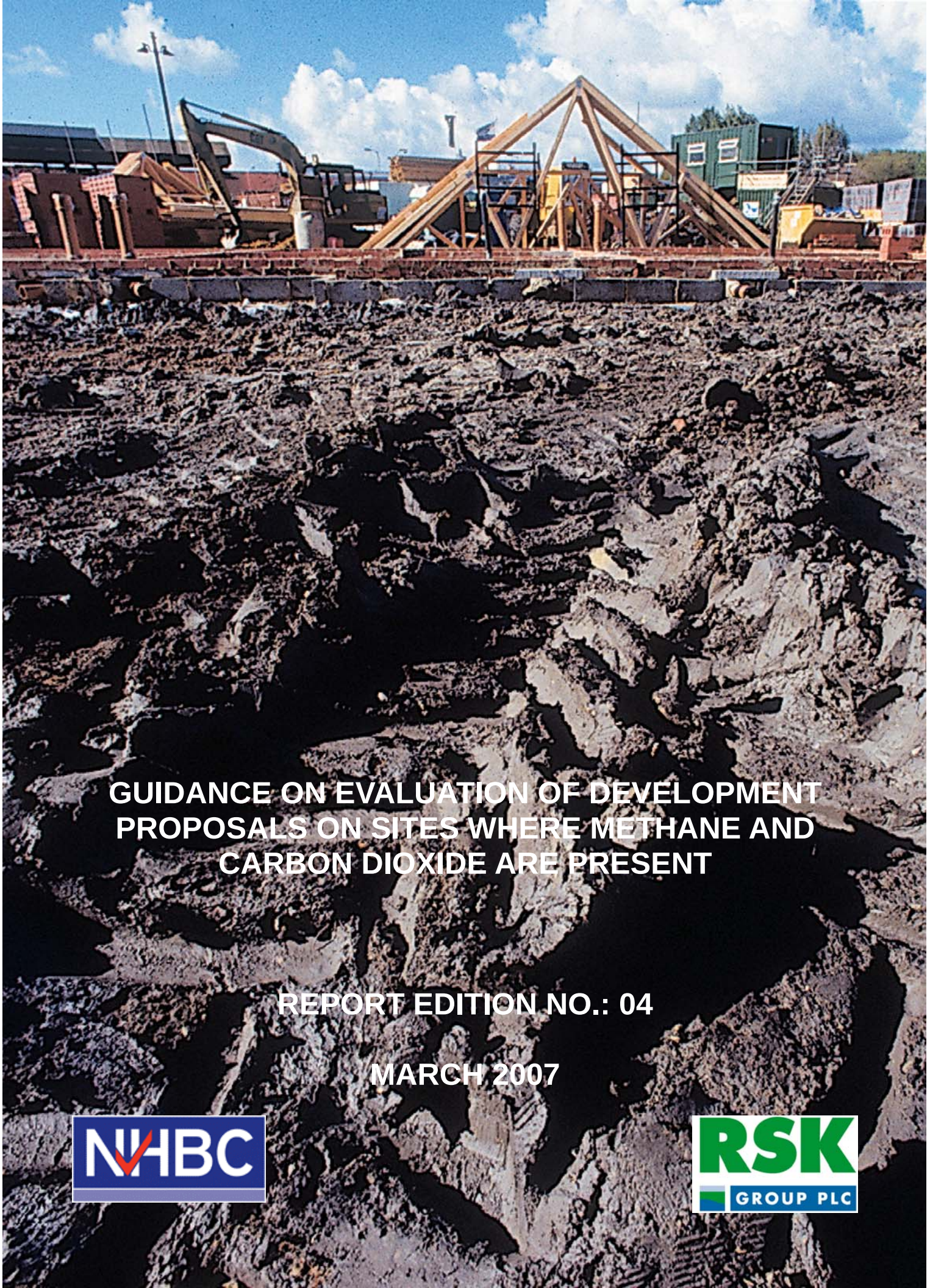

GUIDANCE ON EVALUATION OF DEVELOPMENT PROPOSALS ON SITES WHERE METHANE AND CARBON DIOXIDE ARE PRESENT

REPORT EDITION NO.: 04

MARCH 2007

NHBC

RSK GROUP PLC

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The National House-Building Council (NHBC) is the standard setting body and leading warranty and insurance provider for new and newly converted homes in the UK. It's role is to work with the house-building and wider construction industry to provide risk management services that raise the standards of new homes, and to provide consumer protection to new home buyers.

There are approximately 20,500 house builders and developers on the NHBC's Register (known as registered builders or registered developers), who agree to comply with NHBC Rules and Standards when building new homes.

More than 80% of new homes built in the UK each year are registered with the NHBC and benefit from their 10-year warranty and insurance policy called 'Buildmark'. Around 1.7 million homeowners are currently covered by Buildmark policies, and over the past 40 years, the NHBC has protected more than 30% of existing homes in the UK.

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RSK is an independent, multidisciplinary consulting and technical services company providing specialist support services in the areas of environmental planning and compliance, land assessment, remediation, and health and safety management.

RSK employs nearly 600 technical staff worldwide offering the best international experience with a local response to any health, safety and environmental requirements. RSK's strategic partnerships and close working relationships with local companies, institutions, national governments and environmental agencies enables projects to be completed quickly, achieve cost savings with minimal regulatory delays, and build in-country goodwill.

Since 1989, RSK's mission has been to provide outstanding consultancy services to engender a nurturing working environment and to strive for excellence as professionals. Every project is driven by a commitment to environmental sustainability, corporate responsibility and the health and safety of everyone involved, which is evident in ISO 9001:2000, ISO 14001:2004 and OHSAS 18001:1999 certifications.

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1. INTRODUCTION

RSK Group Plc (hereafter referred to as RSK) was commissioned by the National House Building Council (NHBC) to produce a document principally for use as internal guidance on the best practice methods of dealing with sites where ground gases are present. However, this report is equally relevant to all parties/stakeholders involved in the consideration of land assigned to residential developments (existing or planned) potentially affected by ground gases. The target audience will therefore include: land owners; developers (principally residential); professional advisors/consultants (both engineering and environmental); builders and contractors; and other regulatory bodies (e.g. Environment Agency, local authority, building control, etc.). Within the context of this report, 'ground gases' principally means methane and carbon dioxide, although a few other 'trace gases' are considered briefly. **It is important to note that this document does not include guidance and best practice for any development impacted by radon.**

A number of reports were published in the early- to mid-1990s, principally by the Construction Industry Research and Information Association (CIRIA), on the measurement of ground gases, the assessment of the risk such gases may present and the measures that can be employed to mitigate such risks. Recent guidance has tended to focus on licensed landfill sites and has been produced by the Environment Agency. As a result of the lack of up-to-date documents in the field of ground gases, many investigations and assessments have been open to uncertainty, principally regarding the methods of investigation and the adequacy of monitoring, although the risk assessment and suitable protection measures required have also been subject to ambiguity. Summaries of what the authors consider to be the key existing guidance documents on ground gases are presented within Appendix A.

This report aims, therefore, to provide the latest advice on all of these aspects relevant to residential developments. The techniques and suitability of ground gas measurements in order to characterise the ground gas regime on a given site and details on how best to carry out this monitoring work are included. The ultimate objective of a ground gas survey is to allow confident design of gas protection measures required to ensure that the development of the site is safe and risk free in terms of impacts to on-site developers and the end-users. To this aim, the site investigation must attempt to characterise the ground gas regime in the worst temporal conditions (e.g. pressure, temperature, rainfall, etc.) a site may experience.

In a wide number of instances, both brownfield and greenfield development sites may have some presence of ground gas in subsurface materials. There is currently a degree of discrepancy in how regulatory bodies assess site investigations carried out on such sites. One of the aims of this report is to eliminate the subjective nature currently found in decisions made about ground gas-impacted sites.

Much of the guidance relating to development of sites where ground gases are present has been produced in response to building projects on or close to landfill sites, as both gases are principal constituents of landfill gas. However, development is becoming increasingly common on sites where ground gases are produced by processes other than decay of landfill materials. It is acknowledged that amendments to currently adopted guidance will be required in respect of this restriction. The focus of this report is intended to be sites where the source of the ground gases are not landfill sites

(although some relevance will remain) and where the generation rates of the gases, therefore, are likely to be relatively low but still of significance.

Figure B1 within Appendix B is a flow chart that defines the stages of a site investigation and risk assessment for development on a site with a potential to emit ground gases. The flow chart provides step-by-step details listing the necessary actions that are required, starting with the identification of a ground gas issue and leading onto the consideration of remedial measures to be incorporated into the new development. Importantly, the flow diagram (and the report) identifies places where ground gas investigations either are not required or can be terminated. For ease of reference, the flow diagram refers to the appropriate section of this report and also the most relevant CIRIA report that describes the individual stages. Therefore, it would assist the reader to consult Figure B1 before attempting to read the full text of this report.

The main aim of this report, therefore, is to summarise the existing research in this field. Attention is paid to current best practice in use throughout industry and to the use of site characterisation techniques in improving risk assessment accuracy. Risk assessment and its role in site development is introduced and expanded upon where various methods in determining risk are presented. With this in mind, a key element of this document is an attempt to reduce ambiguity in the choice and installation of ground gas protection measures. A set of 'Traffic Lights' are proposed where if specified methane and carbon dioxide concentrations exceed Typical Maximum Concentrations further evaluation of flow rates is required. A risk-based methodology for deriving threshold concentrations for ground gas flow rates are described in Appendix F. These values have been termed Gas Screening Values (GSVs), which equate to the borehole gas volume flow rate, as defined by Wilson and Card (1999) as the borehole flow rate multiplied by the concentration in the air stream of the particular gas being considered. This approach is consistent with CIRIA Report 659 (2006) that was written at the same time as this report (see Section 1.1).

The Typical Maximum Concentrations can be used as a Tier 1 Gas Risk Assessment. However, in certain circumstances they can be exceeded, when the Conceptual Site Model shows it is safe to do so. Generally, the GSV values should not be exceeded. However, there may be site-specific circumstances that could be used to amend the risk assessment detailed in Appendix F.

The Traffic Lights detail what protection measures should be installed to adequately protect a residential development. The proposed Traffic Lights, together with the Typical Maximum Concentrations and GSVs, are detailed within Section 14 of this report.

Again, to assist the reader, the RSK authors have taken a view on the best practice to be applied by NHBC engineers (**highlighted in bold text**) where current guidance is vague or ambiguous. These judgements have not been subject to peer review by the industry and, therefore, may change when new documentation is published.

1.1 OTHER CURRENT RESEARCH PROJECTS

This report was delayed due to the start of two other research projects on ground gases being carried out, principally by CIRIA and also the Environmental Industries Commission (EIC), the latter of which will apparently be eventually turned into a British Standard 'Code of Practice'. All the research contractors from the three organisations

have co-operated fully to ensure that the results of these projects are complementary and generally consistent with each other and that conflicting advice has not been produced. Indeed, draft versions of this report were made fully available to the CIRIA Research Team and the authors of this report were on the Steering Committee for that document.

The CIRIA document is CIRIA Report 659 (2006) "Assessing risks posed by hazardous ground gases in buildings" by Wilson *et al.*.

1.2 CLR11 COMPATIBILITY

The Environment Agency's 'Model Procedures for the Management of Land Contamination' is the eleventh document within the Contaminated Land Reports series (CLR11, 2004). It was developed to provide the technical framework for applying a risk management process when dealing with land affected by contamination. The process involves identifying, making decisions on and taking appropriate action to deal with land contamination in a way that is consistent with government policies and legislation within the UK, in particular Part IIA of the Environmental Protection Act 1990 regulatory regime and planning policy.

CLR11 recognises that risk assessment is a highly detailed process, particularly where risks are complex and, in the case of land contamination, there are a range of specific technical approaches for different contaminants and circumstances. However, CLR11 considers that these approaches all broadly fit within a tiered assessment structure in line with the statutory frameworks. The tiers are applied to the circumstances of the site under consideration with an increasing level of detail required by the assessor in progressing through the tiers. The three tiers used in CLR11 for the specific context of land contamination are:

1. **Preliminary Risk Assessment (PRA).** Used to develop an Initial Conceptual Site Model of the site and establish whether there are potentially unacceptable risks. Information collection may include that arising from a desk study, site reconnaissance and possible exploratory site investigation.
2. **Generic Quantitative Risk Assessment (GQRA).** Generic assessment criteria are derived using largely generic assumptions about the characteristics and behaviour of sources, pathways and receptors. These assumptions will be conservative in a defined range of conditions Information collection may include that from a staged intrusive site investigation, data review and analysis.
3. **Detailed Quantitative Risk Assessment (DQRA).** Site-specific assessment criteria are values for concentrations of contaminants that have been derived using detailed site-specific information on the characteristics and behaviour of contaminants, pathways and receptors, and that correspond to relevant criteria in relation to harm or pollution for deciding whether there is an unacceptable risk.

This report refers to terms as defined above from CLR11 throughout. In addition, the Traffic Lights may be used as presented within Section 14 as a GQRA, whilst design and foundation criteria may used to refine the Traffic Lights on a site-specific basis as a DQRA.

Following the risk assessment process is the **Options Appraisal**. It comes into play only if risk assessment demonstrates unacceptable risks are associated with a site and these need to be managed. As the Options Appraisal proceeds, therefore, it focuses primarily on those pollutant linkages (relevant pollutant linkages, RPLs) that have been shown through risk assessment to represent unacceptable risks (given the legal and commercial context) and where a decision has been made to undertake remediation. Section 12 details typical ground gas protection measures that may be employed.

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- Table 3.1: The Application of Investigation Methods to Methane and Carbon Dioxide Source Identification (from CIRIA Report 151, 1995);
- Figure 8.1: Simple Diagrammatical Initial Conceptual Site Model for a Hypothetical Site (from CIRIA Report 151, 1995);
- Figure 11.1: Outline of a Fault Tree Analysis Associated with a Methane Explosion (Adapted from CIRIA Report 152, 1995);
- Figure 11.2: Outlines of an Event Tree Analysis Associated with Pipeline Failure (from CIRIA Report 152, 1995).

2. GROUND GASES

In addition to methane (CH_4) and carbon dioxide (CO_2), numerous trace gases may be present in ground gas, depending on the material that is decomposing. Trace constituents principally may include carbon monoxide (CO) and hydrogen sulphide (H_2S). However, in addition, but to a lesser extent, the following compounds may also be present:

- Alcohols ($C_nH_{2n+1}OH$);
- Alkanes (C_nH_{2n+2}), cycloalkanes (C_nH_{2n}) and alkenes (C_nH_{2n});
- Aromatic hydrocarbons (monocyclic or polycyclic);
- Esters (e.g. methyl formate, H-COO-CH_3) and ethers (e.g. ethoxyethane, CH_3-CH_2-O-CH_2-CH_3);
- Halogenated compounds; and
- Organosulphur compounds and mercaptans (also called 'thiols', where the compound contains the functional group -SH).

2.1 HAZARDS ASSOCIATED WITH METHANE AND CARBON DIOXIDE GASES

It is well known that the presence of methane gas can be highly hazardous to human health. However, the fact that methane is a colourless, odourless gas means that there is no simple indicator of its presence until such a time as explosive limits are reached and an incident occurs. For this reason, it is vital that sources of methane are identified prior to any work on a construction site commencing, and that measures are put in place to prevent a dangerous build-up of gas within buildings.

Carbon dioxide is also a colourless, odourless gas, which, although non-flammable, is both a toxic and an asphyxiant. As carbon dioxide is denser than air, it will collect in low points and depressions, which can be an extreme hazard during foundation construction and earth movements on development sites.

2.1.1 Flammability

Methane is a flammable gas. When the concentration of methane in air (oxygen 20.9% by volume (%v/v)) are between the limits of 5%v/v and 15%v/v, an explosive mixture is formed. The Lower Explosive Limit (LEL) of methane is 5%v/v, which is equivalent to 100% LEL. The 15%v/v limit is known as the Upper Explosive Limit (UEL), but concentrations above this level cannot be assumed to represent safe concentrations.

The flammability of gas mixtures is affected by their composition, presence of an ignition source, temperature, pressure and nature of the surroundings. The explosive hazard of a flammable mixture arises from the speed of propagation of the flame in a confined space and the ability of the container to absorb the associated shock wave. The flammability range can vary depending upon different circumstances, for example:

- Where carbon dioxide concentrations of greater than 25%v/v are present, methane is rendered non-flammable; and
- If the oxygen concentration is reduced, the limits of flammability are reduced. For example, at 13.45%v/v oxygen the LEL and UEL for methane are altered to 6.5%v/v and 7%v/v, respectively, whilst at 13.25%v/v oxygen the mixture is incapable of propagating a flame (Hooker *et al*., 1993 [CIRIA Report 130]).

For an explosion to occur, a source of flammable gas or vapour (mixed with air) is required, together with an ignition source and an enclosed space to allow accumulation of the gas (see Loscoe incident in Incident Box 6.1.)

On its own, carbon dioxide is not flammable and does not support combustion.

2.1.2 Toxic Properties

Methane is considered to be a low toxicity gas, but can result in asphyxiation due to its ability to exclude oxygen.

Carbon dioxide is classed as a highly toxic gas. Where 3%v/v carbon dioxide is present, this can result in headaches and shortness of breath, with increasing severity up to 5%v/v or 6%v/v. The next symptoms to develop are visual distortion, headaches, tremors and rapid loss of consciousness at 10%v/v to 11%v/v. Fatality is likely to occur at concentrations of 22%v/v and above. Even with high oxygen levels, carbon dioxide remains toxic.

The UK Health & Safety Executive (HSE) has published information (HSE, 2002) relating to concentrations of carbon dioxide that humans may be exposed to, which uses concentrations contained in the Control of Substances Hazardous to Health Regulations 1999. These are the Long Term Exposure Limit (LTEL, 8 hour period) and the Short Term Exposure Limit (STEL, 15 minute period), which are 0.5%v/v and 1.5%v/v carbon dioxide, respectively.

2.1.3 Asphyxiant Properties

Although methane is considered to be of low toxicity, its capability to displace oxygen means that at high enough concentrations it becomes an asphyxiant. Oxygen starvation occurs at 33%v/v methane, whilst at 75%v/v methane death results after 10 minutes.

Carbon dioxide is an asphyxiant and poses a risk to humans as it excludes oxygen. The density of carbon dioxide means that it can collect in poorly ventilated spaces such as inspection pits and excavations. Concentrations of 6%v/v t0 10%v/v can produce unconsciousness or death in less than 15 minutes. Lower concentrations may cause headache, sweating, rapid breathing, increased heartbeat, shortness of breath, dizziness, mental depression, visual disturbances or shaking. The seriousness of the latter symptoms is dependent on the concentration of carbon dioxide and the length of time the individual is exposed. The response to carbon dioxide inhalation varies greatly even in healthy normal individuals.

2.1.4 Odour

Methane and carbon dioxide do not have odours themselves. However, numerous trace constituents within ground gas can be odorous, with hydrogen sulphide being of most note with a smell of rotten eggs. The presence of an odour may increase the perception of adverse health effects being associated with a development. In addition, any mitigation measures installed within a development (see Section 12) may be perceived to be not functioning correctly due to the odour remaining. Offensive odours can give rise to a nuisance under statutory legislation.

The Environment Agency (2004) identifies odorous trace components of landfill gas to include with any investigation near a landfill site within their 'LFTGN-04: Guidance on Monitoring Trace Components in Landfill Gas'.

2.1.5 Effects on Vegetation

Vegetation dieback has been correlated with the presence of ground gases. This is thought to be a result of carbon dioxide causing toxic reactions in the roots, whilst oxygen deficiency caused by the presence of methane and/or carbon dioxide can occur.

2.2 CHEMICAL AND PHYSICAL PROPERTIES OF METHANE AND CARBON DIOXIDE GASES

Important physical and chemical properties of methane and carbon dioxide are listed in Table 2.1. For further information on trace components of ground gases, the reader is directed towards CIRIA Report 659 (2006) that was written at the same time as this report and Environment Agency (2004) 'LFTGN-04: Guidance on Monitoring Trace Components in Landfill Gas'.

Table 2.1: Physical and Chemical Properties of Methane and Carbon Dioxide

Property	Methane	Carbon Dioxide
Chemical symbol	CH_4	CO_2
Density (g/l)	0.71	1.98
Melting point (˚C)	-182.5	-55.6
Boiling point (˚C)	-162	-78.5 (subliming point)
Colour	Colourless	Colourless
Odour	Odourless	Odourless (acid taste)
Flammability	Flammable in air	Non-combustible
Solubility in water	Very low	Very soluble, forming corrosive liquid
Formation	Anaerobic degradation of organic material	Oxidation and combustion of organic materials and respiration Generation from chalk and limestones
Reactivity	Fairly inert, except with chlorine or bromine in direct sunlight	-
Toxicity	Low	High

2.2.1 Gas Solubility

The solubility of a gas has an impact on the concentration of that gas that will be emitted from the ground. The solubility of gases increases with pressure, meaning that at higher barometric pressures, measured concentrations of gas in the ground may be lower, as more of the gas will be dissolved in water.

Temperature also has an impact on gas solubility, with solubilities of gases generally increasing as temperatures decrease.

Methane can be transported as a dissolved product in groundwater (although solubility is very low), as well as moving through the subsurface in gaseous form.

2.2.2 Gas Density

Methane is lighter than air, but in the mixtures in which it is generally found in the ground, there is little difference in mass to air.

Carbon dioxide is denser than air and will tend to collect in low points and depressions.

2.3 NATURAL CONCENTRATIONS OF GROUND GASES

Background concentrations of methane in soil pore spaces vary from 0.2ppm to 1.6ppm and are rarely greater than 0.1%v/v (1,000ppm) methane unless an identifiable source is present.

The natural concentration of carbon dioxide in the atmosphere is approximately 350ppm.

2.4 SOURCES OF GROUND GASES

Methane is produced from both man-made (anthropogenic) and natural sources. Anthropogenic sources include landfilling activities, decomposition of organic material in made ground, natural gas pipelines and coal mines. Natural methane sources include coal measures deposits and marshland.

As for methane, carbon dioxide has both anthropogenic and natural sources. Decomposition of waste materials with a small organic material content results in the production of carbon dioxide alongside methane. Carbon dioxide may be generated naturally in areas of chalk and limestone by the action of acidic rainwater.

As methane is biochemically reactive, it is generally readily oxidised to carbon dioxide under aerobic conditions. Carbon dioxide, therefore, is often associated with the presence of methane.

The major anthropogenic and natural sources of methane and carbon dioxide are considered below.

2.4.1 Anthropogenic Sources of Ground Gases

2.4.1.1 Landfill Sites

Methane is the principal constituent of landfill gas, often having a concentration of up 65%v/v, alongside carbon dioxide at concentrations up to 35%v/v. Trace amounts of carbon monoxide, mercaptans, volatile aromatic compounds, hydrogen sulphide, organosulphur compounds and esters will generally also be present, potentially along with numerous other compounds (LFTGN03).

Landfill gas is generated by the biodegradation of waste materials due to the actions of micro-organisms and is produced at varying rates during the decomposition cycle. Landfill gas can form under both aerobic and anaerobic conditions (although anaerobic conditions are optimum).

The nature of landfill sites means that large quantities of degradable waste are present, resulting in high gas generation rates over long periods of time.

Municipal solid waste can be rapidly degraded and constituent concentrations reduced due to degradation of organics and the sequestration of inorganics. According to Pohland and Harper (1986), there are five distinct phases of waste decomposition as shown in Figure 2.1.

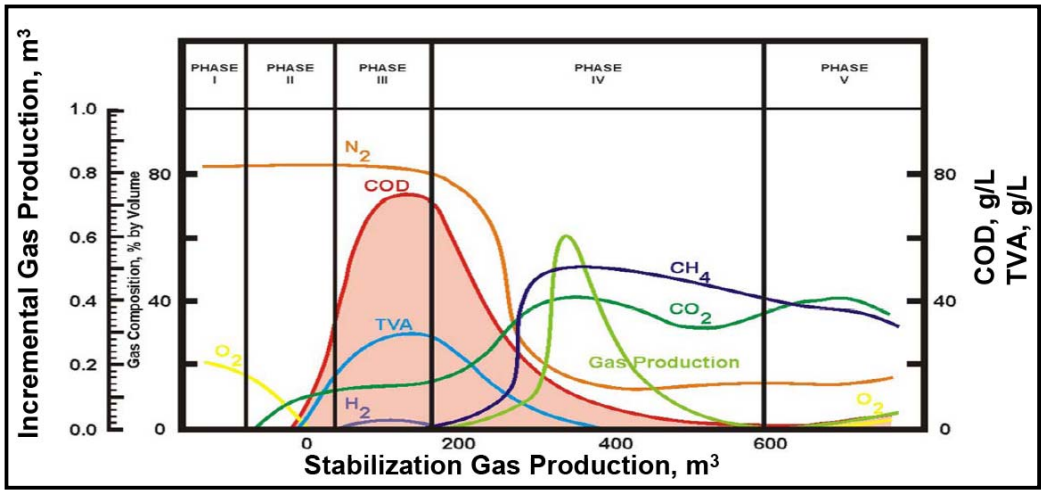

Figure 2.1: Waste Decomposition Phases (Pohland and Harper, 1986)

Each phase, characterised by the quality and quantity of leachate and landfill gas produced, marks a change in the microbial processes within the landfill, and can be described thus:

- **Phase I** (lag phase) is an acclimation period in which moisture begins to accumulate and the oxygen entrained in freshly deposited solid waste begins to be consumed by aerobic bacteria.
- **Phase II** (transition phase) The moisture content of the waste has increased and the landfill undergoes a transition from an aerobic to an anaerobic environment as oxygen is depleted. Detectable levels of total volatile acids (TVA) and an increase

in the chemical oxygen demand (COD) of the leachate signal the increased activity of anaerobic bacteria.

- **Phase III** (acid phase) The rapid conversion of waste to TVAs by acidogenic bacteria results in a decrease in leachate pH in Phase III. This phase is the initial hydrolysis where liquid leaches out the easily degradable organics. The rapid degradation lowers pH to make it more acidic, and mobilises metal species that migrate from the waste into the leachate. Volatile Organic Compounds (VOCs or solvents) are also mobilised. This phase is characterised by peak COD and BOD levels in leachate.
- **Phase IV** encompasses the period in which the acid compounds produced earlier are converted to methane and carbon dioxide gas by methanogenic bacteria. This phase marks a return from acidic conditions to neutral pH conditions and a corresponding reduction in the metals and VOC concentrations in leachate. This phase marks the peak in landfill gas production. The landfill gas production and COD/BOD cycle follow similar first order biodecay constants.
- **Phase V** marks the final stage or maturation to relative dormancy as biodegradable matter and nutrients become limiting. This phase is characterised by a marked drop in landfill gas production, stable concentrations of leachate constituents, and the continued relatively slow degradation of recalcitrant organic matter.

Leachate from landfill sites may also contain dissolved gases or may degrade during migration to produce methane with carbon dioxide and associated gases.

2.4.1.2 Made Ground

On many brownfield sites, made ground deposits will be present that contain variable, and often large quantities, of degradable material. As the material biodegrades, methane will be produced at generally low concentrations, whilst concentrations of carbon dioxide may be significantly elevated. Where made ground contains a higher proportion of carbon rich materials, elevated concentrations of methane may be found.

Although ground gas generation rates in made ground will normally be significantly lower than at landfill sites, which will cause a reduced driving force to lessen the migration potential of the gases, this does not mean that a ground gas risk assessment can be dispensed with. Ground gas may continue to be generated over long timescales in made ground, which will cause a sustained hazard.

2.4.1.3 Natural Gas Plant

Mains gas is derived from the same geological source as methane in coal mines. Leaks into surrounding soils may occur from damaged or poorly maintained underground plant.

2.4.1.4 Other Anthropogenic Sources

Minor sources of methane include: decomposition of organic matter within foundry sands; sewage sludge deposits and nominally ‘inert’ wastes that contain some

degradable materials; compost heaps; fly tipping; cemeteries; buried animal carcasses; and dung heaps.

2.4.2 Natural Sources of Ground Gases

There are two main methods by which methane is formed naturally. These are the production of methane during anaerobic decomposition of organic material, or from burial, compression and subsequent heating of organic material over geological timescales. This latter type of methane is termed thermogenic, while the former is termed bacteriogenic.

Carbon dioxide may be generated in areas of chalk and limestone by the action of acidic rainwater.

2.4.2.1 Natural Sources of Methane through Bacteriogenic Processes

Methane from wetlands (e.g. peat, bogs and other waterlogged vegetation) is produced by the microbial decay of organic material under anaerobic conditions. Methane concentrations will typically be high, whilst carbon dioxide will also be present, usually through methane oxidation by dissolved oxygen in the water. Trace gases, in particular hydrogen sulphide and light hydrocarbons, may also be present.

Ground gases from this source can typically migrate large distances through permeable soil strata, due to the high generation rates of methane.

2.4.2.2 Natural Sources of Methane through Thermogenic Processes

Thermogenic methane forms in association with Coal Measures Deposits, with the major methane formation occurring during later stages in the process of coal formation through the anaerobic decomposition of ancient vegetation trapped within the rock. In addition, other organic-rich rocks and unconsolidated deposits are also potential sources, for example, carbonaceous shale, oil shale and bituminous shale.

Anthropogenic features such as shafts (i.e. mine openings that are principally vertical) and adits (i.e. mine openings that are nearly level), as well as natural features such as fractured rock, can provide migration pathways to the surface, which may cause significant concentrations of ground gases and flow rates. This, coupled with rising groundwater to be found in several areas of the UK, along with flooding of mine workings, can release trapped methane causing a prolonged and pronounced driving force.

If further information on gas from coal mines is required, the reader is directed towards the Department of Environment ‘Methane and Other Gases from Disused Coal Mines: the Planning Response Technical Report’.

2.4.2.3 Natural Sources of Carbon Dioxide

Acidic rainwater infiltration can dissolve calcium carbonate from chalk and limestone bedrock to form carbon dioxide. Extended erosion of the rocks through their natural

porosity and via cracks can lead to a prevention of the release of carbon dioxide. The carbon dioxide may be transported until the groundwater eventually exits the limestone as seepage or an underground creek may cause a release of carbon dioxide to the open air. However, the carbon dioxide content in the groundwater may also be lost to other minerals contained within the limestone where either oxidation or carbonation or both of other minerals may take place.

2.5 RATIO OF METHANE AND CARBON DIOXIDE

The decomposition of organic material results in the production of methane and carbon dioxide in approximately equal proportions. However, solubilities of gases and additional reactions along the migration pathway can affect this ratio to various degrees.

2.6 GENERATION RATES OF METHANE AND CARBON DIOXIDE

The generation rate of ground gas will depend on the environment in which decomposition is occurring. Ideal gas formation conditions, such as a moist anaerobic environment, will encourage greater rates of gas generation.

Rates of ground gas production can be determined using field or laboratory methods. However, it is also possible to estimate ground gas production based on the gas-forming reactions involved.

CIRIA Report 152 (O'Riordan & Milloy, 1995) details the optimum parameters influencing the rate of decomposition and ground gas production as:

- High water content to provide a moisture content between approximately 20% to 26%. Adequate rainfall and water infiltration to keep moisture content at such levels;
- Conditions that are close to anaerobic;
- High proportion of biodegradable materials such as proteins, lipids, cellulose, carbohydrates, lignin and volatile fatty acids;
- Drops in atmospheric pressure;
- pH between 6.5 and 8.5, although ideally verging slightly on the acidic between pH 6 to 7;
- Temperature between 25°C and 55°C;
- High permeability;
- The ratio of the biochemical and chemical oxygen demands (BOD/COD). As a general rule, if the BOD:COD ratio is greater than 1.4, gas production is in decline; and
- Small particle sizes, as finer subsurface materials possess more surface area to provide a growing face for the micro-organisms.

3. IDENTIFICATION OF GROUND GAS SOURCES

Techniques are available for identifying the source of the ground gas. However, it is often the case on development sites that the source has been ascertained prior to the investigation (within the Preliminary Risk Assessment), and the principal issues then become whether the concentration of ground gases are likely to cause harm, or be of significant risk, rather than attempting to eliminate the risk at source.

Table 3.1: The Application of Investigation Methods to Methane and Carbon Dioxide Source Identification (from CIRIA Report 151, 1995)

	Marsh/ peat bogs	Deep peat	Landfill	Made ground	Mines gas	Mains natural gas	Mains coal gas	UG oil/gas reserves
Deep peat	^{14}C							
Landfill	Trace Gas	Trace Gas ^{14}C						
Made ground	Trace Gas	Trace Gas	Trace Gas					
Mines gas	GC Geology ^{14}C ^{13}C	GC ^{13}C Geology	GC Trace Gas Geology ^{13}C ^{14}C	GC Trace Gas Geology ^{13}C ^{14}C				
Mains natural gas	GC Pipelines ^{14}C ^{13}C Higher HCs OS	GC Pipelines ^{13}C Higher HCs OS	GC Trace Gas ^{13}C ^{14}C Pipelines Higher HCs OS	GC Trace Gas ^{13}C ^{14}C Pipelines	GC ^{13}C Geology Pipelines			
Mains coal gas	GC Pipelines ^{14}C	GC Pipelines ^{13}C	GC Pipelines ^{13}C ^{14}C Trace Gas	GC Trace Gas ^{13}C ^{14}C Pipelines	GC Geology Pipelines	GC ^{13}C Pipelines		
UG oil/gas reserves	Higher HCs ^{14}C ^{13}C Geology	Higher HCs ^{13}C Geology	Trace Gas ^{13}C ^{14}C Higher HCs Geology	Trace Gas Higher HCs ^{13}C ^{14}C Geology	GC ^{13}C Geology	GC Geology Pipelines	GC Geology Pipelines	
UG Fires	GC	GC	GC	GC	GC Geology	GC Pipelines	Pipelines	GC Geology

Key:	
UG	Underground
GC	Gas chromatographic analysis of principal gases to determine concentration ratios
Trace gas	GC or GC-MS analysis of trace organic compounds
14C	Determination of 14C:12C ratio by mass spectrometry
13C	Determination of 13C:12C and 2H:1H ratios by mass spectrometry
Higher HCs	GC analysis of longer chain alkanes
Pipelines	Consult relevant bodies or documentation relating to gas/oil distribution routes
Geology	Consult sources of geological and mining information
OS	GC analysis of organosulphur compounds such as mercaptans added to mains natural gas

Identification of sources of specific ground gas streams has not been included in detail in this report, as CIRIA Report 151 (Harries *et al.*, 1995) details extensive information on characterisation of ground gases. However, Table 3.1, as reproduced from CIRIA Report 151, illustrates the applicability of different gas investigation methods based on the conjectured source types. In order to determine the most suitable analytical technique, two potential gas sources require identification (one in the left-hand column and one in the bottom row) and the box where the two lines meet in the table indicates the suitable methodologies for distinguishing between the two gas types. For example, if determination of the source of ground gases could not be determined from made ground across the site and a landfill in the vicinity, the most appropriate analytical technique would be GC or GC-MS analysis of trace organic compounds.

4. FATE OF GASES WITHIN THE GROUND

As methane is a reactive gas, it will undergo chemical reactions under the majority of physical conditions. Methane oxidisation occurs in both aerobic and anaerobic environments, resulting in the formation of by-products including carbon dioxide. This has a resultant impact on the concentrations of gases that will be measured in the ground or are being emitted from the ground. To a lesser degree, carbon dioxide will also be involved in chemical reactions with other compounds and, over time, the concentrations will fluctuate depending on external conditions.

When assessing the fate of ground gases, potential reaction mechanisms where the gases may be altered or formed should be considered, which principally may include:

- Presence or absence of oxygen, causing aerobic or anaerobic conditions, respectively;
- Micro-organisms within soils;
- pH;
- Chemical makeup of source material; and
- Adsorption of certain constituents onto soil particles.

4.1 ADSORPTION OF GROUND GASES

The composition of ground gases may be altered by the selective adsorption of certain constituents onto soil particles. The degree to which this occurs will be wholly dependent on the soil characteristics and the gas constituents. Following adsorption, the gases may be utilised by microbial activity within the soil.

4.2 BIOLOGICAL ACTION

Micro-organisms are present within soil horizons and they will interact with constituents of gases to alter the ground gas composition. This generally tends to result in a reduction of methane concentrations and an associated increase in carbon dioxide concentrations. Certain biological reactions may result in the formation of heat, which may have a subsequent impact on ground gas migration properties.

Under the right conditions, natural microbial action in soil can transform biodegradable compounds, converting hydrocarbons, for instance, ultimately into carbon dioxide and water (under aerobic conditions) or methane and water (under anaerobic conditions). It is common for methane concentrations in the borehole headspace to reduce with time as the surrounding zone of methane in the soil is oxidised.

4.3 CHEMICAL REACTIONS

Gas composition in soils can be affected by chemical reactions such as dissolution of gases in soil water, removal of certain gases by reactions with alkaline substances,

reactions with metals or metal salts. The extent of the impact brought about by chemical activity is dependent on the composition of the soil and/or rock, through which the ground gases are migrating.

A particularly significant impact can be the solution of high levels of carbon dioxide where a high water table is observed. The ratio of methane to carbon dioxide, therefore, will become imbalanced and results will indicate a higher concentration of methane than carbon dioxide, even though generation rates of the two gases will not have altered.

5. MIGRATION OF GROUND GASES

Gas movement through the ground is influenced by a number of factors, the principal of which are the availability of pathways for ground gas flow and the character of the driving force.

5.1 MIGRATION PATHWAYS

Migration pathways include pore spaces (e.g. in sands or gravels), fractures, joints, bedding planes and fault lines. Anthropogenic influences can increase permeability, for example, by activities such as mine grouting, air blast rotary drilling, blasting and mining. All of these can have potentially catastrophic effects on pathways and ground gas movements. In addition, anthropogenic influences include sewers, granular backfill around services, cable ducts, pipes, service ducts, drains and voids such as inspection pits, under floor spaces and basements, all of which may provide preferential ground gas migration pathways.

Where interstitial water is present in rocks and/or sediments, the greater the amount of water present, the less permeable the unit is with respect to ground gases, as there is less volume available for movement of gas.

5.2 DRIVING FORCE

Movement of ground gases are driven either as a result of a variation in concentration (diffusion) or due to a pressure differential (convection). If a pressure differential exists (e.g. due to influx of gas or temperature effects), the high-pressure gas will move to an area of lower pressure to reduce the pressure gradient.

The factors influencing diffusion and convection are discussed in greater detail in Section 6 of this report.

5.3 INGRESS OF GROUND GASES INTO BUILDINGS

There are a number of accepted entry points via which ground gases will enter buildings as depicted in Figure 5.1, which are listed below:

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

Also as illustrated within Figure 5.1, locations for ground gas accumulations are as follows:

A. Roof voids;

B. Beneath suspended floors;

C. Within settlement voids; and

D. Drains and soakaways.

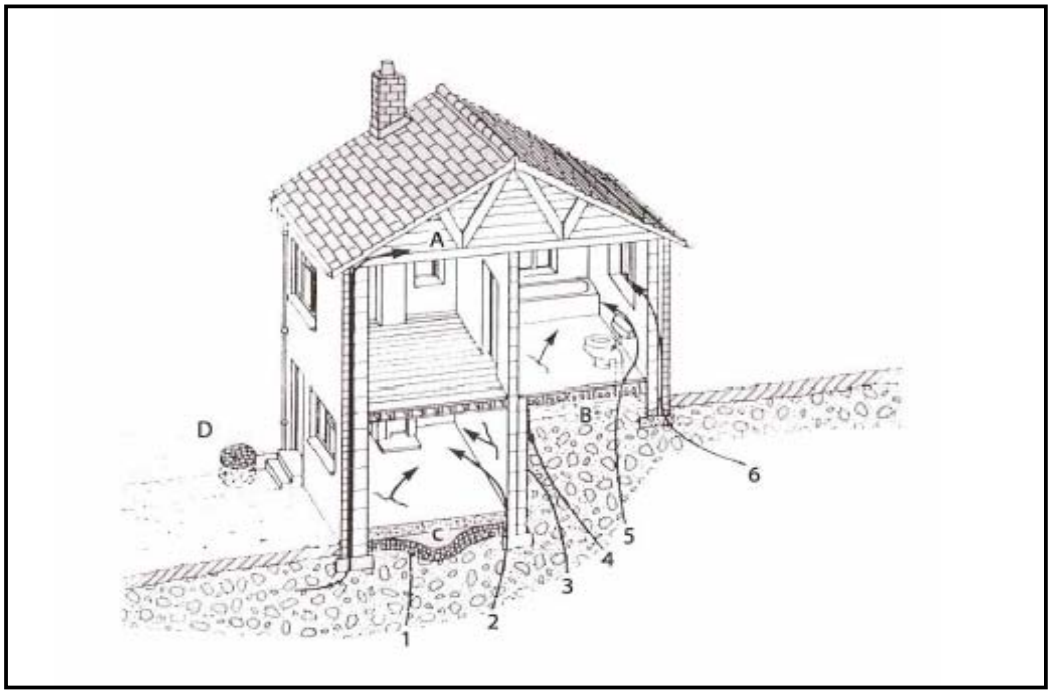

Figure 5.1: Key Ground Gas Ingress Routes and Accumulation Areas within Buildings (from CIRIA 149, 1995)

6. FACTORS INFLUENCING GROUND GAS MIGRATION

As introduced within Section 5, gases may or may not migrate within the ground, depending upon the circumstances. Such temporal conditions that will affect migration are discussed within the subsequent sections and have been grouped into five main categories, as follows:

- Meteorological conditions;
- Tidal effects;
- Geological characteristics;
- Development; and
- Vegetation.

It is of vital importance that the Conceptual Site Model is capable of predicting the worst-case temporal conditions that the site may experience, so that these can then be used in the ground gas risk assessment (see Section 11). This is essential, and cannot be stressed enough, as the ground gas protection measures (see Section 12) installed must be capable of coping with this event.

6.1 METEOROLOGICAL CONDITIONS

Various meteorological conditions may influence the migration of methane and carbon dioxide, and these are discussed below in the order of generally considered influencing significance.

6.1.1 Precipitation

Rainfall will impact ground gas concentrations, as high levels of rainfall will cause a noticeable rise in the groundwater table. This will in turn reduce the available pore space in which methane and carbon dioxide can exist in a gaseous state. Some proportion of the gases will dissolve, although this will be slight. The rise in water table will lead to a marked increase in concentration of ground gases and an associated increase in release of gases to atmosphere. This change in volume of the water table can also occur as a result of changing barometric pressure (see Section 6.1.2). The combination of these factors results in precipitation providing the greatest external influence on ground gas emission rates.

A rise in water table level due to precipitation would increase pressure in soil pore spaces, hence increasing flow of ground gases into service ducts, building voids, etc.

Another effect of precipitation (especially in clay-rich soil) would be a temporary sealing of the ground surface, either trapping ground gases within the ground or causing emissions of ground gases in a different location. Where the ground gas is trapped, generation is likely to continue at the same rate, which will result in increased gas pressure. Further, if prolonged sealing occurs, aerobic conditions may become anaerobic, causing increased methane generation. When the surface dries out, release of ground gases may occur at a faster rate until a state closer to equilibrium is reached.

This would also be witnessed if a hard frost or freezing of the ground surface occurred (see Section 6.1.3.1).

Incident Box 6.1: Loscoe Methane Explosion, Derbyshire, 1986

Figure 6.1: Demolished Bungalow after Methane Explosion in 1986 at Loscoe, Derbyshire

At 6.30 a.m. on 24th March 1986, the bungalow at 51 Clarke Avenue, Loscoe, Derbyshire, was completely destroyed by a methane gas explosion. Three occupants of the house were badly injured (Figure 6.1).

Although natural gas was supplied to the bungalow, gas samples were taken during the resulting investigation from the wreckage soon after the explosion were found to be generally similar to landfill gas. Two more houses within the vicinity were found to be unfit for habitation for the preceding nine months, and others for short periods.

Attention was directed, therefore, to a historical landfill site situated approximately 70m from the bungalow and the consideration of a possible pathway linking the two. In addition, atmospheric conditions were checked and a large fall in barometric pressure was found to have occurred immediately before the explosion where total pressure fell by 29mb in seven hours, with hourly drops in pressure ranging between 3.3mb and 4.8mb. This was identified to have directly caused migration of landfill gas through a permeable sandstone horizon that 'sucked' methane along it (Figure 6.2). A central heating pilot light ignited the methane.

After the explosion, Derbyshire County Council monitored methane levels in the remaining houses immediately around the destroyed bungalow at regular intervals and attempts were made to draw the gas out of the tip by horizontal and vertical methane extraction wells. Flow rates of landfill gas generated from the site measurements subsequently were 150–200m^3 cubic metres (m^3) of gas per hour with a 30–35% methane content and 3–4% oxygen: or approximately 45-70m^3 of methane per hour.

Further information can be found in King *et al.* (1988) 'Report of the Non-Statutory Public Inquiry into the Gas Explosion at Loscoe, Derbyshire, 24 March 1986'.

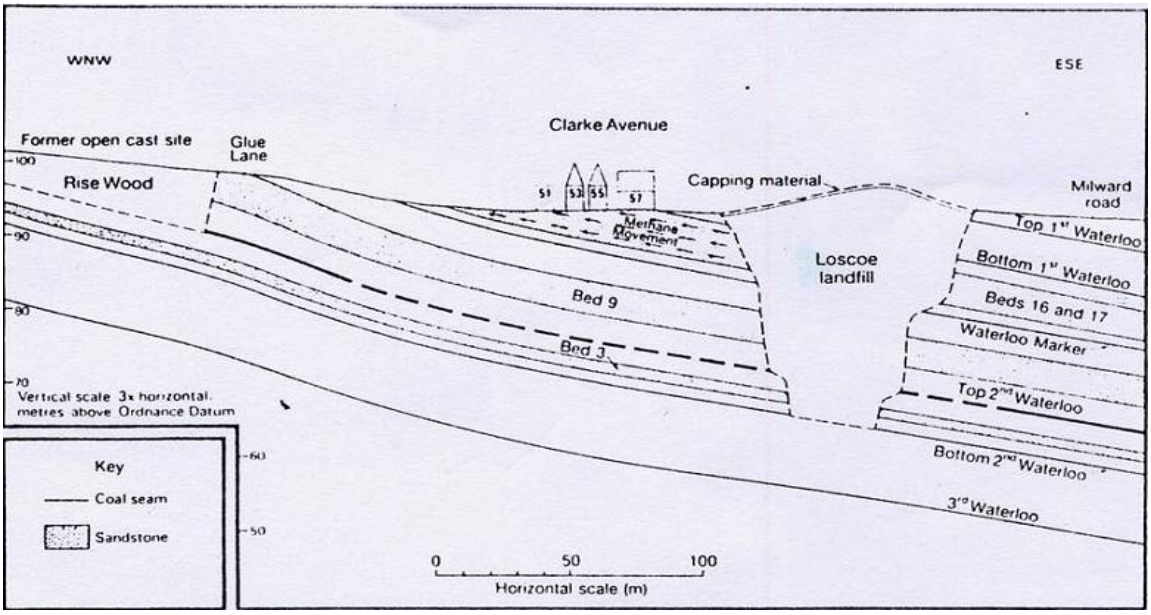

Figure 6.2: Geological Cross-Section at Loscoe, Derbyshire

6.1.2 Atmospheric Pressure

Barometric pressure (measured in millibars, mb) has a key impact on the state of ground gas and is considered to be the second largest influencing factor. At lower pressures, the ground gas will expand, resulting in increased emission rates as the gases increase in volume. Conversely, rising pressure will cause air to flow into the ground, diluting ground gas concentrations.

Barometric pressure also has an influence on gas solubility, with high pressures producing a greater solubility of many gases. On the other hand, low pressures result in these gases being released from water, providing the potential for release of large volumes of ground gases to atmosphere and/or into structures. It should be noted that the rate of change of pressure is the key driving force, with a swift drop over a small pressure range having the potential to produce a greater concentrations and flow rates of ground gases than a gradual drop over a greater pressure range. This was the case in the Loscoe incident (see Incident Box 6.1).

The moisture content of the soil has an impact on the magnitude of this pressure effect. Where soil is dry, the response in relation to pressure changes is swift. However, where the soil is damp or saturated, the barometric pressure changes will be muted to some extent. Time delays of up to 24 hours have been observed.

Pressure gradients can be formed by the effects of wind (the Venturi Effect) and by temperature difference either at the ground surface or beneath. Changes in temperature will impact the density of a gas, but this is a minor impact that is insignificant in relation to diffusion and convection transport processes.

6.1.3 Temperature

Temperature changes (daily and seasonal) will also have an impact on the rate of biological activity, which is responsible for ground gas production. However, little work has been carried out on the magnitude of this effect. It is considered unlikely that there will be a noticeable impact in the types of monitoring programmes generally used for affected sites.

6.1.3.1 Freezing

Similarly to precipitation in clayey soils, freezing temperatures may lead to a temporary sealing of the ground surface, either trapping ground gases within the ground or causing emission of the ground gas to occur in a different location. Where the ground gas is trapped, generation is likely to continue at the same rate, which will result in increased gas pressure. Further, if prolonged sealing occurs, aerobic conditions may become anaerobic, causing increased methane generation. When the surface dries out, release of ground gases may occur at a faster rate until a state closer to equilibrium is reached.

6.1.4 Wind Speed

Wind speed may have a minor impact on ground gas emission rates, but this is only likely to be noticeable when soils are dry. Additionally, it is important to note that ground

gas protection systems that rely on passive venting techniques (see Section 12) are likely to be marginally less effective when periods of little wind occurs, as it is the pressure differences inside and outside buildings that drive the mechanisms that make passive systems effective. Wind direction, as well as wind speed, can also affect passive gas protection systems.

6.2 TIDAL EFFECTS

The effects of the tide can have a marked impact on ground gas behaviour. The changing tide results in rises and falls in the groundwater table, which, as previously discussed, have a follow-on influence on the pressures exerted on ground gases.

This effect can be termed the 'piston effect', which effectively describes the interaction between the expanding groundwater table and the upward or outward movement of ground gas as a result of this.

In addition, lateral tidal effects may occur, especially within highly permeable subsurface materials, which will increase the mobility of ground gases.

6.3 GEOLOGICAL CHARACTERISTICS

The geological characteristics of the strata beneath a site will have a clear impact on the behaviour of ground gas. Where highly permeable strata exist, preferential pathways for ground gas migration will be present (as at Loscoe, see Incident Box 6.1).

Geological factors influencing gas migration include fissures, bedding, faults, fractures and joints within consolidated strata. Grain size, grain shape and packing will all affect permeability within unconsolidated materials.

It has been noted that direct seepage of ground gases through isolated fissures may have a greater potential impact than a more generalised seepage of ground gas through a permeable material such as gravel or sand.

6.4 DEVELOPMENT

Any development at a site where ground gases are present will almost certainly influence the ground gas regime identified. For example, the use of piled or strip foundations for building may create, respectively, preferential migration pathways and obstacles that could divert the migration of ground gas. Any areas of ground covered by hardstanding (e.g. car parks, roads, etc.) or buildings may potentially affect subsurface conditions, potentially affecting ground gas concentrations and movement. Furthermore, such areas will form an effective near-impermeable gas barrier, which may facilitate a build up of concentrations of ground gases, which may cause a significant driving force to cause migration of gases.

The effects on the development on the ground gas regime are extremely important to take into consideration within the Conceptual Site Model (see Section 8) developed and to ensure that adequate ground gas protection

measures (see Section 12) are designed so that they can handle any associated increases in ground gas concentrations and/or more importantly ground gas flow rates. This is especially important as increases in ground gas concentrations and migration may occur towards both on- and off-site buildings.

6.5 VEGETATION

Vegetation will have a slight impact on ground gas concentration due to alterations in the wind actions close to the surface, reducing the diffusion rate of the gas from the ground. Photosynthesis and respiration both involve interaction of gases and will have a minor impact on the ground gas concentrations.

7. PRELIMINARY RISK ASSESSMENT REQUIREMENTS

Prior to determining the requirements for an intrusive site survey, it is necessary to collect as much desk-based information as possible. This has in the past been frequently termed either a Phase 1 or desk top investigation, but, as introduced within Section 1.2, the Environment Agency's CLR11 and associated documentation considers that this investigation should be termed a Preliminary Risk Assessment (PRA).

Guidance on carrying out a PRA is extensively considered in CIRIA Report 131 (Crowhurst & Manchester, 1993) and CIRIA Report 150 (Raybould, Rowan & Barry, 1995). The findings of the PRA will ensure that the intrusive investigation (see Section 10), which is now part of the Generic Quantitative Risk Assessment (GQRA, as defined within Section 1.2) or frequently termed a Phase 2 investigation, is correctly designed.

The authors consider that the key objectives of the PRA are to:

- **Gather site-specific information with relevance to historical use, geology, hydrogeology, hydrology, topography, site services and future intended use;**
- **Define the likely ground gas migration sources and pathways based on the above information to identify the potential ground gas hazards;**
- **Review the potential health and safety implications of the site with relevance to the intrusive investigation phase; and**
- **To provide suitable information for designing the intrusive investigation and ground gas survey.**

This information should be used to define the Initial Conceptual Site Model (ICSM) for the site (see Section 8).

Figure B1 within Appendix B outlines a flow chart that is intended to be an easy-reference staged list of the steps that should be followed during a site investigation and risk assessment for development on a site with a potential to emit ground gases. The flow chart provides further information that should be considered in the PRA and how it is linked with the overall development process.

8. DEVELOPING A CONCEPTUAL SITE MODEL

8.1 DEVELOPING THE INITIAL CONCEPTUAL SITE MODEL

Development of the Initial Conceptual Site Model (ICSM) forms the main part of the PRA and is a simple model of all known site features and supports the identification and assessment of pollutant linkages, which describes all relevant characteristics of the site in diagrammatic or written form (often a combination) detailing all identified or possible combinations of sources, sensitive receptors and pathways between the two. The description of source–pathway–receptor linkages at the site is crucial to the ICSM.

The ICSM will be used to design and focus subsequent investigations, including intrusive site works, where they are necessary, to meet the objectives of the overall investigation. An example of a simple diagrammatical ICSM is shown in Figure 8.1.

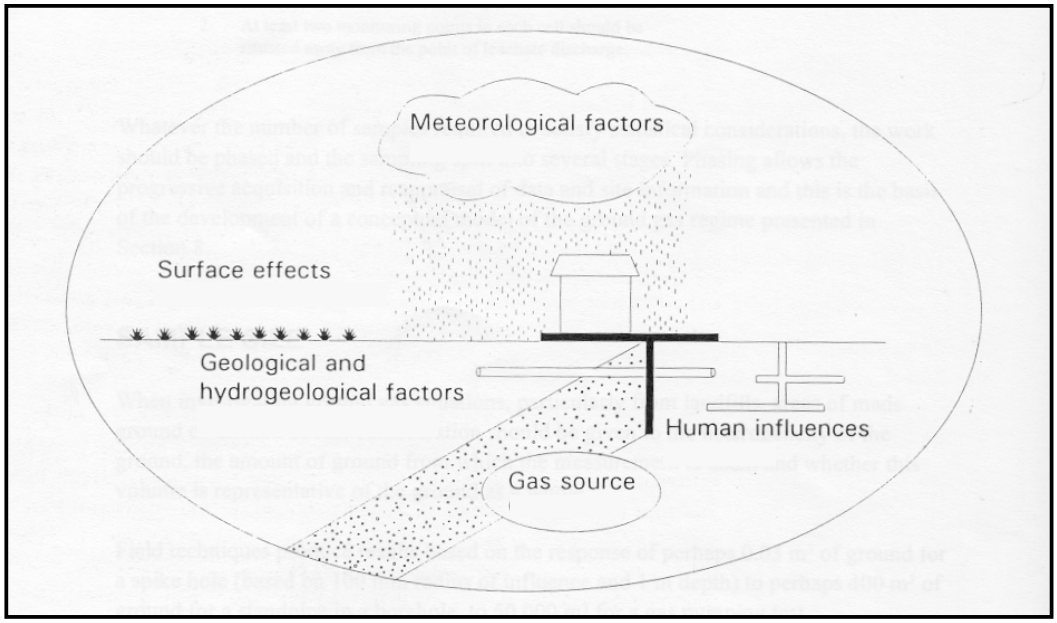

Figure 8.1: Simple Diagrammatical Initial Conceptual Site Model for a Hypothetical Site (from CIRIA Report 151, 1995)

8.1.1 Classifying Risk within the Initial Conceptual Site Model

The authors would recommend the use of Table 8.1 as an excellent tool to assist with classifying risk in the PRA to establish if the site does pose a risk to a proposed development and to assist in defining the ICSM. A version of Table 8.1 was originally presented within CIRIA Report 152 (1995), but it has been amended for use within a PRA as it forms an indicator to establish if further investigations, a GQRA or a DQRA are necessary.

Table 8.1: Classification of Risk for Assistance in Developing the Initial Conceptual Site Model for a Site (Adapted from CIRIA Report 152, 1995)

Aspect Of Risk:												
Source			Information Available			Migration			Development			
Natural soil, low peat/organic		1	Flow measurements, continuous data Reliable gas composition data Source identified long-term gas Generation performance identified		2	Soils and rocks hydraulic conductivity <10^{-9}m/s low pressure gradient/diffusion controlled flow		2	Soft landscaping		2
Natural soil, high peat/organic		2										
Dock silt, low organic		3	Flow measurements, continuous data <6 months Reliable gas composition data Source identified long-term gas Generation performance identified		6	Soils and rocks hydraulic conductivity >10^{-9}m/s low pressure gradient/diffusion controlled flow		6	Roads, hard landscape, car parks		3
Carbonate deposits		4										
Dock silt, high organic		5							Domestic housing within 1,000m of source		4	
Landfill, pre 1960		6	Flow measurements, intermittent data Reliable gas composition data Source identified as long-term gas Generation performance identified		8	Soils and rocks hydraulic conductivity <10^{-9}m/s high pressure gradient		8				
Mineworking susceptible to flooding		7							Domestic housing within 100m of source		9	
Mineworking unflooded and active		8										
Mineworking flooded		9	Sparse data		10	Soils and rocks hydraulic conductivity >10^{-9}m/s high pressure gradient		10	Domestic housing within 10m of source		10	
Landfill site, post 1960		10										

Average classification	2	3	4	5	6	7	8	9	10
Average classification (site grey tone)									
Risk strategy for protection	Control of water vapour through a damp proof course may be the only protection measures necessary.	Well-constructed ground gas barrier incorporating permeability contrast and membrane may be adequate.	GQRA obligatory, with DQRA possibly required.						

Table 8.1 shows the characterisation of a site by four main aspects that will be present that affect the overall ground gas hazard. The four main aspects that require consideration are as follows:

1. The potential source;

2. The quantity and reliability of investigation information;
3. The migration potential of the ground gas; and
4. The proposed development at the site.

A grey tone was first proposed for each aspect of risk in CIRIA Report 152 (1995); however, the authors propose that a numerical value is associated with each category, both as presented within Table 8.1, as it was felt that the allocation and averaging of the grey tones, especially the latter, was a very subjective approach to a potential fatal problem. The use of a numerical value presents a more objective procedure.

The number for each of the four aspects shown in Table 8.1 would be noted. The final number is the average of the four aspects. The number should then be compared to the lower table, which would indicate the ground gas protection strategy that may be necessary. For example, consider the following two scenarios:

1. A proposed development of a car park may be affected by a ground gas source of carbonate deposits where there is a very good information database available; all structures to be constructed on soils and rocks with a hydraulic conductivity <10-9m/s, where low pressure gradient/diffusion controls flow. This leads to an average classification of (4+2+2+3)/4 = 2.75.
2. Another proposed development of domestic housing is within 10m of source of ground gas generated from a mine working susceptible to flooding. However, there is sparse data on the gas regime, but the soils and rocks are known to have a hydraulic conductivity >10-9m/s, where low pressure gradient/diffusion controls flow hydraulic. This leads to an average classification of (7+10+6+10)/4 = 8.25

The ICSM will indicate that a detailed ground gas investigation may not be required for the Scenario 1 site. However, the ICSM for the Scenario 2 site indicates that an intrusive site investigation, with ground gas monitoring and assessment of the results, which may have to be carried out over several phases to refine and assess the data will be required for the GQRA, whilst a DQRA may also be required.

Although a GQRA or, if necessary, DQRA is recommended only for sites achieving a classification of 4-plus (the darker grey scales), this is not restrictive and, if thought necessary, a GQRA or even DQRA should be carried out where the risk is lower than the shown limit.

The authors point out that the use of Table 8.1 should only be as a preliminary tool within the PRA for development of the ICSM and cannot remove the need entirely for ground gas monitoring data to characterise the ground gas regime, as other sources of ground gases may be present that may not have been identified with the PRA and ICSM.

8.2 DEVELOPING THE CONCEPTUAL SITE MODEL

The ICSM will then be refined or revised into the Conceptual Site Model (CSM) as more information and understanding is obtained through the GQRA and DQRA risk assessment processes as increasing site-specific data is gathered during the intrusive stage of the investigation. Therefore, the CSM is a dynamic model that may change a

number of times during the investigation of a site. As a result, it should be considered to be a 'living model'.

It is important to note that the features identified in the CSM produced during site investigation work may be altered considerably due to the activities carried out on site during construction. For example, the site development may result in significant changes to the ground gas regime, perhaps due to consolidation of the ground resulting in impacts on the height of the water table, which in turn will affect the ground gas emission rates. In addition, piled foundations may create pathways linking sources with receptors that were not considered to represent a viable source–pathway–receptor linkage within the ICSM.

Equally, it should be made clear that a CSM relating to ground gas issues at a site does not investigate all other aspects of the site and, therefore, will not provide information on, for example, soil contamination and groundwater contamination.

A key aspect of the CSM is that it demonstrates an understanding of how potential issues may affect the site. The production of the CSM is a requirement of the British Standard BS 10175: 2001 'Investigation of Potentially Contaminated Sites – Code of Practice' and is documented extensively within the Environment Agency's (2004) 'CLR11: Model Procedures For The Management Of Land Contamination' and associated documentation.

The information presented within the CSM should be sufficient to allow the GQRA and, if required, a DQRA to be undertaken for all potentially impacted receptors. This should include an assessment of potential impacts on neighbouring sites, which may occur as a result of changes on the development site. As a result, factors to be included are as follows:

- Source of the ground gas (see Section 3);
- Natural and anthropogenic (for example, such as presence of services) migration pathways and influences already present at the site (see Section 5);
- Meteorological conditions (see Section 6.1), in particular the effects of the worst temporal conditions a site may experience on the ground gas regime;
- Geology (see Section 6.3) and hydrogeology (see Section 6.2); and
- Surface effects (e.g. vegetation, evenness of surface, flat or hilly site, etc.).

In addition, it is very important that the CSM should also take into account predicted changes that may occur to the ground gas regime due to the actual development itself (see Section 6.4).

It is of vital importance that the CSM is capable of predicting the *worst-case* temporal conditions that the site may experience, so that these can then be used in the GQRA and, if required, DQRA. This is essential, and the authors cannot stress this enough, as the ground gas protection measures installed must be capable of coping with this event.

With respect to ground gas presence within the CSM, it is important that an assessment is provided of the likely permeability of the soil, as low permeability is likely to trap ground gases, retaining high methane and carbon dioxide levels within the ground.

The accurate interpretation of the ground gas regime is crucial in the formation of the CSM. In order to achieve accuracy, it is important that the information gathered is applicable and that it is interpreted correctly. The development of the CSM requires continuing inputs from desk-based work and intrusive site work, until satisfaction is reached that the model is fit for its intended purpose.

In order to gradually remove uncertainty relating to the CSM, phases of site investigation work should include intrusive exploration (involving logging of ground conditions and sampling of soils) to determine details about depths and composition of any made ground, other soil types, ground gas monitoring results, etc. A review should also be made of the potential pathways connecting sources of ground gas hazards to receptors, such as site neighbours, construction workers and end-users of the site.

As part of the CSM, it will be necessary to provide an evaluation of the quality of the information that has been provided. This will indicate where any assumptions have been made regarding data and what data gaps exist. The reliability and accuracy of data sources should also be commented upon.

The principal uses of the CSM are primarily to determine current site conditions with respect to ground gas and secondly to provide a view as to potential future ground gas regime to be expected at the site following development.

Figure B1 within Appendix B outlines a flow chart that is intended to be an easy-reference staged list of the steps that should be followed during a site investigation and risk assessment for development on a site with a potential to emit ground gases. The flow chart provides further information that should be considered in the CSM and how it is linked with the overall development process.

9. ISSUES RELATING TO GROUND GAS MONITORING

In relation to monitoring specific ground gas parameters on site, the authors comment that the first issue to consider is the importance of predicting the *worst-case* temporal conditions at the site, so that these can then be used in the GQRA and, if required, the DQRA. This is essential, and cannot be stressed enough, as the ground gas protection measures installed within any development, but particularly a residential development, must be capable of coping with this event.

It was concluded by Hartless and Collins in 'Investigation of Techniques to Measure Flows of Landfill Gas from the Ground' that the worst conditions for ground gas emissions occur during falling pressures. They stated that the rate of change in barometric pressure is the key influence, as a swift drop over a small range has the potential to release a greater concentration of gas than a gradual drop over a greater pressure range, as was the case in the Loscoe incident (see Incident Box 6.1). However, the most severe pressure drops occur only intermittently, so clearly it is not feasible to expect to be able to carry out measurements that always reflect the worst-case scenario.

The authors consider that there are a number of issues that should be considered in the process of selecting methods of ground gas measurement, and the parameters that should be monitored, which are as follows:

- **It is important that a distinction be made between ground gas emission rates and ground gas generation rates (Section 10.3.1);**
- **The construction of a monitoring point for ground gas in itself may produce a false reading, due to the creation of a preferential release point for the gases; and**
- **The units in which different parameters are measured are also important, as a number of options are available. It would be sensible to standardise the units to those used by the more common measuring instruments. For example, ground gas concentration is often measured in percentage by volume (%v/v), or, for methane, by percentage of the lower explosive limit (% LEL). It is considered that methane, carbon dioxide and oxygen should be recorded as percentage by volume, with methane then being converted into percentage of the lower explosive limit as well. Other ground gases, in particular, hydrogen sulphide and carbon monoxide, should be reported in parts per million.**

Despite the difficulties mentioned above, measuring the ground gas regime is essential as it provides input data for calculations for emission rates and concentrations, and for risk assessments. Although methane is the gas most commonly discussed with regard to ground gas issues on development sites, there are also important issues relating to the presence of carbon dioxide that need addressing, for which information on the concentrations of the gas is vital (see Section 2).

The ultimate objectives of the monitoring work must be determined prior to selection of monitoring installation, locations for sampling points and choice of instrumentation. The PRA and ICSM will aid in all these decision-making processes.

9.1 INTRUSIVE SITE WORKS

The drilling and installation of monitoring wells will introduce artificially high concentrations of oxygen into the ground, which will cause aerobic conditions to develop. Biological micro-organisms in the ground that thrive in such conditions will not generate methane, although they will generate carbon dioxide. Any trace amounts of methane generated would typically be expected to be readily oxidised. As the micro-organisms consume the oxygen, the ground conditions will revert back from aerobic to anaerobic (oxygen deficient). At which time, micro-organisms that thrive in such conditions will succeed the aerobic micro-organisms and the production of methane will recommence and the ground gas regime will revert back to that before any disturbance of the ground occurred before the drilling works. Notwithstanding the above, initial monitoring round(s) even immediately after monitoring well installation may offer important information regarding the reversion of the monitoring well from aerobic to anaerobic conditions, which may help in assessing the ground gas generation potential of the site.

Monitoring points can be constructed in a variety of different ways, and the method of construction of these should be selected based on the intended use of the results, together with the length of time for which the monitoring well is to be required. Further details can be found in Section 10.2 of this report.

9.2 MONITORING INSTRUMENTATION

Ground gas monitoring can be carried out *in situ*, using measuring apparatus on site, or *ex-situ*, where a sampling vessel is used to transport a gas sample to an analytical laboratory. However, due to recent rapid improvements in field-based monitoring equipment, laboratory testing is becoming seen as a less necessary aspect of ground gas monitoring.

Notwithstanding this, it is considered good practice to take some ground gas samples (e.g. from monitoring wells with the highest ground gas concentrations) for testing at an analytical laboratory. This will act as a check on the field-based measurements and to establish the cause of any anomalies that may have been encountered.

As part of the ground gas monitoring survey, it is essential that meteorological data is recorded in order to help explain variations in recorded flow rates and concentrations of the ground gases. Atmospheric pressure and rainfall will affect gas flow rates (Section 6.1) and not gas concentrations.

Numerous instruments are available for the measurement of ground gases. There are some limitations to different types, but a small amount of research by the site investigation contractor/consultant should indicate the suitability or otherwise of an instrument to the required purpose (O'Riordan & Milloy, 1995 [CIRIA Report 152]). A thorough and up-to-date listing of equipment, together with its advantages and disadvantages and when it should be used is to be found within CIRIA Report 659 (2006) that was written at the same time as this report. The interpretation requirements should be reviewed as part of the process of selecting the measurement techniques. Where a greater level of interpretation is required, higher costs of investigation may be

necessary in order to ensure that the information gathered is of suitable quality for the intended use.

9.2.1 Infra-Red Monitoring Instrumentation

In particular, it is important to note that infra-red gas monitor equipment readings of methane can be interfered with by other hydrocarbons, which may affect the concentrations reported (see Section 10.4.1.1).

10. METHODS FOR INVESTIGATING GROUND GASES

The ultimate objective of all investigations – as viewed by landowners, scheme promoters or regulators – should be identical, namely to ensure that a proposed development may take place safely, with appropriate precautions taken, and remain safe (CIRIA Report 150, 1995). The selection of an appropriate site investigation strategy is vital, therefore, as the methods used for the collection of ground gas data will influence the ultimate use to which the data can be put.

The potential influences on a site investigation strategy are detailed in CIRIA Report 150 (Raybould *et al.*, 1995), where the relationships between various site characteristics and measurable factors are considered. This relates the parameters that influence ground gas characteristics to both the development context and their identified or potential hazard.

A number of issues will require consideration during the planning process and these are listed in the subsequent sections in this chapter. Environment Agency (2004a) document 'LFTGN 03: Guidance on the Management of Landfill Gas', which updates the Department of the Environment's (1991) 'Waste Management Paper 27: a Technical Memorandum Providing Guidance on the Monitoring and Control Of Landfill Gas', states that the ground gas monitoring exercise should be undertaken for the following main components:

- Source;
- Emissions; and
- Meteorology.

Figure B1 within Appendix B outlines a flow chart that is intended to be an easy-reference staged list of the steps that should be followed during a site investigation and risk assessment for development on a site with a potential to emit ground gases. The flow chart provides further information that should be considered in the site investigation and how it is linked with the overall development process.

10.1 ISSUES RELATING TO DESIGN OF GROUND GAS MONITORING PROGRAMME

10.1.1 Objective of the Ground Gas Monitoring Exercise

The objective of the ground gas monitoring exercise is to establish ground gas concentrations and emission rates at the worst-case temporal conditions (see Section 6.0). Alternatively, monitoring outside of the worst-case temporal conditions may allow for a prediction of the ground gas regime at the potential worst-case temporal conditions to be made. However, predicting the ground gas regime during the possible worst-case temporal conditions that a site may experience is not straightforward, as the ground gas regime will vary significantly from site to site with copious possible responses and variations.

The ground gas conditions during the worst-case temporal conditions that a site may experience will primarily be used to establish the potential risk to end users of the site,

enabling design decisions to be made as to what ground gas protection measures and, if required, remediation actions are necessary.

10.1.2 Choice of Suitable Ground Gas Monitoring Locations

Prior to selecting the most appropriate locations in which to monitor ground gases, it is essential that the PRA and ICSM have been formulated and both appropriately describe what possible ground gas influences may be present and what source-pathway-receptor linkages are possible (see Section 8.0). This will allow optimum monitoring locations to be chosen according to the key objectives of the monitoring programme. In addition to the selection of the most appropriate monitoring locations, care should be taken to target the appropriate horizons within the soil to generate sufficient information on the ground gas regime (see Section 10.1.3).

The primary locations for monitoring should be within the site to determine the type, concentrations and flow rates of the ground gas(es) present and to ensure that access to the monitoring points is available whenever necessary. Ideally, several off-site monitoring locations should also be established to provide baseline data (outside any specific areas of concern) or to show the migration behaviour of the ground gas. However, this is often not possible due to logistical or access reasons.

The proposed development plans for the site should also be considered in reviewing the locations for ground gas monitoring installations. However, the locations selected are often chosen on the basis of foundation locations and for the purposes of geotechnical surveys, not for ground gas investigation objectives.

10.1.3 Targeting Appropriate Subsurface Strata and Sources

The appropriate depth of ground gas monitoring points and the selection of response zones is based on characterisation of geological and hydrological conditions at the site, the presence of identified gassing sources and on the perceived level of risk associated with ground gas. The depth of wells should be sufficient to intercept any gassing sources or migration pathways. It is important, therefore, that experienced and appropriately qualified personnel – who can design appropriate monitoring well installations based on encountered ground conditions – supervise all aspects of intrusive investigations.

It is important to note that a common error is to conclude that there are no ground gases at a site when the monitoring points have not been installed deep enough to intercept the source, or insufficient monitoring points have been installed to obtain information from multiple gassing sources. For example, Figure 10.2 (from Wilson and Haines, 2005) illustrates a potential development site where there is more than one potential source of ground gases present (i.e. deep peat layer, waste disposal (landfill) area and deep areas of made ground) and where there may be a number of potential pathways. As a result, numerous wells may need to be installed with their response zones appropriately sealed into different strata rather than the common method of installing a gravel surround along the whole length of the borehole. Within Figure 10.2 it can be seen that monitoring wells have been installed and sealed into the different strata to determine the ground gas regime from all sources. If the deep wells had not been

installed then it is likely that the presence of ground gas below parts of the site would not have been identified. In addition, some wells were installed:

- Above the peat layer to identify if any significant vertical migration; and
- Outside of the landfilled area to identify any significant lateral migration.

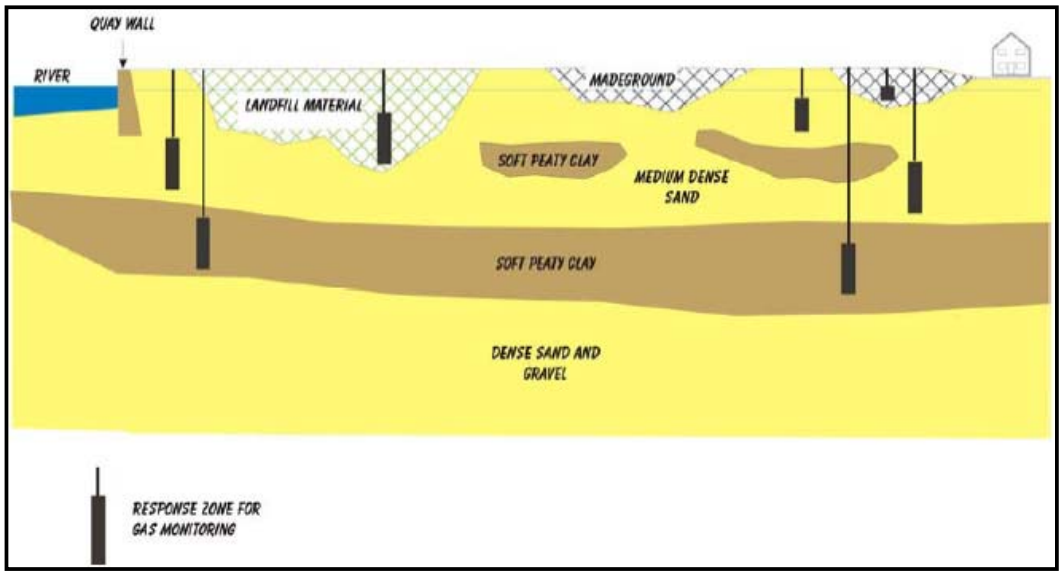

Figure 10.1: Examples of Targeting Gas Well Response Zones (from Wilson and Haines, 2005)

10.1.4 Types of Monitoring Installations

The type of ground gas installations required will vary widely depending on the objectives of the monitoring work. Temporary or permanent installations could be used, with increasingly complicated designs depending on the type of information to be collected. Further details of monitoring installations are provided in Section 10.2 of this report.

10.1.5 Monitoring Instrumentation

The equipment used to carry out the monitoring will have a bearing on the measurements that can be taken and, therefore, on the ultimate application of the results. The most commonly used site-based monitoring equipment for ground gases is an infra-red gas monitor as methane, carbon dioxide, oxygen, carbon monoxide and hydrogen sulphide can all generally be measured at the same time. However, this sort of equipment may be liable to recording high levels of methane when in fact there is cross contamination occurring from other hydrocarbons (see Section 10.4.1.1). As a result, **it is recommended that detailed logging of the ground is carried out in accordance with British Standard BS 5930 (1999) 'Code of Practice for Site Investigations', in conjunction with the guidance contained within British Standard BS 10175 (2001) 'Investigation of Potentially Contaminated Sites – Code**

of Practice', to assess the possibility of other hydrocarbon gases being present. In addition, during the first monitoring round, all monitoring points should be screened with a photo-ionisation detector (PID).

The information required during a ground gas monitoring round is contained within Section 10.4, whilst an example pro forma for recording site-based ground gas monitoring data is contained within Appendix C.

10.1.6 Frequency of Monitoring

In general, the frequency and overall period of ground gas monitoring required will be determined by the PRA and ICSM, the findings of subsequent GQRA and, if relevant, DQRA and any particular regulatory requirements. It may be that the investigation is a due diligence and target limited assessment to ascertain preliminary information to attempt to ascertain costing information prior to the purchase of a site or development. In such a case, time constraints may be very limited and it may only be possible to obtain vague information. If this is the case, no detailed design of ground gas protection measures should be attempted.

Although the timescale may be an important consideration, it must be noted that the quicker and simpler intrusive techniques are not always the most accurate and reliable. Further discussion on investigation techniques can be found in Section 10.2.

Guidance provided in CIRIA Report 150 (Raybould *et al.*, 1995) includes the following issues:

- The ground gas monitoring rounds should encompass varying climatic conditions (specifically atmospheric pressure), including at least one period of falling pressure and one after/during heavy rainfall;
- Regular monitoring rounds over a period of stable conditions will determine the existence of variations in ground gas presence that are not due to changes in weather; and
- Where regular fluctuations in the water table occur (e.g. in tidal regions), ground gas monitoring should be carried out throughout the cycle to determine influences on the ground gas regime and the presence or absence of a time lag in response to such water table changes.

Waste Management Paper 27 (DoE, 1991) suggests that monitoring should be carried out at barometric pressures below 1,000mb, when the pressure is falling. This is applicable to both landfill and non-landfill sources, and is most useful where the ground gas driver is convection.

Bearing in mind the potential temporal variables, as a minimum, the NHBC should be requiring six ground gas-monitoring rounds over a three-month period. In many cases, however, substantially longer periods of ground gas monitoring could be required to enable the effects of the worst temporal conditions to be defined.

However, extended periods of monitoring (and possibly the installation of additional gas monitoring wells) for sites that consistently record high or variable concentrations may be necessary to determine the nature of the soil gases and/or vapours regime.

Notwithstanding the above, it is important to consider that there is a balance to be considered between the cost of additional ground gas monitoring rounds and any improvement in confidence in the results that may occur. The benefits of the additional information and, more importantly, whether they are likely to change the scope of ground gas protection measures required at a development should also be considered, together with the consequences of failing to adequately characterise pollutant linkages (see Sections 7 and 8). It is imperative that ground gas investigations should always provide sufficient information to allow prediction of the worst-case ground gas regime and, therefore, enable a confident GQRA to be undertaken to design appropriate ground gas protection measures. As a result, a small data set may result in a reduction in the confidence of the risk assessment and increased ground gas protection measures, therefore, may be required to alleviate additional factors of safety and/or levels of confidence.

10.2 TYPES OF MONITORING INSTALLATIONS

The natural variability of ground gas concentrations across a site means that to gain confidence that the ground gas regime of a site has been accurately determined, large numbers of monitoring locations are generally required in proportion to the complexity of subsurface conditions.

A number of methods exist for the construction of monitoring points, ranging from simple probes inserted into soft ground to deep permanent wells targeting a specific horizon. **For all monitoring points, there must be an adequate seal around the top of the pipe to ensure that the readings being taken are of the ground gas, not atmospheric conditions or gases that are influenced by atmospheric oxygen.**

Intrusive locations may be either targeted or non-targeted, but whatever method is used it should be flexible enough to be able to adjust in response to conditions encountered during the intrusive works on site. It may be worthwhile to investigate any ground gas regime on site through the use of non-intrusive gas surveys (see Section 10.2.7), which may be able to allow a more refined targeted intrusive investigation to be undertaken.

However, it is important to note that not all monitoring points offer the same degree of accuracy and/or confidence in the results that are obtained. The main intrusive techniques are discussed within the subsequent sections and are listed in order of the amount of confidence the assessor may have in the information obtained. **The authors recommend that, in general and as agreed within the CIRIA guidance, ground gas monitoring standpipes installed within boreholes and probeholes (Section 10.2.1) are to be recommended, whilst soil nail techniques (Section 10.2.5) and standpipes in trial pits (Section 10.2.4) should be avoided at all costs as little confidence can be gained from the results.**

Table 10.2 is taken from CIRIA Report 152 (O'Riordan & Milloy, 1995) and indicates the key advantages and drawbacks of the main ground gas monitoring points. These issues should be considered when interpreting the results of any ground gas investigation (see Section 10.5).

Table 10.2: Advantages and Drawbacks of Different Ground Gas Monitoring Points (from CIRIA Report 152, 1995)

Technique	Advantages	Drawbacks
Spiking - metal spike pushed into the ground and removed, creating hole from which sample can be taken	Very quick, cheap and easy to use	Maximum depth 1m
		Very poor accuracy
		Hole may become blocked
		Confirms gas presence but not absence
Shallow probes - hollow rigid perforated pipe, sealed at top with connection to gas detection device, pushed into the ground	Quick, cheap and easy to install	Maximum depth 2m unless special tubes used
		Perforations can become blocked
		As for spiking, can only indicate gas present
Auger - a hand-held auger with extendable sections is used to bore into the ground	Cheap and simple to use	Physically difficult
	Allows sampling of solids	Cannot penetrate difficult ground
	Deeper than spiking/ shallow probes	Can be time consuming
Driven probes - hollow casing tube with solid nose-cone is driven into the ground mechanically, monitoring pipe installed inside the casing, casing extracted leaving nose-cone behind	Minimal ground disturbance	Cannot examine strata
	Light, easily portable machinery, thus access problems unlikely	Will not penetrate obstructions
	Normal maximum depth 10m	
Trial pits - a wheeled or tracked excavator is used to dig trenches, into which a perforated standpipe is placed and the pit backfilled with arisings	Relatively quick and cheap	Maximum depth 5m to 6m
	Allows inspection of the sample strata during excavation and can therefore form part of main ground investigation	Causes ground disturbance (must allow longer stabilisation periods)
		Backfilled material may allow venting
		May cause a hazard to public health and a danger to persons on site
		Spark arrestors needed for plant in hazardous areas
		Possible access problems
		Depth may be limited by collapse
		Brings contaminated material to the surface
Boreholes (cable-percussive) - a cased borehole is sunk by cable percussive techniques into which a perforated standpipe is installed with gravel surround, and the casing withdrawn	Great depth attainable	Relatively slow and expensive
	Minimal disturbance to ground	May have access problems (needs large area)
	Can install several standpipes in one borehole to	Brings contaminated material to the surface
	Can inspect and sample strata during boring and, therefore, can form part of main ground investigation	Spark arrestors needed for plant in hazardous areas
	Can be used to monitor groundwater	
Boreholes (rotary) - similar to above, but hole is drilled by a rotary tool and flushed with air or water	As above, but quicker than cable percussive techniques (especially air flush), relatively mobile rig	As above, but also air flush method does not prevent sparking, thus potentially hazardous on gassing sites
		Water flush can spread contamination
Surface sampling (flux boxes) - inverted container placed on site surface and gas is sampled via a valve	Gives an indication of gas emission rates at surface	Box is easily disturbed, so is usually used as a temporary installation
	Cheap and easy to install	Value of the information obtained is not certain
	Non-intrusive	

10.2.1 Gas Monitoring Standpipes

Monitoring standpipes are permanent installations inserted into boreholes, probeholes or trial pits. However, the use of the latter is to be discouraged (see Section 10.2.4). The standpipes are generally made of unplasticised poly vinyl chloride (uPVC), polypropylene or high-density polyethylene (HDPE) tubes, although ones made from aluminium are available for use when the ground contains highly aggressive organics[1].

Slotted or perforated sections are combined with solid (plain) sections to allow selective sampling of specific geological units. **Pipe sections should be connected with screwed/threaded ends rather than with glues and adhesives, which are to be heavily discouraged as their use can heavily distort ground gas readings.** Push-fit couplings are available, but are less satisfactory.

The diameter of the standpipe and the size and type of perforation may also affect the ground gas readings; therefore, records of the details of the installations should be kept and referred against when interpreting the results. However, there is research that the diameter of the standpipe may present no discernible difference in ground gas monitoring results (see Section 10.2.1.3).

10.2.1.1 Standpipes in Boreholes

Typically ground gas monitoring boreholes would be drilled during site investigation work and would be put to the dual purpose of supplying information on ground conditions and providing a monitoring location for collecting ground gas and groundwater data. Ground gas monitoring boreholes are suitable in situations where data is required from deeper strata. The design of the borehole should be finalised only after drilling has been completed to allow the most suitable geological horizons to be targeted for monitoring. To this end, suitably qualified field personnel should be present during drilling to record the geology of the borehole. A vandal-proof lockable cover should be provided for the finished borehole (either flush with the ground or up-standing, depending on specific site requirements).

The borehole dimension would typically be 150mm, allowing for the installation of a 50mm internal diameter standpipe. A filter pack of washed and uniformed size sand or gravel, of a larger size than the slots in the perforated section of pipe, should be placed around the perforated section of the pipe. This filter pack facilitates ground gas movement into the monitoring point and, therefore, should replicate the ground conditions wherever possible. The filter pack should not include the use of carbonate gravels as these can produce carbon dioxide.

A bentonite pellet seal suitably wetted, if required, should be placed approximately 0.20m above the top of the perforated section, to restrict the ground gas penetrating the standpipe to a specific geological unit. In addition, a bentonite pellet seal suitably wetted, if required, of at least 0.50m thick should extend from the ground surface within the borehole to prevent the ingress of atmospheric gases, particularly oxygen, which

[1] **Note:** for sites where aluminium standpipes are used, there would be a significant likelihood of hydrocarbon vapours being produced, which would heavily distort methane concentrations reported with an infra-red gas monitor (see Section 10.4.1.1). Alternative ground gas monitoring equipment may be required, which may have to be intrinsically safe.

may distort future ground gas readings and cause a reduction in the natural anaerobic conditions, if present, within the subsurface. However, depending upon the conditions, this upper seal may have to be substantially thicker in highly permeable deposits. An example detail for such an installation is included as Figure 10.3. Please note that although it presents a flush cover, a raised covers is equally as good, as long as surface water is prevented from entering the monitoring well.

Ideally, to allow recirculation of ground gas during monitoring, the standpipe should be fitted with a bung with two valves (not shown on Figure 10.3). A pipe should extend from one of these valves to the base of the borehole (or to just above the water table). This will ensure maximum recirculation and, as standard, the ground gas input to the analyser should come from the valve without the additional length of pipe.

The use of nested standpipes is included in some guidance documents (i.e. several pipes within the same borehole sealed with bentonite between the response zones of each standpipe) to allow analysis of ground gas from different horizons. However, the quality of results gained from these is highly variable due to the difficulty in adequately sealing horizons, particularly where the drilled horizon is small (i.e. less than 200mm). The use of nested standpipes, therefore, should be avoided.

The authors consider that it is better practice to install multiple boreholes within reasonably close proximity to each other to target different strata within the ground. However, care must be taken that the boreholes are suitably distanced from one another so as not to introduce atmospheric gases, particularly oxygen, which may distort future ground gas readings and cause a reduction in the natural anaerobic conditions, if present, within the subsurface.

Slight disturbance of the ground directly around the borehole is unavoidable, but there should not be a long-term effect on ground gas penetration if the borehole has been sealed appropriately and the ground gas composition will ultimately not be affected. The ground gas regime may need up to approximately a week to return completely to its original condition following completion of drilling, as atmospheric gases, particularly oxygen, will have been introduced into the borehole, which will skew any ground gas regime. However, monitoring at such a time may present interesting information on the recovery of the ground gas regime and rates of ground gas production. Indeed, monitoring immediately after borehole installation may, on occasions, be beneficial. For further information, see Section 9.1.

This technique is favoured in site characterisation exercises, with all other installation types providing data of reduced robustness due to a variety of reasons. A potential downside to the use of standpipes in boreholes is that the ground gas concentrations and flow rates noted at the base of the borehole, may have little relationship with the ground gas emission rates at the surface. The use of flux box methods (Section 10.4.1.3) may supplement borehole standpipe monitoring.

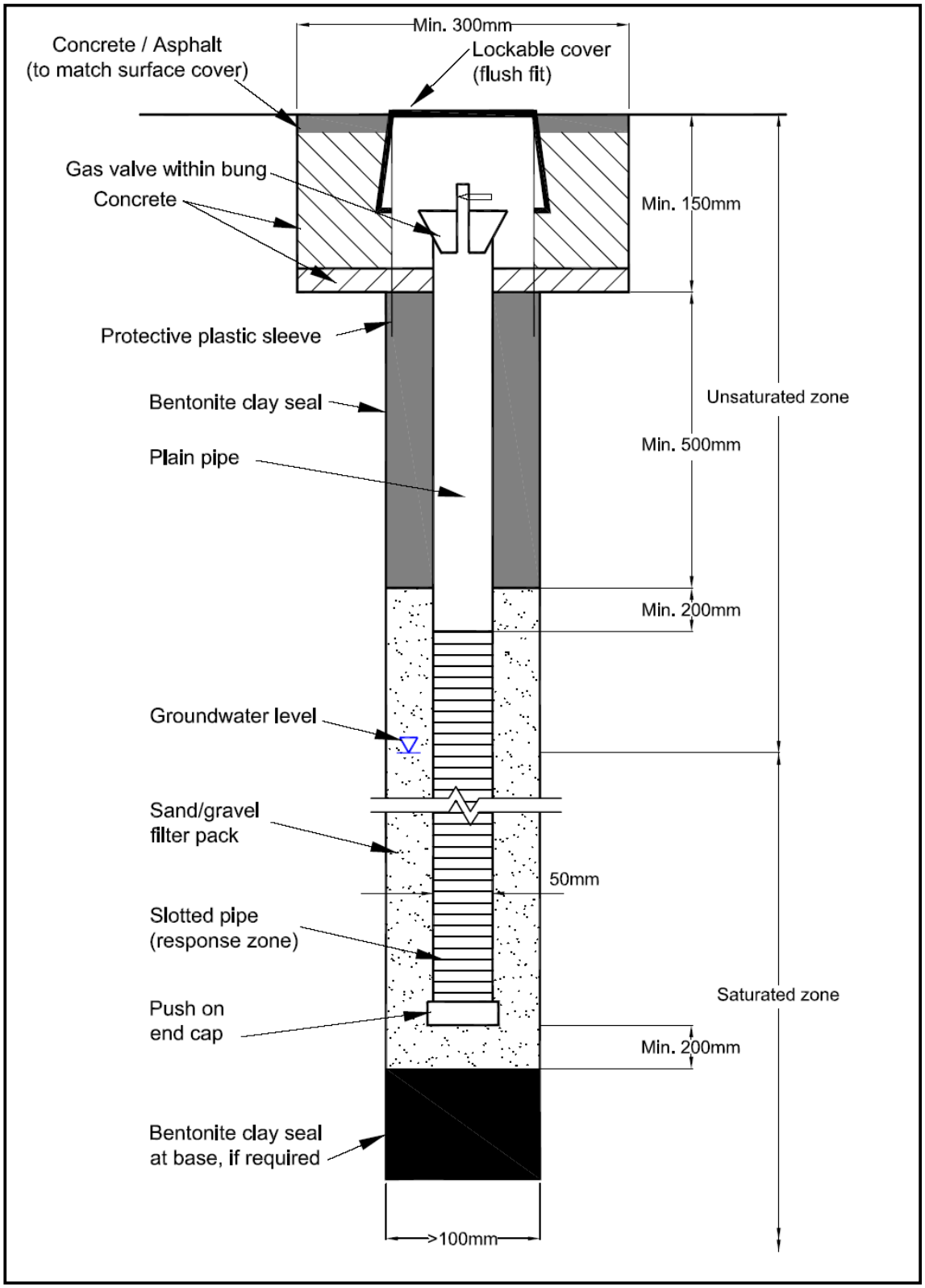

Figure 10.3: Example Ground Gas-Monitoring Installation in Borehole

10.2.1.2 Standpipes in Probeholes

Installations in probeholes are very similar to those constructed in boreholes and again Figure 10.3 shows standard installation details. However, sometimes the diameter of the standpipe installed is smaller, typically 35mm, 25mm or even 19mm internal diameter, as the probehole equipment may produce a narrower diameter borehole than a borehole rig in difficult ground conditions. Also, the depths obtained are generally shallower than those for boreholes.

10.2.1.3 Influence of the Internal Diameter of the Standpipe On Ground Gas Monitoring Results

There has been debate over the compatibility and comparability of ground gas monitoring results from monitoring points installed with different internal diameter standpipes. Wilson and Haines (2005) found no practical difference between ground gas monitoring results for both concentrations and flow rates obtained from 50mm and 19mm internal diameter standpipes installed within boreholes.

It is currently considered, therefore, that the lack of any correlation between different standpipe sizes is probably because the monitoring wells are normally left closed and do not vent continuously. As a result, the monitoring well is simply a space that comes into equilibrium with the ground gas regime. In addition, if there are any variations due the well diameter, it is possible that they are likely to be masked by a multitude of other variables in ground gas regimes, such as complex responses to, for example, temporal conditions.

The authors recommend that as there is still debate as to the reliability and applicability of comparing results from different internal diameter ground gas monitoring wells, they should all be constructed from 50mm internal diameter standpipes, if possible. This will allow for a direct comparability to the Traffic Lights presented within Section 14.

10.2.2 Spiking Techniques

This simple technique involves the formation of a hole in the ground by driving a steel spike to a given depth (often 1.00m below ground level [bgl]). Once the spike has been extracted, the concentration of ground gas within the hole is measured. This technique does not produce a permanent monitoring location, but can provide a quick and basic method of collecting larger volumes of ground gas data across a site. Some mixing of ground gas and atmospheric air will occur between the removal of the spike and insertion of the monitoring device, whilst mixing can also occur during sampling, as a good seal is difficult to achieve between the sampling tube and the top of the hole.

A key issue with this technique is that it can provide an indication of the presence and concentration of ground gas, but it cannot be used to prove the absence of ground gas. A spike survey is often carried out in conjunction with a preliminary intrusive investigation, such as trial pitting, before returning to site to install monitoring wells in boreholes.

10.2.3 Gas Probes

10.2.3.1 Shallow Hand-driven Gas Probes

Shallow probes are inserted directly into soft strata (such as peat) and are generally made of either plastic or galvanised steel pipes. A variety of such probes exist, ranging from perforated steel tubes, from which the ground gas sample is taken and then the pipe is removed, to semi-permanent probes, which are disposable and are left in place for monitoring after the initial sampling has been conducted. Heavy-duty probes could be driven to a depth of up to 4.00m bgl, given suitable ground conditions.

Problems with probes include smearing of the sides of the hole, especially in clayey subsurface materials, causing poor gas penetration into the probe. It is important to note that this technique can only be used to provide an indication of the presence and concentration of ground gas, but it cannot be used to prove the absence of ground gas.

10.2.3.2 Mechanically Driven Gas Probes

The technology associated with mobile ground probing systems is being improved constantly. These systems utilise weights and hydraulic equipment to drive probe rods into the ground. Ground gas samples can be obtained in a similar way to hand driven probes, but greater depths can be achieved, although this is still highly dependent upon the subsurface conditions.

The same problems with mechanically driven probes as hand driven probes exists, which includes potential smearing of the sides of the hole, causing poor ground gas penetration into the probe. Again, it is important to note that this technique can only be used to provide an indication of the presence and concentration of ground gases, not to prove their absence.

10.2.4 Standpipes in Trial Pits

It is possible to insert monitoring standpipes (again generally made of uPVC or HDPE) into trial pit excavations prior to backfilling. It should be considered that in this scenario, the ground has been disturbed and, therefore, it is not possible to obtain an entirely accurate picture of ground gas concentrations and flow rates. The type of material into which the trial pit has been excavated will have a significant impact on the efficiency of the monitoring location. A sheet of polythene should be placed across the trial pit close to the surface and sealed against the surrounding undisturbed ground in order to prevent air from the surface entering the monitoring well. In addition, a common mistake is to hastily infill the trial pit not taking care to avoid returning organic matter, such as plant material once at ground level, into the trial pit, as when this starts to degrade it will start generating methane, which may lead to ‘false-positive’ identifications in an area that may have no ground gas regime.

Standpipes in trial pits should not be relied upon as a sole means of information, but can be useful in supplementing more robust measurement techniques. Again, it is important to note that this technique can only be used to provide an indication of the presence and concentration of ground gases, not to prove their absence.

As a result of the above, it is generally accepted that standpipes in trial pits should not be used.

10.2.5 Soil Nail Techniques

This technique adopts the use of an instrument that fires a steel rod into the ground using a charge of compressed air. If a perforated tube replaces the steel rod, ground gas sampling can be carried out.

The main problem with this method of installing a monitoring location is that there is little control over the depth to which the probe is installed, as penetration will vary with ground conditions, whilst smearing is also possible. **Consequently, this technique is very rarely used and is not recommended.**

10.3 DEEP GAS SURVEYS

In some cases, it may be necessary to conduct an investigation for deep ground gases. Such situations include:

- Where the ground gas source is at depth (e.g. coal measures, mine gas or deep landfill);
- Where piled foundations are to be used for the development, or part of the structure is to be constructed at depth;
- Where the ground gas source may feed into permeable strata that passes beneath the site;
- Where deep buried structures (such as tunnels) are likely to pass through ground gas-bearing strata; and
- Where the subsurface conditions between a deep ground gas source and the development site are unknown.
-

10.3.1 Non-Intrusive Ground Gas Survey Techniques

Although the vast majority of ground gas investigations solely rely on intrusive techniques, there are non-intrusive techniques available that may be used within the PRA and ICSM stage of the investigation. Further, non-intrusive site work may be possible. If used, the results of non-intrusive works may aid the design of a targeted and cost-effective intrusive investigation. For more information, the reader is directed towards CIRIA guidance, although non-intrusive ground gas surveys may encompass those listed within Table 10.3.

Table 10.3: Non-Intrusive Ground Gas Survey Techniques

Non-Intrusive Ground Gas Survey Technique	Brief Overview
Non-Intrusive Techniques For Use Within PRA	
Aerial False Colour Infra-red Photography	Healthy and stressed vegetation, for example when methane is present, emit different infra-red spectra. Signs of stressed vegetation may be very subtle and not apparent to naked eye, but easy to identify when photographed using infra-red sensitive film. (*Note: film not generally superseded by digital techniques.*)
Aerial Thermography	Infra-red scanner used instead of conventional camera to locate areas of underground combustion and methane generation, as such areas will have a higher surface temperature.
Satellite Imagery/Aerial Photography	Based on aerial photography or locating satellite imagery for a 'birds eye' view of site and surrounding area. May be able to identify, for example, historical mining features.
Hyperspectral Scanning	Based on the use of an optical scanning technique fitted to an aircraft.
Non-Intrusive Techniques For Use On Site	
Internal Gas Survey	Use of a portable flammable gas detector within buildings/structures or in the area of services/voids. May not be intrinsically safe.

10.4 MONITORING PARAMETERS AND ASSOCIATED OBSERVATIONS

Two example pro formas for recording site-based ground gas monitoring data are contained within Appendix C, both of which have been partially filled out with example comments. The first pro forma (Table C1) is for use with multiple monitoring installations at a site, whilst the second pro forma (Table C2) is for use with only one monitoring installation. For Table C1, the peak and steady state concentrations of methane, carbon dioxide and oxygen should be recorded, together with the ranges of flow rate detected. Table C2 sets out set times from initial (zero seconds) to 600 seconds (10 minutes), although the monitoring may require substantially more or less time than this on a site- and monitoring installation-specific basis.

The monitoring steps should generally be completed as both pro formas are read from left to right, top to bottom, which is also in the order as listed below:

1. Site and job/reference number, together with the time and date of monitoring;
2. The reference number of the monitoring point being monitored;
3. Ground gas flow in litres per hour (l/hr). For Table C1, the initial flow rates should be recorded and a note made of what the steady flow decreases to, together with what the steady flow rate is. For Table C2, the flow rates should be recorded at the set intervals.
4. Borehole pressure in Pascals (Pa). It is often possible to record at the same time as flow rate (Item 3);
5. Concentrations of methane, carbon dioxide and oxygen as follows:
    A. Methane in percentage by volume (CH_4 %v/v) and as a percentage of the Lower Explosive Limit (CH_4 % LEL), the latter of which can be worked out back at the office. For Table C1, both the initial and steady states should be

recorded, together with the time it takes to become steady. If the concentration does not become steady, record the length of time monitoring occurred, which should typically not be less than 10 minutes. For Table C2, the concentrations should be recorded at the set intervals.

B. Concentration of carbon dioxide in percentage by volume (CO_2 %v/v). For Table C1, both the initial and steady states should be recorded, together with the time it takes to become steady. If the concentration does not become steady, record the length of time monitoring occurred, which should typically not be less than 10 minutes. For Table C2, the concentrations should be recorded at the set intervals.

C. Concentration of oxygen in percentage by volume (O_2 %v/v). For Table C1, both the initial and steady states should be recorded, together with the time it takes to become steady. If the concentration does not become steady, record the length of time monitoring occurred, which should typically not be less than 10 minutes. For Table C2, the concentrations should be recorded at the set intervals.

6. Concentration of other ground gases[2], usually carbon monoxide (CO) and hydrogen sulphide (H_2S) in parts per million (ppm);
7. Depth to water in metres below ground level (m bgl)[3];
8. Name and position of the person carrying out the monitoring;
9. Atmospheric pressure (millibars, mb) at the time of monitoring. Also record the range if it changes during the monitoring at the site, together with if it is rising or falling;
10. The weather conditions, including, for example, wind, precipitation, frost, etc.;
11. The temperature in degrees centigrade (°C), noting the operating range of the equipment in use (for infra-red gas monitors it is typically between -10°C and +40°C);
12. The equipment used and the next date of calibration;
13. Any visible signs of vegetation stress at the site, especially within the vicinity of the monitoring point;
14. The reference numbers of the monitoring points sampled for submission to an analytical laboratory; and
15. Any other comments and/or observations deemed pertinent.

Several of the more important parameters are discussed in greater detail in the following Sections of this Report.

[2] **Note:** The exact components of ground gases that may need to be measured can vary considerably if the source gas identified within the PRA and ICSM is a nearby landfill. As a result, this will affect the equipment used.

[3] **Note:** It is imperative that the depth to water is recorded after the ground gas flow rates and concentrations, as this involves removing the monitoring well bung, which will release all ground gases to the atmosphere.

10.4.1 Methods of Measuring Specific Parameters of Ground Gases

Hartless and Collins carried out a study of currently available techniques used in ground gas monitoring in their paper entitled 'Investigation of Techniques to Measure Flows of Landfill Gas from the Ground'. They documented the instruments that can be used, their specific applications, and how they compare to each other. This is supplemented by CIRIA Report 131 (Crowhurst & Manchester, 1993) and earlier BRE work by Crowhurst (1997), which lists instruments capable of measuring specific ground gases and their limitations. Further, the new CIRIA document brings the potential equipment that may be used up to date and should be consulted for further information.

The sections below give brief details of the parameters that can be measured as part of a ground gas survey and the most suitable methods. For further information, we would recommend consulting any of the documents described above.

10.4.1.1 Ground Gas Flow Rate

The purpose of measuring ground gas flow rates is to predict surface emissions and from these deduce the potential for ground gas ingress into properties.

Where ground gas flow is measured, it is necessary to provide further information from the monitoring location. For example, in order to allow the quantity of the constituent gas to be determined in a specific volume of gas, the pressure (Section 10.4.1.4) and temperature of the gas will be required, along with the composition.

Instruments used for monitoring ground gas flows include hot wire anemometers, rotating vane anemometers, Pitot tube and orifice plate/constricted tube systems. These instruments all measure gas velocity, which is converted to gas flow by applying monitoring pipe dimensions, etc. Flow can also be measured directly by using a bubble flow meter or rotameter.

The ground gas flow can be used to determine the ground gas emission rate, but there is no set way of correlating these two parameters. Several techniques could be adopted for assessing the results. A worst-case scenario would involve taking the highest measured flow rate, and correcting this to provide an emission rate per square metre for the site as a whole. A less cautious approach would be to assume that the flow measured in each borehole relates to an approximate surface area of $10m^2$, which was proposed by Pecksen (1985) and was further expanded by Ove Arup & Partners (1996) for computational fluid dynamics modelling to predict the suitability of passive protection measures. The emission rate from the surface of the whole site could then be calculated.

Purging tests can be used in scenarios where very low ground gas flow rates are present. This involves flushing the installation with an inert gas (preferably nitrogen or helium). Once no further ground gases are detected in the gas stream, purging ceases and the concentrations are given time to recover. An instrument would then be used to determine ground gas concentrations (with the expelled gas being recirculated), and the change in concentration is measured over time. Godson and Witherington (1996) devised a method of using purging tests, and included in their paper a spreadsheet that allows the change in methane volume to be converted into methane flow rate.

The flow of a ground gas can refer to both the volume of gas being emitted from a monitoring well per unit time, and the movement of gas through permeable strata. In comparison, the emission rate is used to describe the volume of ground gas that is released from a unit area of ground surface.

10.4.1.2 Ground Gas Composition (Concentration)

The composition of ground gases are always measured as part of a ground gas study, but the means by which it is measured may vary. Field instruments are available for determining ground gas concentrations, whilst laboratory analytical methods can also be used. Field-based monitoring of methane, carbon dioxide and oxygen should be reported as percentage by volume (%v/v) of both initial and steady state concentrations, whilst methane should also be reported as a percentage of the Lower Explosive Limit (% LEL). Other gases should be reported in parts per million (ppm).

Concentrations of the gases are of vital importance, as it is the ratios of gases within the ground gas that will determine asphyxiant properties or the risks due to explosion or toxicity. The limitations of the method utilised should always be considered when interpreting results.

Recirculation of ground gas is the preferred composition measurement technique, as it provides a more accurate indication of subsurface conditions.

Conditions within the Monitoring Well

The drilling and installation of monitoring wells will introduce artificially high concentrations of oxygen into the ground, thus allowing aerobic conditions to develop. Biological micro-organisms in the ground that thrive in such conditions will not generate methane, although they will generate carbon dioxide. Any trace amounts of methane generated would typically be expected to be readily oxidised. As the micro-organisms consume the oxygen, the ground conditions will revert back from aerobic to anaerobic (oxygen deficient). At which time, micro-organisms that thrive in such conditions will succeed the aerobic micro-organisms, the production of methane will recommence and the ground gas regime will revert back to that before any disturbance of the ground occurred before drilling. Notwithstanding the above, initial monitoring rounds may yield important information regarding the reversion of the monitoring well from aerobic to anaerobic conditions, which may help in assessing the methane generation potential of the ground.

Hydrocarbon Interference of Infra-Red Gas Monitors

Although it is highly likely that during the installation of the monitoring point the subsurface ground conditions would have been logged according to British Standard BS 5930 (1999) ‘Code of Practice for Site Investigations’ in conjunction with the guidance contained within British Standard BS 10175 (2001) ‘Investigation of Potentially Contaminated Sites – Code of Practice’, it is possible that hydrocarbon gases and/or vapours may be present. The presence of other hydrocarbons may interfere with the operation of infra-red gas monitors, since methane is filtered at a frequency specific to hydrocarbon bonds. Therefore, if other hydrocarbons are present within the sample

(e.g. ethane, propane, butane or even petroleum vapours), the reported methane reading will be higher (never lower) that the actual methane concentration being monitored. The extent to which the methane reading is affected depends upon the concentration of the methane in the sample, the types of hydrocarbons present and the concentration(s) of the other hydrocarbons. The effect is non-linear and difficult to predict.

Therefore, the authors consider that during the site investigation all soils should be screened during logging using a photo-ionisation detector (PID). In addition, during the first ground gas monitoring round, all monitoring points should also be monitored with a PID and the concentration (in ppm) of hydrocarbons be recorded. Further, a proportion of the monitoring point samples should be submitted to an analytical laboratory. If the PID records levels of hydrocarbons, alternative ground gas monitoring equipment should be used.

Under no circumstances should the concentration of methane present be 'calculated' by subtracting the contentions of the other hydrocarbons.

10.4.1.3 Gas Screening Value

Gas Screening Values (GSVs), which equate to the borehole ground gas volume flow rate, as defined by Wilson and Card (1999) as the borehole flow rate multiplied by the concentration in the air stream of the particular gas being considered have been calculated from a risk-based methodology for deriving threshold concentrations for gas flow rates (see Section 14). This approach is consistent with CIRIA Report 659 (2006) that was written at the same time as this report (see Section 1.1).

The Gas Screening Value (GSV) of a particular ground gas being considered equates to:

- GSV (l/hr) = borehole flow rate (l/hr) x gas concentration (%v/v).

10.4.1.4 Ground Gas Surface Emission Rate

This parameter is the volume of ground gas escaping from a unit area of ground in a unit of time. The Environment Agency (LFTGN 03, 2004a) states that the flux box is currently the most cost-effective technique for the verification of methane and carbon dioxide surface emissions from landfills.

Flux boxes are enclosed chambers used to measure the rate of change in ground gas concentrations above a specific, small area of the ground surface. This involves the placement of an open-based box on the ground surface, as shown diagrammatically in Figures 10.4 and visually in Figure 10.5). By measuring the flux at a number of representative sampling points, an estimate can be made of the total emissions from a zone.

Once equilibrium has been achieved in the box, the concentration of different ground gases within the emission gas is measured, along with the flow rate. It must be noted that the presence of the box may alter the ground gas conditions in a minor way.

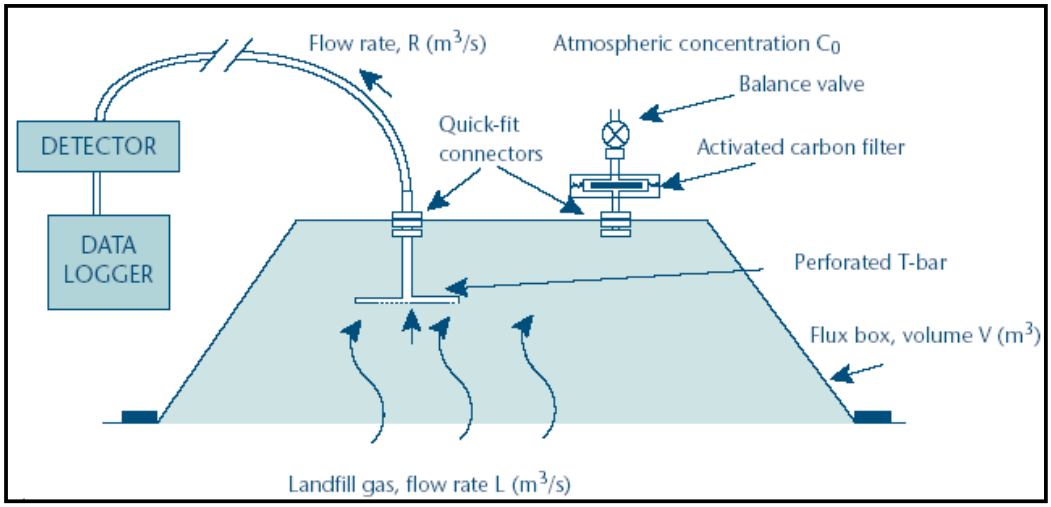

Figure 10.4: Schematic of a Flux Box for Surface Emissions of Gas Measurement (from Environment Agency LFTGN 03, 2004a)

Figure 10.5: Photograph of a Flux Box for Surface Emissions of Gas Measurement

A major advantage of the flux box technique is that it provides data on the emission rates of ground gas over a given surface area, which can then be related directly to volumes that will accrue in buildings. Industry experience suggests, however, that this technique is very rarely employed during site investigations.

For further information, the Environment Agency (2004a) document 'LFTGN 03: Guidance on the Management of Landfill Gas' should be consulted.

10.4.1.5 Ground Gas Pressure

Atmospheric pressure should always be recorded alongside ground gas concentrations. In addition, the pressure of the ground gas within the monitoring well should also be measured. However, despite this being possible with most gas analysers, it is less often logged, principally as there is a lack of guidance on how to interpret the results. Problems are also presented in that the act of sampling the pressure affects the pressure, unless a technique that recirculates the gas is employed.

Experience shows that a gas under pressure will travel greater distances in the subsurface and will be more capable of penetrating ground gas membranes and migrating via buried structures. Increased borehole pressure is included as a risk factor within CIRIA Report 149 (Card, 1995). **As a result, ground gas pressure within monitoring wells should always be recorded.**

10.4.1.6 Ground Gas Generation Rates

The ground gas generation rate is the amount of gas produced per unit mass or volume per unit time. It is far more complicated to measure ground gas generation rates rather than flow or emission rates. Therefore, measurements of ground gas generation rates are uncommon within site investigation practices. This is a drawback on many ground gas-impacted sites, as the rate of generation is very useful in determining the risk posed by ground gases. This parameter would also provide details on the likely term of the ground gas generation capabilities of a specific ground gas source, thus indicating how long a hazard due to ground gases may exist.

Ground gas pumping tests can be employed to determine a gas extraction rate that balances with the gas generation rate. The main use for such tests is in determining the viability of extracting gas from landfill sites for commercial purposes.

10.4.1.7 Automatic Data Logging Equipment

Equipment is available that functions automatically and virtually continuously, if required. This type of apparatus could be used to supplement a manual monitoring exercise, and provides a greater degree of accuracy. Two significant uses of continuous logging of ground gases would be where the groundwater is subjected to tidal influences (see Section 6.2) and obtaining an increased number of readings of atmospheric pressure, which is important in developing the CSM and assessing worst-case conditions at a site.

Edwards and Huish (1996) in 'The Study Of Hazardous Subsurface Gases By The Use Of Automatic Data Logging Equipment' provide further information on the use of such equipment.

10.4.1.8 Biological Methane Production Tests

It is possible to take representative samples of subsurface materials that are considered most likely to generate methane gas and submit them to a laboratory for a Biological Methane Production Test. Biological Methane Production Tests are carried out under

strict laboratory conditions and are designed to establish theoretical maximum gas generation rates from the soils.

10.5 ASSESSMENT AND INTERPRETATION OF GROUND GAS MONITORING RESULTS

Interpretation of results of the ground gas investigation is very complex and requires good characterisation of the ground gas regime at the worst temporal conditions any site may experience. It is important that the CSM for a ground gas regime (see Section 8) allows the relationship between ground gas measured at monitoring locations (and ground gas present across the site generally) and, hence, potentially within the buildings to be determined.

Once the site investigation has been completed, the next step is to ensure that the information gathered is sufficiently reliable to show that the intended development can be constructed safely (either with or without the incorporation of ground gas protection measures, as appropriate, see Section 11). However, the varying constraints to the reliability and credibility of the different ground gas monitoring points (Table 10.2) should be fully appreciated and taken into account. In particular, it should be noted that some ground gas monitoring points can only be used to provide an indication of the presence and concentration of ground gas, but cannot be used to prove their absence, whilst the results from some monitoring points are so doubtful that they should not be used at all.

It should be noted at this stage that the monitoring data will be indicative of conditions at a given location and time, and that longer periods of monitoring data may be required where complex ground gas regimes are encountered. The monitoring programme should aim to incorporate a variety of atmospheric conditions and, in particular, the worst-case temporal conditions that a site may experience (see Sections 9 and 10).

Problems to be aware of include the stratification of the ground gases within the monitoring installation due to density differences of the constituent gases, which is likely to occur when the gas valve is left closed between monitoring visits. However, leaving the gas valve open between monitoring visits will allow mixing of air with ground gas, which will produce a markedly different gas composition reading than if the valve had remained closed, principally due to the introduction of oxygen. With the valve open, air diffusion into the standpipe will be driven by wind, changes in atmospheric pressure or ground gas pressure. Where larger diameter standpipes are used, and where low ground gas flows are present, this will have a much greater impact on recorded results.

Useful results can be gathered by sampling under both conditions (i.e. with the valve closed, and then following a period of the valve being open), as characteristics of ground gas flow can be determined, which will allow for refinement of the risk assessment.

Another difficulty is that whilst high concentrations of ground gases are sometimes recorded, this does not always constitute a greater risk. Often the risks associated with low concentrations can be of more significance where flows are substantial. Consultation of property designs are important when interpreting the results and assessing the risks, as the presence of carbon dioxide may be more important than the presence of methane, for example, in buildings likely to have basements.

When assessing the results, consideration should be given to the requirement within the revised version of Approved Document C (DTLR, 2004) of The Building Regulations 2000, for a ground gas risk assessment to be carried out where ground gas issues are likely to exist.

10.6 CURRENT PRACTICE IN GROUND GAS INVESTIGATIONS

CIRIA Report 150 (Raybould *et al.*, 1995) includes a review of the current procedures in use for ground gas monitoring in the UK. This involved a literature review, a review of site investigation practices used by experienced practitioners and a review of the site investigation procedures required by the statutory authorities. Key conclusions identified included the fact that although it can often be seen that there is an inconsistency between the approaches adopted by practitioners, this can often be at odds with the expectations of statutory bodies. This is likely to be a result of the limited amount of guidance relevant to development on sites where the source of the ground gas is other than a landfill site. Further, it was noted that the statutory authorities often adopt an inflexible approach based on the existing guidance. This is mainly due to the lack of appropriate guidance for sites other than landfills, and a lack of experience or understanding of the standards for site investigations.

Current practice in the United Kingdom is led by the statutory documents that are available and by a number of guidance documents. The key statutory documents are the Building Regulations (1991) (specifically Approved Document C), BR414 (Johnson, 2001), which first introduced concentrations of 1.0%v/v methane and 1.5%v/v carbon dioxide, and circulars relating to control of landfill sites issued by the Environment Agency. These, and much of the guidance, are targeted specifically at sites where the sources of the ground gases are landfill sites. It has been recognised for some time that there is a scarcity of guidance relating to brownfield sites, where the source of ground gas is more commonly made ground or decomposition of small amounts of waste.

CIRIA Report 150 (Raybould *et al.*, 1995) includes a comprehensive discussion on the requirements of a ground gas study, from the preliminary stages of the PRA to the intrusive investigation and any supplementary investigation that may be required based on the findings. As part of the document, a literature review of available guidance was carried out and can be summarised as follows:

- Guidance is mainly generic and is not straightforward to apply to site-specific scenarios;
- Guidance focuses on landfill sites, rather than sites adjacent to landfills, or where the ground gas source is not a landfill;
- Some inconsistencies relate to monitoring periods and the best techniques to apply during monitoring;
- The general nature of the guidance often results in recommendations being unspecific;
- Attempts to standardise an approach to treating ground gas-impacted sites may lead to over cautiousness and, consequently, over-engineering of developments to incorporate ground gas protection measures; and

- There is no information on the best way to assess results.

Despite these shortcomings, there are also aspects in the guidance that are very useful, including the requirements for collation of site-specific data (during the PRE and undertaking intrusive investigations), and the involvement of experts in determining the actions necessary, including design of any ground gas protection measures, based on the results obtained.

Some local authorities would require that the following recommendations be adhered to when considering ground gas requirements for new developments, as detailed in Waste Management Paper 27 (DoE, 1991):

- Where methane concentrations by volume are greater than 1.0%v/v, further advice should be taken;
- Carbon dioxide levels of between 1.5%v/v and 5.0%v/v would generally mean that some of the ground gas protection measures recommended in BRE (1991) would be adopted; and
- Carbon dioxide levels of over 5.0%v/v would result in ground gas protection measures being a requirement.

However, it is necessary to recognise that these figures were developed for landfill sites, and information aimed at other gassing sites has since been produced, which recommends a risk-based approach (Environment Agency, 2003, & LTLR, 2004).

It is now recognised that ground gas protection measures should ideally be passive for residential developments (i.e. not requiring the use of alarms or mechanical devices), and it is very rare that any different approach would be utilised. Further, it is rare that Building Control bodies (Local Authority building control (LABC) and Approved Inspectors, including the NHBC) enforcing compliance with the Building Regulations would approve other ground gas protection measures.

10.7 RECOMMENDED PRACTICE IN GROUND GAS INVESTIGATIONS

The key objective in any ground gas monitoring exercise should be that of determining the ground gas concentrations and flow rates during the worst-case temporal conditions that any site may experience, and this should be kept in mind at all times. The gas-monitoring programme should be designed around achieving readings that, with interpretation, will provide information on this. Table 10.4 lists details relating to various issues that should be considered during the design of a ground gas monitoring survey.

The most measured parameter in ground gas monitoring surveys is the concentration of gases. The reliance on this measurement often means that parameters such as ground gas flow and ground gas emission rates are overlooked. The main impact of this approach is that it is more problematic to adopt a risk-based method to apply necessary remediation actions to an impacted site.

It is generally the view that ground gas flow rates should be more widely measured as part of investigations. This requires increased timescales for monitoring, but provides better confidence in the data collected.

The wide variety of monitoring installations that are used means that it is often difficult to compare data from different sites.

Previously, considerable weight has been given to the recommendations given in various reincarnations of Approved Document C (DTLR), requiring further consideration of necessary actions where the methane percentage exceeds 1.0%v/v. In addition, carbon dioxide concentrations of greater than 1.5%v/v require consideration of what gas measures may be appropriate, and more specific solutions are likely to be necessary at 5.0%v/v carbon dioxide. However, the latest fully revised version of Approved Document C (DTLR, 2004) no longer endorses this approach, and guidance is included to use a risk-based approach in interpreting the findings of a ground gas monitoring survey.

Table 10.4: Summary of Recommended Practice in Ground Gas Investigations

Issue	Comments
Installation Type	Ground gas monitoring boreholes are the most reliable and, in the majority of cases, other methods should be considered to provide indicative results only. However, information from the CSM should be reviewed in order to determine the most appropriate techniques for a specific site. Borehole standpipes should be standardised at an internal diameter of 50mm.
Gas Valve	The gas valve on the installation should be left open where flow rates are high, and closed where flow rates are low (in this case, stratification may occur, which should be combated by recirculating the ground gases during sampling).
Sampling	Recirculation of ground gases should be used in all cases except where the amount of gas being generated exceeds the amount being removed by the monitoring instrument.
Duration of Monitoring	Minimum requirement is fortnightly monitoring of ground gases for three months (six monitoring results) with at least one during the worst-case temporal conditions a site may experience.

Although regulatory bodies have set thresholds for some solid and liquid contaminants, this is not a viable option for ground gases. The main reason for this is the changeable composition of ground gases, the generation of which is often highly variable and dependent on many other issues.

With the safety of site users being the overriding concern with respect to ground gas on a site to be developed, the key concern is at what concentration of the harmful gases is it considered safe. In the case of flammable gases, the safe concentration can be considered to be below the lower explosive limit of the gas. For hazardous, toxic or asphyxiant gases, the occupational exposure limit or the concentration at which the gas becomes asphyxiating is adopted. However, applying these limits in practice becomes highly problematic, because it is not feasible to constantly monitor ground gas concentrations. In addition, the variable nature of gas generation and gas flows means that even if a site has been shown to have generally low concentrations of harmful gases, this cannot be guaranteed under all environmental and/or temporal conditions. Taking this into consideration, a margin of safety above the ground gas concentration could be considered. However, this in itself causes the further question as to what could be deemed an acceptable error margin.

In an attempt to overcome the problems associated with the above, this report sets out a series of 'Traffic Lights' where the use of certain ground gas protection measures should be used for residential developments. Further, upper limits are proposed: if these are exceeded, residential developments should not occur. For further information, please see Section 14.

10.7.1 Over-Engineering

Comments have been made that due to the lack of a formal, recognised system for grading sites affected by ground gas issues, statutory consultees are requiring over-engineered solutions for ground gas protection measures (see Section 12). This often results in developments incurring prohibitive costs, which in turn means that brownfield sites may remain undeveloped, while further greenfield sites are targeted.

The attitude of regulatory bodies is often necessarily conservative, but this can be taken to extremes in the absence of definite guidance on ground gas issues.

Again the 'Traffic Lights' set out within Section 14 aim to address this issue.

10.7.2 Guidance Documents

A number of guidance documents exist that are widely used by developers, regulators and insurers in determining requirements for conducting an adequate ground gas survey, and methods for interpreting the results. The most extensively used of these documents are summarised in Appendix A.

11. AN APPROACH TO RISK ASSESSMENT

11.1 INTRODUCTION

Risk assessment is defined as "the formal process of identifying, assessing and evaluating the health and environmental risks that may be associated with a hazard".

As introduced within Section 1.2, the Environment Agency's (2004) 'CLR11: Model Procedures for the Management of Land Contamination' and associated documentation considers that three tiers of risk assessment for the specific context of land contamination are as follows:

1. **Preliminary Risk Assessment (PRA).** Used to develop an Initial Conceptual Site Model of the site and establish whether or not there are potentially unacceptable risks. Information collection may include that arising from a desk study, site reconnaissance and possible exploratory site investigation.
2. **Generic Quantitative Risk Assessment (GQRA).** Generic assessment criteria are derived using largely generic assumptions about the characteristics and behaviour of sources, pathways and receptors. These assumptions will be conservative in a defined range of conditions. Information collection may include that from a staged intrusive site investigation, data review and analysis.
3. **Detailed Quantitative Risk Assessment (DQRA).** Site-specific assessment criteria are values for concentrations of contaminants that have been derived using detailed site-specific information on the characteristics and behaviour of contaminants, pathways and receptors, and that correspond to relevant criteria in relation to harm or pollution for deciding whether there is an unacceptable risk.

This report refers to terms as defined above from CLR11 throughout.

The term 'risk' is widely used in different contexts and circumstances, often with differing definitions. In Government publications about the environment, most notably since the Department for Environment, Food and Rural Affairs, Environment Agency and Institute for Environment and Health (2000) jointly commissioned report 'Guidelines for Environmental Risk Assessment and Management', it has been given the following standard definition:

> "Risk is a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence."

At the outset of the risk management process, the context of the problem and the objectives of the process must be identified. This forms the starting point for risk assessment, which provides a structured mechanism for identifying risks and making judgements about the consequences. Risk assessment is an essential component in achieving effective management of the risks from land contamination and, as such, underpins both Part IIA of the Environmental Protection Act 1990 regulatory regime and current planning policy.

A key issue to consider in evaluating gassing sites is the safe concentration(s) of ground gas(es) that can be present within a building. Any risk assessment and design for ground gas ingress preventative measures must ensure that the lower explosive limit for methane (i.e. LEL of 5.0%v/v) and the Short Term Occupational Exposure Limit (15 minute period) of carbon dioxide (i.e. STOEL of 1.5%v.v) can never be reached.

Figure B1 within Appendix B outlines a flow chart that is intended to be an easy-reference staged list of the steps that should be followed during a site investigation and risk assessment for development on a site with a potential to emit ground gases. The flow chart provides further information that should be considered in the risk assessment and how it is linked with the overall development process.

11.2 OBJECTIVE OF RISK ASSESSMENT

The principal objective of a risk assessment is to determine as accurately as possible the potential risks on a site as a result of any contamination issues. This report deals solely with risk assessments in relation to ground gases and not all risks that may be present on a site. **It is important to note that this document does not include guidance and best practice for any development impacted by radon.**

The risk assessment is constructed upon a considerable quantity of information, which is typically collected gradually throughout the site investigation process. Where hazards are initially identified, either in the PRA or in preliminary intrusive work, these will be specifically investigated in greater detail in subsequent stages of investigation so that the problem is better delineated. This will allow for GQRA and, if required, DQRA to be carried out.

It is important that the CSM and risk assessment takes into account changes to the ground gas regime due to the impact of the development itself. For example, the use of piled foundations will impact the subsurface conditions, potentially affecting ground gas movement by causing a linkage between, for example, a deep peaty horizon once sealed through the existence of an impermeable clay layer. Covering a site with hardstanding and buildings will effectively seal off the emission of ground gases to atmosphere, which will cause a build up.

11.3 ADOPTION OF A RISK-BASED APPROACH

As part of the risk assessment process, it is vital to recognise that the risks may vary depending on the development type, the properties of the ground gas(es), the type of receptor and the intervening pathways.

It is slowly becoming more acceptable to adopt a risk-based approach in determining the necessary actions for ensuring that a ground gas-impacted site does not result in harmful conditions for the site user.

The revised version of Approved Document C (DTLR, 2004) recommends that a risk-based approach be adopted in reviewing sites where ground gas is found to be an issue. An Environment Agency consultation document on building developments on or within 250m of landfill sites (closing date for responses October 2003) has been in circulation for some time, which also sanctions the use of a risk-based approach in preference to the cut-off approach such as that developed in Waste Management Paper 27 (DoE, 1991).

The latest Environment Agency documentation on landfill gases (LFTGN 03, 2004a) continues to sanction the use of a risk-based approach through a structured approach to the assessment of the risks.

11.4 STAGES OF RISK ASSESSMENT

The risk assessment process generally involves several steps, as outlined below, which should allow for a transparent and practical process to aid decision-making (Environment Agency, 2004a):

1. **Identification of Hazard:** this involves the development of an ICSM, which should include establishing contaminants present and their source(s), identifying sensitive receptors on or near the site, and delineating the pathways or routes along which the contaminants may travel from the source to the receptor. This stage of the investigation would normally be restricted to a comprehensive review of desk-based information with a brief site walkover. CLR11 terms this stage as the Preliminary Risk Assessment (PRA). With ground gases, the following issues should be identified:
    A. The sources of the ground gases;
    B. The ground gas distributions;
    C. The ground gas concentrations;
    D. The rates of ground gas generation; and
    E. The potential for future ground gas generation.
2. **Assessment of Hazard:** this stage involves more detailed investigation of the issues identified in the hazard identification stage, with additional information being collated and preliminary intrusive investigation work being undertaken. The principal aim of this stage is to more completely understand the contaminant pathways and potential risks. Some interpretation of results of site work will be made based on generic criteria. CLR11 terms this stage as part of the Generic Quantitative Risk Assessment (GQRA).
3. **Receptor Characterisation:** potential targets of the contamination should be identified. Consideration should be given to toxicity and explosive nature of components of ground gas. CLR11 terms this stage as part of the Generic Quantitative Risk Assessment (GQRA).
4. **Pathway Characterisation:** the potential pathways leading to exposure of a receptor should be identified. CLR11 terms this stage as part of the Generic Quantitative Risk Assessment (GQRA).
5. **Estimation of Risk:** this section of the risk assessment process would involve identifying all possible consequences due to actions of the contaminants on the receptors. A review of the potential magnitude of these consequences would also be made. Detailed ground investigation will be carried out during this phase to augment information already gathered. This will include further information of contaminants and concentrations. CLR11 terms this stage as part of the Generic

Quantitative Risk Assessment (GQRA), whilst any detailed risk modelling will be termed a Detailed Quantitative Risk Assessment (DQRA).

6. **Evaluation of Risk:** the risk evaluation stage results in decisions being agreed upon as to whether risks posed to sensitive receptors are unacceptable or not. Any assumptions made during the risk assessment process will be taken into account within this risk evaluation phase. This stage should compare the levels of risk to associated background levels in the area and the generally acceptable levels. CLR11 terms this stage as part of the Generic Quantitative Risk Assessment (GQRA), whilst any detailed risk modelling will be termed a Detailed Quantitative Risk Assessment (DQRA).
7. **Remedial Design:** if the risk assessment indicates that the ground gas concentrations and/or emission rates are unacceptable, potential remedial options should be investigated. CLR11 terms this stage as part of the Options Appraisal to mitigate the risk.

11.5 DEFINITIONS OF RISK

In order for the risk assessment process to be effective, the input data must be as accurate as possible. The accuracy of data will impact on the degree to which the risk can realistically be reduced based on the known information. One of the key inputs is a list of the hazards that may potentially occur at the site. In this context, a hazard is defined as a situation with the potential for human injury, damage to the environment or that incurs financial loss. The risk associated with this hazard is then defined as the likelihood of this hazard occurring. Therefore, it can be said that:

Risk = Hazard x Vulnerability

(Equation 1)

Equation 1 is used throughout risk assessment, not just in the field of ground gas investigations. In practical terms, lessening either the magnitude of the hazard or the degree of vulnerability can reduce the risk. On a brownfield site, if the source of ground gas cannot be removed or has not been identified, there are options for integrating mitigation measures into the newly built housing or into cover systems in the ground. The severity of the ground gas problem on a site will dictate the remediation measures that may need to be employed and the ground gas protection measures that may have to be installed within the properties.

A second equation can also be used to determine risk at a given site:

Risk = Probability x Consequence

(Equation 2)

In this case, the probability (frequency) at which the hazard occurs and the magnitude of the consequences of the given hazard both directly influence the scale of risk that is perceived to occur at a site (see Section 11.6 for more information).

11.6 CLASSIFICATION OF RISK

In order to carry out an effective risk assessment, it is first necessary to classify the site in terms of the source of pollutant, migration pathways, the available investigation data and potential future changes to the site situation (i.e. how it is to be developed). This is effectively the production of the CSM, as discussed within Section 8.

Once the site investigation has been carried out the GQRA will be required to evaluate potential risk in descriptive terms. Tables 11.1 to 11.4 are taken from CIRIA C552 (Rudland *et al.*, 2001) 'Contaminated Land Risk Assessment – A Guide To Good Practice' and describe the risk evaluation process in greater detail when establishing the risk from the probability and consequence of the event (Equation 2), as determined using the matrix presented within Table 8.1. To get to this stage, first the magnitude of the probability is considered (Table 11.2) and then the extent of the potential consequences is considered (Table 11.3). The combination of the consequence and probability is the resulting level of risk, examples of which are described in Table 11.4.

Table 11.1: Risk Matrix – Comparison of Consequence and Probability (from CIRIA C552, 2001)

Risk = Probability x Consequences		Consequence			
		Severe	Medium	Mild	Minor
Probability	High likelihood	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

Table 11.2: Classification of Probability (from CIRIA C552, 2001)

Probability Classification	Definition
High Likelihood	There is a pollution linkage and an event that either appears very likely in the short term and almost inevitable over the long term, or there is evidence at the receptor of harm or pollution.
Likely	There is a pollution linkage and all the elements are present and in the right place, which means that it is probable that an event will occur. Circumstances are such that an event is not inevitable, but possible in the short term and likely over the long term.
Low Likelihood	There is a pollution linkage and circumstances are possible under which an event could occur. However, it is by no means certain that even over a longer period such event would take place, and is less likely in the shorter term.
Unlikely	There is a pollution linkage but circumstances are such that it is improbable that an event would occur even in the very long term.

The evaluation can be applied to each of the scenarios identified in the risk model and the overall risk assessed. Justification should be provided for all the inputs so that regulators can easily check the model.

It is important to note that for ground gases the consequence of the event happening (Table 11.3) will either be Severe for a methane explosion or asphyxiation causing death from carbon dioxide (or methane) or Medium from the lesser effects of asphyxiation.

Table 11.3: Classification of Consequence (from CIRIA C552, 2001)

Classification	Definition	Examples
Severe	Short-term (acute) risk to human health likely to result in "significant harm" as defined by the Environment Protection Act 1990, Part IIA. Short-term risk of pollution (note: Water Resources Act contains no scope for considering significance of pollution) of sensitive water resource. Catastrophic damage to buildings/property. A short-term risk to a particular ecosystem or organisation forming part of such ecosystem (note: the definitions of ecological systems within the Draft Circular on Contaminated Land, DETR, 2000).	High concentrations of cyanide on the surface of an informal recreation area. Major spillage of contaminants from site into controlled water. Explosion, causing building collapse (can also equate to a short-term human health risk if buildings are occupied).
Medium	Chronic damage to Human Health ("significant harm" as defined in DETR, 2000). Pollution of sensitive water resources (note: Water Resources Act contains no scope for considering significance of pollution). A significant change in a particular ecosystem or organism forming part of such ecosystem, (note: the definitions of ecological systems within Draft Circular on Contaminated Land, DETR, 2000).	Concentration of a contaminant from site exceeds the generic or site-specific assessment criteria. Leaching of contaminants from a site to a major or minor aquifer. Death of a species within a designated nature reserve. Lesser toxic and asphyxiate effects of carbon dioxide
Mild	Pollution of non-sensitive water resources. Significant damage to crops, buildings, structures and services ("significant harm" as defined in the Draft Circular on Contaminated Land, DETR, 2000). Damage to sensitive buildings/structures/services or the environment.	Pollution of non-classified groundwater. Damage to building rendering it unsafe to occupy (e.g. foundation damage resulting in instability).
Minor	Harm, although not necessarily significant harm, which may result in a financial loss or expenditure to resolve. Non-permanent health effects to human health (easily prevented by means such as personal protective clothing, etc). Easily repairable effects of damage to buildings, structures and services.	The presence of contaminants at such concentrations that protective equipment is required during site works. The loss of plants in a landscaping scheme. Discoloration of concrete.

Table 11.4: Classification of Risks and Likely Action Required (from CIRIA C552, 2001)

Risk Classification	Definition
Very High Risk	There is a high probability that severe harm could arise to a designated receptor from an identified hazard OR there is evidence that severe harm to a designated receptor is currently happening. This risk, if realised, is likely to result in a substantial liability. Urgent investigation (if not undertaken already) and remediation are likely to be required.
High Risk	Harm is likely to arise to a designated receptor from an identified hazard. Realisation of the risk is likely to present a substantial liability. Urgent investigation (if not undertaken already) is required and remedial works may be necessary in the short term and are likely over the longer term.
Moderate Risk	It is possible that harm could arise to a designated receptor from an identified hazard. However, it is relatively unlikely that any such harm would be severe. If any harm were to occur, it is more likely that the harm would be relatively mild. Investigation (if not already undertaken) is normally required to clarify the risk and to determine the potential liability. Some remedial works may be required in the longer term.
Low Risk	It is possible that harm could arise to a designated receptor from an identified hazard, but it is likely that this harm, if realised, would at worst be mild.
Very Low Risk	There is a low possibility that harm could arise to a receptor. In the event of such harm being realised, it is not likely to be severe.

11.7 RISK REDUCTION

In order to ensure that the potential impact of a given hazard is reduced to an 'acceptable' level, it is necessary to apply some degree of management to the risk assessment process. The use of ground gas control measures should be considered on the basis of reducing the risk to that which is 'as low as reasonably practicable' (ALARP principle).

11.8 METHODS OF ASSESSING RISK

A number of approaches for assessing the risk posed by ground gases have been suggested and, to varying degrees, put into practice over recent years. Two of these have become widespread and accepted as the principle method for assessing risk from ground gases. These are Fault Tree and Event Tree analyses, which are described briefly below along with the benefits and disadvantages of their use. For both of these techniques, logic diagrams are employed to represent the propagation of events or faults through a system of individual failures that lead to the unwanted 'top event', for example, a methane gas explosion or asphyxiation due to carbon dioxide in a small room. However, since they approach the failure mechanism from different directions, it is often found that the choice of technique depends upon the particular problem. Consequently, the authors recommend that expert advice is always sought when assessing the risks posed by particular sites.

11.8.1 Fault Tree Analysis

Fault tree analysis can be used to assess the probability of a system failure in the absence of actual data. However, the technique does require information on the failure rates of components within a system, which is often not known or difficult to obtain. Combining such data can provide an estimate of the probability of system failure over time or of failure on demand (e.g. failure of a ground gas membrane to operate). The aim is to take an undesired event (system failure) and describe how it might occur. Figure 11.1 outlines a fault tree analysis associated with a methane explosion.

The fault tree approach is based around a tree-shaped combination of events. The apex of the tree is occupied by the 'top event' or worst-case event, which for methane and carbon dioxide are death by explosion and asphyxiation, respectively. The lower levels of the tree provide details on potential combinations of events that would lead to the top event occurring. Details are included in the form of "AND" and "OR" gates to indicate whether events need to occur concurrently in order to cause the top hazard to occur, or whether they could occur independently with the same ultimate effect. It would be standard practice to extend the fault tree only as far as the individual components for which sufficient data are available. The fault tree is produced in descending order, with the main failure event being identified first and the lesser elements being built up below this (as shown in Figure 11.1).

By determining the possible frequencies of occurrences for each element of the fault tree, a frequency of occurrence for the top event can be calculated. A fault tree is more suitable for use when the final event is clearly defined (e.g. explosion).

The restrictions of this technique of risk assessment must be considered. The primary downfall is the narrow nature of the result, allowing only one final outcome and not acknowledging the presence of numerous alternative outcomes. It should also be noted that the use of a fault tree results in a highly conservative approach, with the worst-case scenario often being considered in each step of the tree.

The minimisation of venting (V) within the Fault Tree Analysis considered within Figure 11.1 is considered the best control option. Godson and Witherington (1996) attempted to define ground gas emissions and flow rates for development control purposes around this technique (see Section 11.10.1), as did the Partners in Technology report (see Section 11.10.2). This is further expanded upon within the proposed Traffic Lights contained within this report (see Sections 11.10.3 and 14).

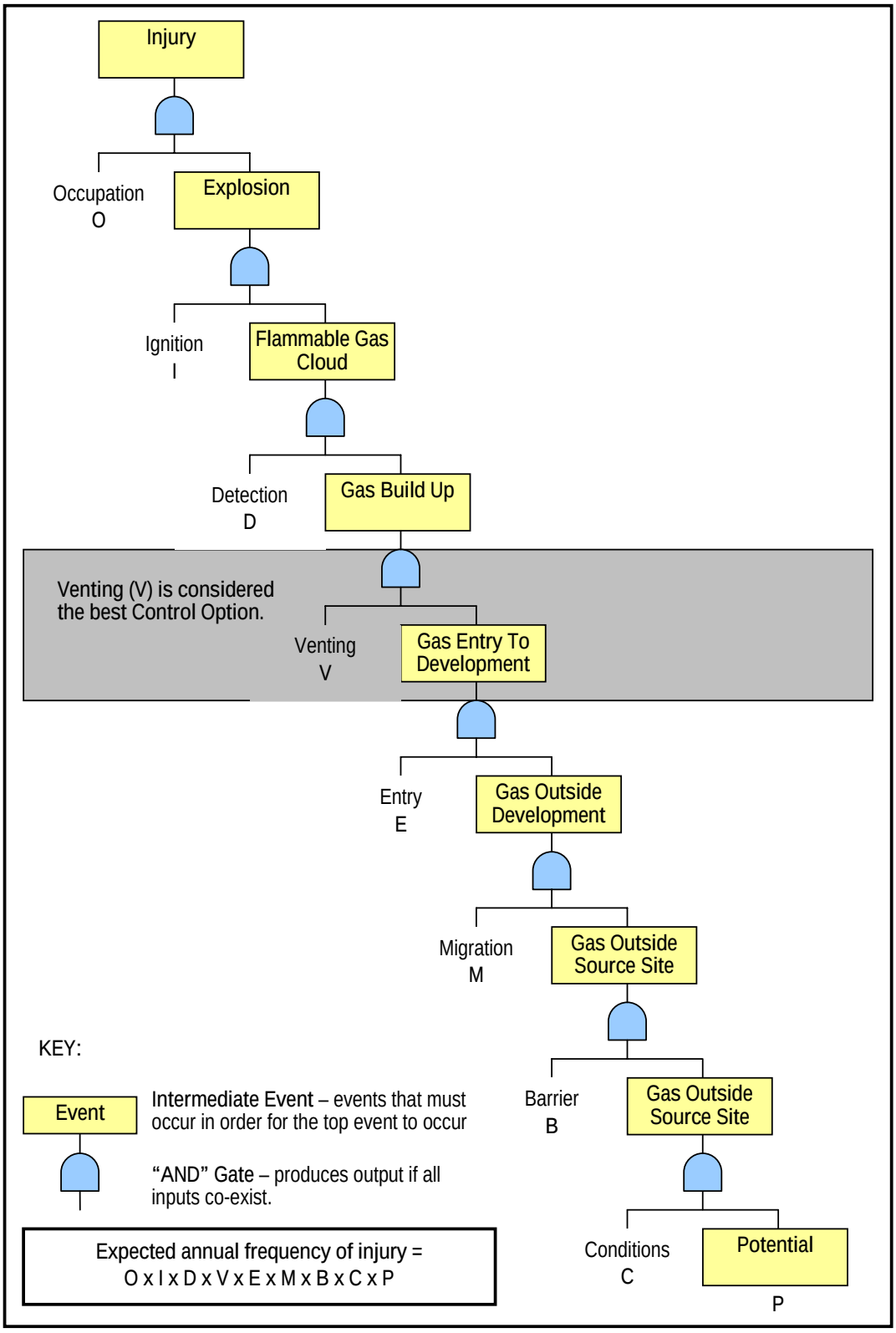

Figure 11.1: Outline of a Fault Tree Analysis Associated with a Methane Explosion (Adapted from CIRIA Report 152, 1995)

11.8.2 Event Tree Analysis

In contrast to fault tree analysis, event tree analysis begins with the "initiating event", such as the presence of methane, and builds up the structure of the tree based on the additional events that would be necessary in order to bring about the final event in a chronological manner. Figure 11.2 outlines an event tree analysis associated with a significant pipeline failure, from which it may be seen that a variety of outcomes arise from an initiating event.

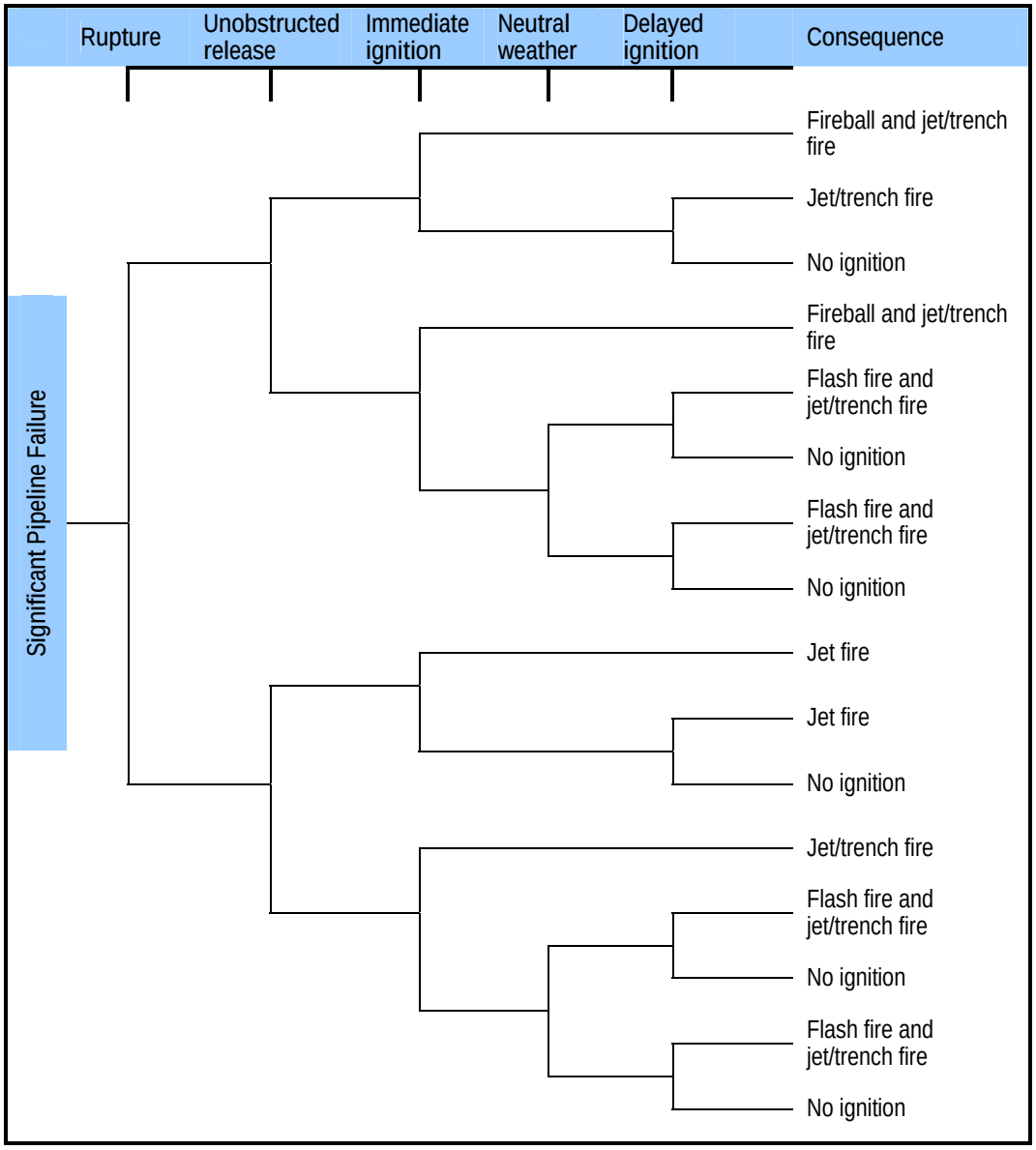

Figure 11.2: Outlines of an Event Tree Analysis Associated with Pipeline Failure (from CIRIA Report 152, 1995)

As the branches on the event tree meet, there are two options: either the two initial events will combine to move on to the next event or the events will not be

complementary, and no further events will occur. In this manner, the final outcome of a given combination of events can be identified, these final outcomes ranging from the identified unwanted event, to a series of lesser events and harmless conclusions.

A benefit of an event tree analysis over a fault tree analysis is that a variety of end points can be reached, which is a more realistic indication of actual incidents that may occur on site.

11.9 ADVANCEMENTS IN RISK ASSESSMENT TECHNIQUES

It is increasingly being emphasised that the current threshold approach to recommending ground gas protection measures, as detailed in Waste Management Paper 27 (DoE, 1991) and earlier versions of Approved Document C (DTLR), is inappropriate in many cases, which is why the latest fully revised version of Approved Document C (DTLR, 2004) no longer endorses the approach. The main reason for this is that the key parameter to which thresholds are applied is the concentration of the ground gas, whereas in the majority of cases it is the emission rate of the ground gas that is of greater significance. More recent documents, for example, the Environment Agency's CLR11 (2004) and LFTGN 03 (2004) sanction the use of a risk-based approach that takes into account site-specific conditions and should, therefore, avoid the incorporation of unnecessary ground gas protection measures.

As has been mentioned previously, it is recognised that the risk assessment process when applied to ground gas issues requires further work to produce a more robust approach. The house building industry would benefit from a standardised approach being developed and widely adopted, with guidance that is specific to brownfield sites to augment currently available guidance for landfill sites. With this in mind, Figure B1 within Appendix B outlines a flow chart that is intended to be an easy-reference staged list of the steps that should be followed during a site investigation and risk assessment for development on a site with a potential to emit ground gases. The flow chart provides step-by-step details listing the necessary actions that are required, starting with the identification of a ground gas issue, leading onto the consideration of remedial measures to be incorporated in the new development and post-construction monitoring, if required. The flow diagram refers to the appropriate section of this report and also the most appropriate CIRIA report for further guidance. Again to facilitate standardisation, the Traffic Lights proposed within this report (Sections 11.10.3 and 14) are recommended for use with all low-rise residential developments.

As well as an improvement in the techniques that can be applied to risk assessment, focus should be given to the collection of site investigation data during the course of a ground gas study. Greater standardisation of the methods of collecting data will ease the process of comparing data from different sites.

11.10 EVALUATION OF RISK ASSESSMENT

11.10.1 Godson and Witherington (1996)

Godson and Witherington (1996) attempted to define ground gas emissions and flow rates and proposed a way of interpreting such data for development control purposes.

In order to calculate the probability of an explosive concentration of ground gas being present in a confined space (e.g. cupboard or sub-floor void), the risk assessment adopted by CIRIA Report 152 (O'Riordan & Milloy, 1995) can be enhanced by reference to a simple mass balance equation, as given in BRE Digest 206 (BRE, 1997).

As an example, and as presented by Godson and Witherington (1996), consider a confined space of a broom cupboard in a residential development that is affected by methane gases. The broom cupboard has dimensions of 1.00m x 1.00m x 1.00m, and internal volume of 1,000 litres. It would reach the LEL, of 5.0%v/v methane, when the cupboard contained 50 litres.

If it is assumed that the methane entering the confined space mixes perfectly with air and the methane concentration is 0.0%v/v at time zero and there is no methane present in the incoming air, then Equation 3 gives the concentration of methane in the confined space at any given time, thus:

$$C = \frac{q}{(Q+q)}\left[1 - \exp\left(\frac{-(Q+q)t}{V}\right)\right]$$

(Equation 3)
(Godson & Witherington, 1996)

where:

- C = concentration of methane at time, t;
- Q = volume flow rate of ventilating air;
- q = volume flow rate of methane into the confined space; and
- V = volume of the confined space.

After a period of time, the methane concentration will reach a steady state of equilibrium. The corresponding equilibrium methane concentration (Ce) can be predicted by re-arranging Equation 3 and is given by:

$$Ce = \frac{q}{(Q+q)}$$

(Equation 4)
(Godson and Witherington, 1996)

If the WMP 26A (DoE, 1993) flow rate of 15l/hr is introduced into the above equations, it becomes apparent that the steady state methane concentration would be 26.47%v/v and the LEL would be reached in 3.70 hours. It is also likely that the UEL would be reached in 16.53 hours. However, since the act of opening the cupboard door would introduce air into the cupboard, it has been deemed that the probability that an explosive gas concentration being present if the cupboard is entered once a week is one.

However, it must be borne in mind that the WMP 26A emission value of 15l/hr is based on 100%v/v methane. If the methane concentrations are lowered, the volume flow rate must correspondingly be increased. For example, if ground gas concentrations comprised 1.0%v/v methane, 1.50m^3/hr (1,500l/hr) of total gas flow would be required to correspond to a figure of 15l/hr methane.

11.10.2 Partners in Technology (1997)

The Partners in Technology (Ove Arup, 1996) report discusses appropriate uses of systems for preventing ground gas ingress into buildings, focussing on passive methods. The aim of the report was to provide additional information to complement BRE Report 212 (1991), which was done by the use of computational fluid dynamic modelling of gas movement within the ground and buildings.

The results and recommendations presented in the report have been developed by:

- The performance of a desk study review of passive ground gas protective systems;
- The undertaking of computational fluid dynamic (CFD) modelling to assess the performance of various different ventilation media and arrangements; and
- The application of Ove Arup & Partners' and the steering group members' experience in designing and installing passive ground gas protective systems.

Within the CFD modelling programme, a combination of two- and three-dimensional (2D and 3D) CFD model simulations were carried out to allow calculation of ventilation flow patterns, pressure and ground gas concentrations. The ventilation systems were modelled on two idealised foundation widths (5.00m x 5.00m and 30.00m x 30.00m) with side vents on two (front and rear) sides only. A range of applied pressure differentials was considered to represent wind speeds that would be exceeded 55–95% of the time, based on annual mean percentage frequency data for Birmingham, Bournemouth, Edinburgh and Glasgow. The CFD calculations were run to define steady state conditions of pressure, flow and concentration in the ventilation layer.

The report presents the ventilation performance of the different ventilation media over six different ground gas regimes, which were based on the range of Characteristic Situations presented in CIRIA Report 149 (Card, 1995). Equivalent total ground gas flow velocity from a 50mm-diameter borehole were calculated from the emission rate using that presented by Pecksen, which assumes that borehole have a influence on the surrounding 10m^2 area. However, the authors have identified errors within Table 6 of the initial calculations of ground gas emission rates from boreholes. Here, all calculations produce emission rates that are a factor of ten out and all figures presented to be 10^{-6} are actually 10^{-5}. Therefore, this unfortunately causes a knock-on effect for all subsequent calculations and, presumably, the CFD modelling.

11.10.3 Gas Screening Value

As introduced within Section 10.4.1.3, the Gas Screening Value (GSV) equates to the borehole ground gas volume flow rate, as defined by Wilson and Card (1999), which is

defined as the borehole flow rate multiplied by the concentration in the air stream of the particular gas being considered, thus:

- GSV (l/hr) = borehole flow rate (l/hr) x gas concentration (%v/v).

These should be calculated for each borehole under consideration and used to form the risk-based methodology for deriving threshold concentrations for gas flow rates (see Section 14). This approach is consistent with CIRIA Report 659 (2006) that was written at the same time as this report (see Section 1.1). It should be used for both low-rise residential and commercial/industrial developments (see Sections 11.10.4 and 11.10.5, respectively).

The gas Screening Values for methane and carbon dioxide are calculated slightly differently, as follows:

- **Methane Gas Screening Value.** In order to calculate the Gas Screening Value (GSV) for methane, it is recommended that the assessor should always use the initial concentrations of methane together with the initial flow rates recorded from each monitoring installation from the monitoring rounds. This is because the worst possible consequence of a methane build up is an instantaneous explosion, with the potential for a considerable loss of life and property. Such an event could occur at any time.
- **Carbon Dioxide Gas Screening Value.** In order to calculate the Gas Screening Value (GSV) for carbon dioxide, it is recommended that the assessor should use the steady state concentrations of carbon dioxide together with the steady state flow rates recorded from each monitoring installation from the monitoring rounds. This is because although the worst possible consequences of a carbon dioxide build up is death, this event would occur over a more extended timescale than a methane explosion, which is instantaneous. As a result, the event could be more easily mitigated against by the actions of a person(s) affected by, for example, increasing ventilation within the space if they felt drowsy or nauseous.

The worst-case gas Screening Value should be used to drive all further risk assessments work during the comparison to the Traffic Lights (see Sections 11.10.4 and 14) and Revised Wilson and Card Classification (see Section 11.10.5).

11.10.4 Traffic Lights

At the request of the NHBC, the RSK authors have utilised current guidance to develop a system of 'Traffic Lights' to remove ambiguity and assist the NHBC engineers in determining the adequacy of technical submissions. Classification of the Traffic Lights to any low-rise residential development provides the relevant ground gas protection measures that should be installed to adequately mitigate the risk. The proposed Traffic Lights, together with the associated Typical Maximum Concentrations and Gas Screening Values, are detailed completely within Section 14 of this report.

11.10.5 Revised Wilson and Card Classification

There has become a common practice within the industry to compare ground gas concentrations and/or flow rates for either methane and/or carbon dioxide measured at a

site to 'Characteristic Situations' and to determine protection measures using Tables 28 and 29 presented in CIRIA Report 149 (Card, 1995). However, it is imperative that the use of these Characteristic Situations is clarified to cease the extensive and improper use of this technique to 'design' ground gas protection measures for developments.

Tables 28 and 29 from CIRIA Report 149 (Card, 1995) are generally consulted with little regard to the nature of the gassing source or flow rates and the estimated surface emissions. In addition, protection measures are stated that are now considered wholly inappropriate to certain developments and consequently should never be used. As the author of CIRIA Report 149 freely states in a later paper (Card & Wilson, 1999):

> "[the] tables were never intended to be used as a definitive design tool and were only prepared to show the typical scope of measures for gas control that were in current use at the time the tables were produced."

Work by Card and Wilson (1999) to refine the CIRIA Report 149 Characteristic Situations further emphasises the need for appropriate assessment and use of the use of ground gas concentrations, borehole flow rates, surface emission rates and the characterisation and nature of the gassing source in determining the site ground gas regime. Table 5 of their paper characterises ground gas situations based on a variety of parameters, including concentration, borehole flow velocity and borehole gas volume flow. Comparison is made between the Characteristic Situations given in CIRIA Report 149 and the Partners in Technology regimes.

An important fact to note with this article is that Table 5 has missing footnotes regarding the proposed length of times ground gas monitoring should be carried out for. However, the reader's attention is brought to the following footnote accompanying Table 5:

> "Site characterisation should be based on gas monitoring of concentrations and borehole flow rates for a minimum period of one year and covering a range of atmospheric conditions. For readings covering six months, increase Characteristic Situation by 1. For readings covering less than six months but over three months, increase Characteristic Situation by 2."

The RSK authors consider it misguided to recommend such an approach, as poor quality information on a site's ground gas regime collected at nothing like the worst temporal conditions a site may experience may be passed off relatively lightly and be classified as Characteristic Situation 2 or even Characteristic Situation 1. If information is considered lacking on the ground gas regime, there can be no substitute for obtaining more information to adequately define the ground gas regime. The authors consider that NHBC engineers should always be able to view the worst-case ground gas conditions when reviewing proposed ground gas protection measures for any development, which must be designed robust enough in the first case to adequately handle any increases in ground gas concentrations and, more importantly, flow rates that may result during the worst temporal conditions a site may experience.

Consequently, it is recommended that the Card and Wilson approach is not used for low-rise residential housing. Instead, the Traffic Lights risk-based classification scheme as detailed within Section 14 should be used. The Card and Wilson approach can be used for all other types of development. CIRIA Report C659 (2006), which was written at the same time as this report (see Section 1.1), endorses this approach.

However, notwithstanding the above, the new CIRIA Report C659 that was written at the same time as this report (see Section 1.1) presents a Revised Wilson and Card Classification as refined from the incorrectly used from CIRIA Report 149. This method should be used for flatted developments, as well as those of commercial/industrial premises, and is presented within Tables 11.1 and 11.2.

The GSV should be calculated for both methane and carbon dioxide and the worse case value adopted, with the result compared to the value within Table 11.1. The higher the classification the greater the risk posed by the presence of gas. It is important to recognise that the GSV is a guideline value and not an absolute threshold. That is, the GSV quoted in Table 8.5 can be exceeded in certain circumstances should the conceptual site model indicate it is safe to do so. Similarly, consideration of the additional factors (such as concentration, flow rate etc) can lead to consideration of the appropriateness of an increased Characteristic Situation. The Characteristic Situation can then be used to define the general scope of gas protective measures required, as presented within Table 11.2.

Table 11.1: Modified Wilson and Card Classification (CIRIA Report 659)

Characteristic Situation (CIRIA Report 149)	Risk Classification	GSV (CH_4 or CO_2) (l/hr) [1]	Additional factors	Typical source of generation
1	Very low risk	<0.07	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" Made Ground
2	Low risk	<0.7	Borehole flow rate not to exceed 70l/hr. Otherwise consider increase to Situation 3	Natural soil, high peat/organic content. "Typical" Made Ground
3	Moderate risk	<3.5		Old landfill, inert waste, mineworking flooded
4	Moderate to high risk	<15	Quantitative risk assessment required to evaluate scope of protective measures	Mineworking susceptible to flooding, completed landfill (WMP 26B criteria)
5	High risk	<70		Mineworking unflooded inactive with shallow workings near surface
6	Very high risk	>70		Recent landfill site

Notes:

1. Gas screening value: litres of gas/hour is calculated by multiplying the gas concentration (%) by the measured borehole flow rate (l/hr);
2. Site characterisation should be based on gas monitoring of concentrations and borehole flow rates for the minimum periods as defined within within CIRIA Report 659;
3. Source of gas and generation potential/performance must be identified;
4. Soil gas investigation to be in accordance with guidance contained within CIRIA Report 659;
5. If there is no detectable flow, use the limit of detection of the instrument;
6. The boundaries between the Partners in Technology classifications do not fit exactly with the boundaries for the above classification.

Table 11.2: Typical Scope of Protective Measures Required for the Revised Wilson and Card Classification (CIRIA Report 659)

Characteristic Situation (From Table 11.1)	Residential building (Not low-rise traditional housing) [1]		Commercial /industrial development	
	Number of levels of protection	Typical scope of protective measures	Number of levels of protection	Typical scope of protective measures
1	None	No special precautions	None	No special precautions
2	2	a) Reinforced concrete cast in situ floor slab (suspended, nonsuspended or raft) with at least 1200g DPM9 and underfloor venting b) Beam and block or pre-cast concrete and 2000 g DPM/reinforced gas membrane and underfloor venting. All joints and penetrations sealed. 1 to 2	1 to 2	a) Reinforced concrete cast in situ floor slab (suspended, non-suspended or raft) with at least 1200g DPM9 b) Beam and block or pre cast concrete slab and minimum 2000g DPM/reinforced gas membrane c) Possibly underfloor venting or pressurisation in combination with a) and b) depending on us All joints and penetrations sealed.
3	2	All types of floor slab as above. All joints and penetrations sealed. Proprietary gas resistant membrane and passively ventilated or positively pressurised underfloor sub-space.	1 to 2	All types of floor slab as above. All joints and penetrations sealed. Minimum 2000g/reinforced gas proof membrane and passively ventilated underfloor sub-space or positively pressurised underfloor sub-space
4	3	All types of floor slab as above. All joints and penetrations sealed. Proprietary gas resistant membrane and passively ventilated underfloor subspace or positively pressurised underfloor sub-space, oversite capping or blinding and in ground venting layer.	2 to 3	All types of floor slab as above. All joints and penetrations sealed. Proprietary gas resistant membrane and passively ventilated or positively pressurised underfloor sub-space with monitoring facility.
5	4	Reinforced concrete cast in situ floor slab (suspended, non-suspended or raft). All joints and penetrations sealed. Proprietary gas resistant membrane and ventilated or positively pressurised underfloor sub-space, oversite capping and in ground venting layer and in ground venting wells or barriers.	3 to 4	Reinforced concrete cast in-situ floor slab (suspended, non-suspended or raft). All joints and penetrations sealed. Proprietary gas resistant membrane and passively ventilated or positively pressurised underfloor sub-space with monitoring facility. In ground venting wells or barriers.

Characteristic Situation (Table 11.1)	Residential building (Not low-rise traditional housing)[1]		Commercial /industrial development	
	Number of levels of protection	Typical scope of protective measures	Number of levels of protection	Typical scope of protective measures
6	5	Not suitable unless gas regime is reduced first and quantitative risk assessment carried out to assess design of protection measures in conjunction with foundation design.	4 to 5	Reinforced concrete cast in-situ floor slab (suspended, non-suspended or raft). All joints and penetrations sealed. Proprietary gas resistant membrane and actively ventilated or positively pressurised underfloor sub-space with monitoring facility, with monitoring. In ground venting wells and reduction of gas regime.

Notes:

1. Not suitable for use with low rise traditional housing. Use the Traffic Lights instead (see Section 14);
2. Typical scope of protective measures may be rationalised for specific developments on the basis of quantitative risk assessments;
3. Note the type of protection is given for illustration purposes only. Information on the detailing and construction of passive protection measures is given in BR414 (Johnson, 2001). Individual site specific designs should provide the same number of separate protective methods for any given characteristic situation. See CIRIA Report 49;
4. In all cases there should be minimum penetration of ground slabs by services and minimum number of confined spaces such as cupboards above the ground slab. Any confined spaces should be ventilated;
5. Foundation design must minimise differential settlement particularly between structural elements and ground-bearing slabs;
6. Commercial buildings with basement car parks, provided with ventilation in accordance with the Building Regulations, may not require gas protection for Characteristic Situations 3 and 4;
7. Floor slabs should provide an acceptable formation on which to lay the gas membrane. If a block beam floor is used it should be well detailed so it has no voids in it that membranes have to span, and all holes for service penetrations should be filled. The minimum density of the blocks should be 600kg/m^3 and the top surface should have a 4:1 ratio sand to cement grout brushed into all joints before placing any membrane (this is also good practice to stabilise the floor and should be carried out regardless of the need for ground gas membranes);
8. The ground gas-resistant membrane can also act as the damp-proof membrane;
9. Based on Building Regulations Approved Document C (Office of the Deputy Prime Minister, 2004a),which states that "a membrane below the concrete could be formed with a sheet of polyethylene, which should be at least 300mu thick (1200 gauge)". Please note the alteration from 300mm (as stated in the Approved Document C) to 300mu, as 300mm is a typographical error that has been recognised and corrected for within this report and CIRIA Report 659.

12. GROUND GAS PROTECTION MEASURES

12.1 INTRODUCTION

This section details ground gas protection measures that are currently considered as best practice in new residential development sites, relating these to the results of the ground gas monitoring that has been carried out.

Because residential developments (especially low-rise houses) are considered to be the most sensitive receptor to ingress of ground gases, it is of paramount importance that expert advice is sought in all circumstances to ensure that the ground gas protection measures have been fully justified through an Options Appraisal and are the most appropriate. Further, it is imperative that any measures required should be installed correctly (see Section 12.6).

Only once the following steps have been carried out can the most appropriate ground gas protection measures (if any) that are applicable for the site development be designed. Preliminary steps to the Options Appraisal of ground gas protection measures are:

1. **PRA to develop ICSM;**
2. **Intrusive site investigation with ground gas monitoring at the worst-case temporal conditions to refine ICSM to CSM with accurate, consistent and reliable results; and**
3. **GQRA and, if required, DQRA to fully establish hazards to site users.**

12.2 TYPES OF GROUND GAS PROTECTION MEASURES

Ground gas protection measures usually work by breaking the source-pathway-receptor linkage(s) that are present on the site. In general, for ground gas protection the linkage is normally broken at the receptor. However, certain ground gas protection measures are directed towards the source, for example, landfills have active collection of the gases, whilst removal of on-site landfilled materials may be required.

Ground gas protection measures for a development can be broadly summarised into two main categories, which will be discussed further in the subsequent sections of this report. These are:

- **Active Ground Gas Protection Measures.** These are measures designed to prevent the build up of ground gas within a building through mechanical pumping of gases. **These are not generally considered acceptable for low-rise residential developments** (see Section 12.3); and
- **Passive Ground Gas Protection Measures.** These are measures designed to prevent the build up of ground gas within a building through the controlled release and dispersal of gases via preferential pathways and special surface outlets (see Section 12.4).

Table 12.1 presents an outline of the principal ground gas protection measures that are commonly installed within developments for the mitigation of gas risk.

12.3 ACTIVE GROUND GAS PROTECTION MEASURES

Although properly designed and controlled active ground gas protection measures in buildings are very effective at removing gases, it is generally considered that they are not suitable for use in low-rise residential developments due to general maintenance required to keep them operational, together with issues relating to residents not understanding the systems' necessity and being generally unwilling to pay for their day-to-day operation. The Building Regulations (ODPM, 2004) reinforce this, stating that active gas protection systems are "unlikely to be appropriate for owner occupied properties".

Notwithstanding the above, it is possible that active ground gas protection measures may be supported by Building Control bodies (LABC and Approved Inspectors, including the NHBC) enforcing compliance with the Building Regulations for use in residential developments comprising flats, provided that properly legally binding management and maintenance companies and controls are in place to ensure that any active ground gas measures installed are always fully functioning. Further, such management and maintenance companies must develop and effectively communicate to all residents a system for dealing with any alarm (if fitted) if it were to go off.

As a result of the above, only brief information is presented within this report on active ground gas protection measures within Table D1 within Appendix D, which presents a synopsis of measures. Should further information be required, the reader is directed towards other guidance, in particular CIRIA Report 149 (Card, 1995) and CIRIA Report 659 (2006) that was written at the same time as this report.

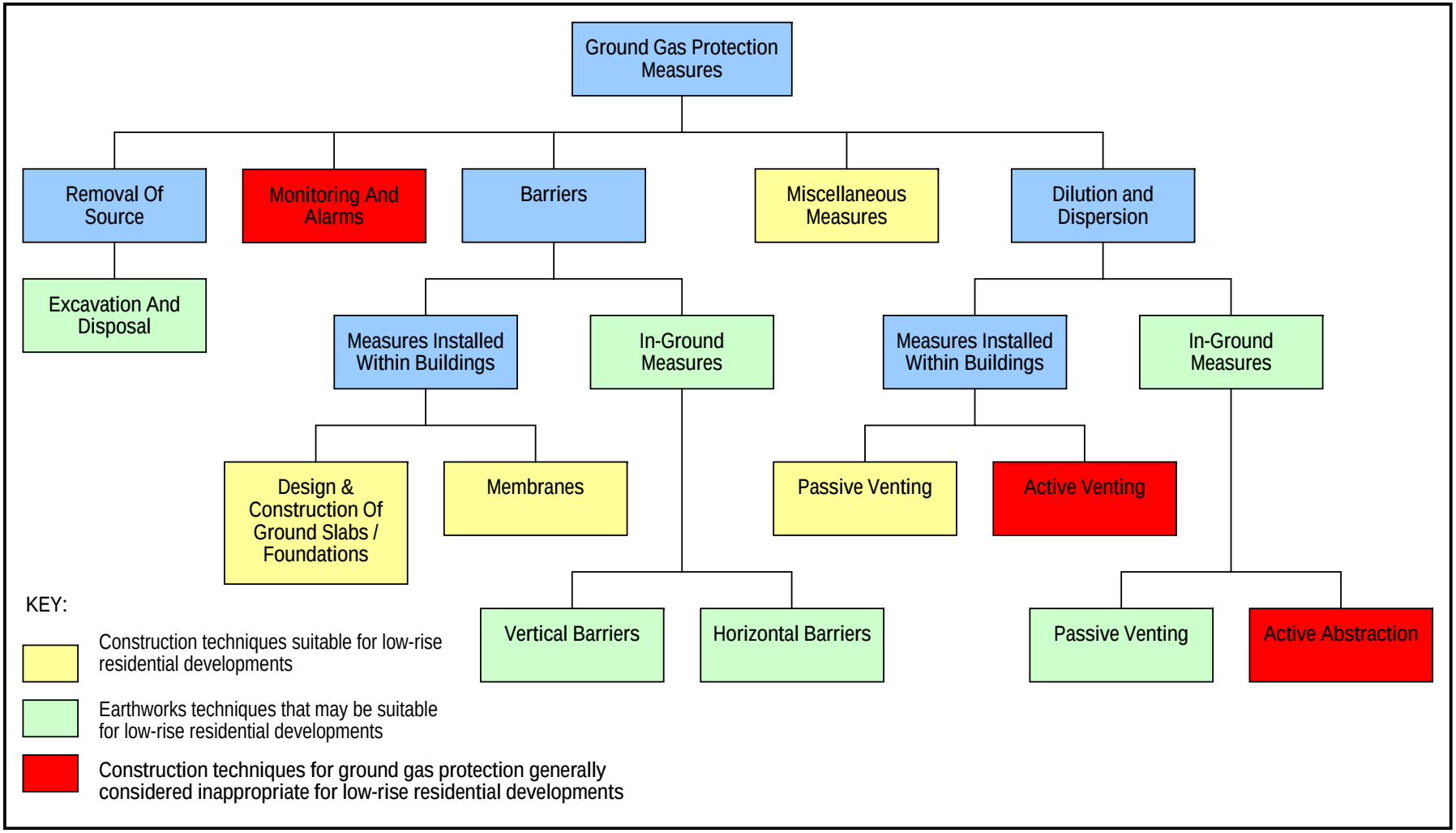

Figure 12.1: Principal Ground Gas Protection Measures (Adapted from CIRIA Report 149, 1995)

12.4 PASSIVE GROUND GAS PROTECTION MEASURES

Of the passive ground gas protection measures available, two technologies account for the bulk of the techniques available for the prevention of ground gas ingress into buildings:

- **Barriers:** techniques for preventing or minimising ground gas emissions or ground gas migration from the source; and
- **Dilution and Dispersion:** techniques for preventing migration and accumulation of ground gas in confined spaces in buildings.

In addition, however, three other options may be available to developers:

- **Removal of Source:** removal of the ground gas source removes the problem;
- **Gas Monitoring and Alarms:** continuous ground gas monitoring with audible alarms; and
- **Miscellaneous:** other techniques.

The five above options of passive ground gas protection measures are considered within Table D1 within Appendix D where a synopsis of each measure is presented. More detailed descriptions with information on specific requirements and components of protective ground gas measures are provided in CIRIA Report 149 (Card, 1995), including in-ground barriers, in-ground venting, venting for buildings, installation of ground gas membranes and the operation of ground gas monitoring and alarm systems. CIRIA Report C659 expands on the ground gas protection measures available.

BRE Report 212 (BRE, 1991) includes design details for a number of construction scenarios for a wide variety of types of ground gas protective measures. The Ove Arup and Partners (1996) report discusses appropriate uses of systems for preventing ground gas ingress into buildings, principally focussing on passive methods, by providing additional information to complement BRE Report 212, which is done by the use of computational fluid dynamic modelling of ground gas movement within the ground and buildings. Those documents should be referred to for further information on the wide variety of available solutions and their most appropriate uses.

It is important to note that achieving a perfect ground gas-proof seal is acknowledged to be very difficult. As this is the case, it is important that a permeability contrast is formed, which can be achieved by the use of airbricks and voids as part of the construction. Indeed, the use of an airbrick ventilated sub-floor void with a membrane is the most common ground gas protection method employed at the current time and, as a result, is discussed further within Section 12.7. Notwithstanding the above, all due care and attention should be applied on installing the protection measures correctly following the BRE Report 414 (Johnson, 2001) for each ground gas protection method. Further, on certain sites, the installation of certified gas-proof ground gas protection measures may be required.

Depending on the degree of impact due to ground gas that is identified during the site investigation work, remedial measures may be required. Such measures could include removal of the ground gas-generating material, capping or cover systems, the provision of impermeable layers and the use of in-ground passive or active venting systems.

Table D1 within Appendix D again indicates the principal protection measures available for ground gas mitigation.

12.5 INSTALLATION OF VENTILATED SUB-FLOOR VOID WITH MEMBRANE

The use of an airbrick ventilated sub-floor void with a membrane is the most common ground gas protection method employed at the current time within low-rise residential properties and, as a result, requires further discussion. This is particularly the case due to the ease of which the protection can be damaged during and after installation, which can render the development unprotected and potentially at risk from either an explosion of accumulated methane or that an occupant may die of asphyxiation from accumulated carbon dioxide.

Another useful document is BRE Report 414 (Johnson, 2001), which is endorsed by the Environment Agency. This document assumes that the ground gas regime has been determined and goes forward to identify the design and construction requirements for passive ground gas protection measures for both new and existing residential developments. Of particular relevance within the document are construction details to identify the principal components of each ground gas protection measure and a list of 'Watchpoints' that offers practical information for installation and buildability, highlighting where particular attention is required to the detail drawings and during the on-site construction. These are expanded upon within Appendix E. The most common ground gas entry routes into buildings (see Section 5.3 and in particular Figure 5.1) will be significantly reduced if the BRE Report 414 (Johnson, 2001) Watchpoints and those within Appendix E for each ground gas protection method are followed. To reinforce these points, Appendix E presents a series of photographs from a particularly poorly installed sub-floor void with membrane that has had to be extensively replaced at significant cost to facilitate adequate protection of the buildings and occupants. This site was determined as Part IIA contaminated land due to ground gases by the relevant Local Authority in 2006.

Of interest within Appendix E are Figures E1 to E4, which provide typical principal construction details for use with a membrane with ventilated sub-floor void.

13. POST-DEVELOPMENT VERIFICATION

Changes in the site's characteristics will occur as a result of the development (see Section 6.5). Impacts may occur due to foundation construction, dynamic compaction, piling, etc. Further monitoring to confirm the efficiency of the installed system would be the ideal aim of post-development verification and it would be useful for future work to have records detailing the degree to which current methods of ground gas ingress prevention are effective. Post-development monitoring is a requisite of Environment Agency document CLR11 (2004c).

However, in reality, it is considered almost impossible to carry out post installation verification of the installed ground gas protection measures due to the presence of homeowners. Indeed, the Environment Agency rarely requests that such testing be carried out within low-rise residential properties. In addition, the Building Regulations (ODPM, 2004) do not include any specific information for post-installation verification of ground gas protection measures.

As a result, it is imperative that any alterations in the ground gas regime, which may impact on-site users or neighbours, are identified within the CSM (see Section 8) and that such changes are planned and taken into account when conducting the Options Appraisal and designing the most appropriate ground gas protection measures that will be required for the development. The ground gas protection measures designed must be robust enough in the first instance to adequately handle any increases in ground gas concentrations and, more importantly, flow rates that may result.

As an aid to this, the opinion that the best way to avoid such ambiguity is to accurately define a series of "threshold concentrations," which will make the design and control of ground gas protection measures easier and will allow for agreement as to what should be used when. It is considered that this is the most appropriate way to ensure that dangerous situations do not arise. The proposal, therefore, is that the use of Traffic Lights based upon a risk-based assessment of the ground gas regime will enable standardisation of the ground gas protection measures required (see Section 14.)

14. TRAFFIC LIGHT SYSTEM

14.1 INTRODUCTION

In order to remove ambiguity from ground gas risk assessments, the authors have taken into account all existing publications to derive a series of 'Traffic Lights' that NHBC engineers could apply to the assessment of registrations that are specific to a low-rise housing development[4] with a clear ventilated sub floor void. This is a risk-based approach that is designed to allow quick and easy design of gas protection for a low-rise housing development by comparing the measured gas emission rates to generic Traffic Lights. The Traffic Lights include 'Typical Maximum Concentrations' are provided for initial screening purposes and risk-based Gas Screening Values (GSVs) for consideration for situations where the Typical Maximum Concentrations are exceeded. The GSVs equate to the borehole gas volume flow rate, as defined by Wilson and Card (1999) as the borehole flow rate multiplied by the concentration in the air stream of the particular gas being considered. However, the assessor must carefully evaluate the ground gas regime before proceeding with a design where the Typical Maximum Concentration is exceeded. It should be noted that the method used to develop the GSVs is based on a number of assumptions regarding the proposed structures and designers should ensure that these assumptions are appropriate to their site. If the proposed low-rise housing development differs significantly from the 'model' low-rise housing development (for example, deeper sub-floor void, increased ventilation or larger building footprints), Appendix F presents sufficient information so that the assessor can derive site-specific GSVs.

The calculations should be carried out for both methane and carbon dioxide and the worst-case adopted in order to establish the appropriate protection measures.

Any further considerations will typically take into account factors such as the value of the gas concentrations and/or the flow rate, the robustness of the data, the source characteristics and the specifics of the development (e.g. foundation conditions, footprint size), etc.

It is also important to note that the GSVs are derived based on one air change per day in the sub-floor void, in order to provide a simple assessment. As previously stated, if the designer can adequately demonstrate that vent rates are greater (for example, when calculated using BS 5925) then higher site-specific GSVs may be calculated. However, any such alternative assessment should include a sensitivity analysis to take into account the effects of occupiers blocking air vents, for example by construction of patios.

The Traffic Lights have then been related to appropriate remedial measures (presented in Section 14.2), which can be applied to conventional residential developments, as detailed in Table 14.1.

Not withstanding the Traffic Lights, the authors believe it is vital that the developer employs a specialist consultant to undertake the ground gas evaluation, undertake any further Gas Risk Assessment if required and to design

[4] In this instance, a low-rise residential development is considered to be a non-flat/apartment development consisting of one to three storeys in height. The Revised Wilson and Card Classification should be used for a residential development comprising flats/apartments (see Section 11.10.5).

the required protection measures and determine, if necessary, remedial measures to reduce gas concentrations.

14.1.1 Examples of Traffic Lights Classifications

A series of examples into the use of the Traffic Lights follows:

Example 1

Site to be developed for low-rise housing and the ground gas investigation has identified a maximum carbon dioxide concentration of 3.5% with a worst-case flow rate of 2.0l/hr. The GSV can thus be calculated as:

- 0.035 x 2.0 = 0.07l/hr.

With a GSV of 0.07l/hr and a maximum concentration of carbon dioxide of 3.5%, the site will be characterised as Green.

Example 2

Site is to be developed for low-rise housing and the ground investigation has identified a maximum methane concentration of 4.2% with a worst-case flow rate of 5.0l/hr. The GSV will therefore be calculated as:

- 0.042 x 5.0 = 0.21l/hr.

With a GSV of 0.07l/hr and a maximum concentration of methane of 4.2%, the site will be characterised as Amber 1.

Example 3

Site is to be developed for low-rise housing and the ground investigation has identified a maximum methane concentration of 14% and a worst-case flow rate of 2.5l/hr. The GSV will therefore be calculated as:

- 0.14 x 2.5 = 0.35l/hr.

The GSV puts the site in Amber 1. However, the concentration is nearly three times the Typical Maximum Value for Amber 1. Therefore, consideration should be given as to whether the site should be characterised as Amber 2. The further considerations will typically take into account factors such as the value of the ground gas concentrations and/or the flow rate, the robustness of the data, the source characteristics and the specifics of the development (e.g. foundation conditions, footprint size), etc.

Example 4

Site is to be developed for low-rise housing and the ground investigation has identified a maximum methane concentration of 1.2% and a worst-case flow rate of 1.5l/hr. The GSV will therefore be calculated as:

- 0.012 x 1.5 = 0.018l/hr.

The GSV puts the site in Green (by an order of about a magnitude). However, the maximum methane concentration is above the 1% Typical Maximum Value and, therefore, consideration should be given as to whether the site should be characterised as Amber 1. In this case, further consideration will reflect upon the marginal exceedance of the Typical Maximum Value and the very low flow rate. Provided the data was robust (i.e. the result of a comprehensive monitoring programme) and there

was real confidence that the recorded maximum was most unlikely to be substantially exceeded, the characterisation of Green would be appropriate.

Example 5

Site is to be developed for low-rise housing and the ground investigation has identified a maximum methane concentration of 69.3% and a worst-case flow rate of 1.7l/hr. The GSV will therefore be calculated as:

- 0.693 x 1.7 = 1.178l/hr.

The GSV puts the site in Amber 2. However, as the gas concentration is extremely high, at nearly three and a half times the Typical Maximum Value for Red. Therefore, consideration should be given as to whether the site should be characterised as Red. To still progress with a development, the assessor must be extremely confident that a very thorough site investigation has been carried out and that the ground gas regime, in particular in relation to the flow rates, has been appropriately characterised over a suitable length of time and at the worst-case temporal conditions that the site may experience. Further, all possible methane generation and migration potentials must have been fully characterised within a sound CSM, which must take into consideration how the ground gas regime (especially flow rates) may be impacted by partial sealing of the site with the new buildings and roads specific to the development.

Table 14.1: Gas Risk Assessment - Traffic Lights with Typical Maximum Concentrations and Gas Screening Values

Traffic Light Classification	Methane [1]		Carbon Dioxide [1]	
	Typical Maximum Concentration [3] (%v/v)	Gas Screening Value [2,4] (l/hr)	Typical Maximum Concentration [3] (%v/v)	Gas Screening Value [2,4] (l/hr)
Green				
	1	0.16	5	0.78
Amber 1				
	5	0.63	10	1.56
Amber 2				
	20	1.56	30	3.10
Red				

Notes:

1. The worst-case ground gas regime identified on the site, either methane or carbon dioxide, at the worst-case temporal conditions that the site may be expected to encounter will be the decider as to what Traffic Light is allocated;
2. Gas Screening Value is the Borehole Gas Volume Flow Rate, in litres per hour, as defined in Wilson and Card (1999), which is the borehole flow rate multiplied by the concentration in the air stream of the particular gas being considered;
3. The Typical Maximum Concentrations can be exceeded in certain circumstances should the Conceptual Site Model indicate it is safe to do so;
4. The Gas Screening Value thresholds should not generally be exceeded without the completion of a detailed ground gas risk assessment taking into account site-specific conditions.

14.2 GROUND GAS PROTECTION MEASURES REQUIRED

Based upon the Traffic Light classification that is calculated for the site for low-rise housing development only (as presented within Table 14.1), the ground gas protection measures required can be defined as presented within Table 14.2.

As stated within Table 14.2, certification of ground gas membranes are required for sites classified Amber 2. Details of correct integrity testing is contained within Appendix E.

Table 14.2: Ground Gas Protection Measures Required for the Traffic Lights

Traffic Light	Ground Gas Protection Measures Required
Green	Ground gas protection measures are not required.
Amber 1	Low-level ground gas protection measures are required, using a membrane and ventilated sub-floor void that creates a permeability contrast to limit the ingress of gas into buildings. Gas protection measures are to be installed as prescribed in BRE 414. Ventilation of the sub-floor void should be designed to provide a minimum of one complete volume change per 24 hours.
Amber 2	High-level ground gas protection measures are required, creating a permeability contrast to prevent ingress of gas into buildings. Gas protection measures are to be installed as prescribed in BRE 414. Membranes used should always be fitted by a specialist contractor and should be fully certified (see Appendix E). As with Amber 1, ventilation of the sub-floor void should be designed to provide a minimum of one complete volume change per 24 hours.
Red	Standard residential housing is not normally acceptable without further Ground Gas Risk Assessment and/or possible remedial mitigation measures to reduce/remove the source of the ground gases. In certain circumstances, active protection methods could be applied, but only when there is a legal agreement assuring the management and maintenance of the system for the life of the property.

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APPENDIX A: SUMMARY OF KEY EXISTING GUIDANCE DOCUMENTS

Appendix A: Summaries Of Key Existing Guidance Documents

A number of guidance documents exist that are widely used by developers, regulators and insurers to determine requirements for conducting an adequate ground gas survey, and methods for interpreting the results. The most extensively used of these documents are summarised below:

CIRIA Report 130 (1993) "Methane: its Occurrence and Hazards in Construction"

PJ Hooker and MP Bannon

This is the first document in CIRIA's methane series and provides details of the nature of methane and associated ground gases. Hazards relating to the gases and the sources of the gases are detailed, with emphasis on the specific hazards that relate to construction sites.

CIRIA Report 131 (1993) "The Measurement of Methane and Other Gases from the Ground"

DS Crowhurst and SJ Manchester

The principal purpose of this report was to explain the methods by which gas surveys can be conducted. Methane and landfill gas form the report focus, but carbon dioxide and other hazardous gases are included. Guidance is included on detecting gas, identifying its source and measuring and sampling gases. A section is included on the interpretation of results, including the numerous factors that may impact the results.

CIRIA Report 149 (1995) "Protecting Development from Methane"

GB Card

The largest of the CIRIA documents, this report includes information on why buildings need to be protected from methane ingress (and other gases) and details the key means by which such protection can be achieved. Specific details are provided on the components of the gas ingress preventative system, including integral ground-slabs, in-ground barriers, in-ground venting, active gas abstraction, venting of buildings, gas membranes and gas monitoring and alarm systems. Current UK uses of different techniques in different ground gas regimes are reviewed, and information included on long-term management of gas-control systems.

CIRIA Report 150 (1995) "Methane Investigation Strategies"

JG Raybould, SP Rowan and DL Barry

This report focuses on the requirements of a site investigation that is being carried out to determine the ground gas regime. The report includes reviews of guidance documents in use at the time and has also benefited from the advice of regulators, developers, funders and insurers. The report emphasises the importance of recognising differences between specific sites. Good practice is included, with a focus on general strategies and procedures rather than specific techniques.

CIRIA Report 151 (1995) "Interpreting Measurements of Gas in the Ground"

R Harries, PJ Witherington and JM McEntee

This document is aimed at underlining the importance of accurate monitoring results in assessing a ground gas regime and the resultant risk to site users. Details are provided on the most robust methods for collecting data, and subsequent data interpretation. Impacts on results due to external factors are discussed, as is the need for measuring certain parameters. Current gas measurement techniques are evaluated and recommendations are made on how to standardise and improve measurement techniques and accuracy in interpretation.

CIRIA Report 152 (1995) "Risk Assessment for Methane and Other Gases from the Ground"

NJ O'Riordan and CJ Milloy

This document reviews the importance of accurate assessments of risk in determining action required on a site affected by ground gases. A methodology is proposed for evaluation of gas hazards and the subsequent risk assessment. The principles of risk assessment are detailed in the context of ground gas in buildings, with a section on tolerable risks. A qualitative risk assessment process leads on to a more predictive quantitative procedure.

CIRIA Report 659 (2006) "Assessing Risks Posed by Hazardous Ground Gases in Buildings"

S Wilson, S Oliver, H Mallett, H Hutchings and G Card

This document was written at the same time as this report and provides up to date advice by consolidating good practice for both ground gases and other vapours that may be encountered in investigations. This includes how to collect relevant data and how to design monitoring programmes in a risk based approach to gas contaminated land. In addition, the measures that can be employed to mitigate such risks are extensively discussed.

BRE (1987) "Measurement of Gas Emissions from Contaminated Land"

Guidance is provided in this document on site investigation techniques that should be applied in the context of gas emissions from landfill sites.

Details are included of the parameters that should be measured during an investigation and the methods by which these should be obtained. Where the site fits any of the characteristics listed below, it is suggested that a specific gas investigation should be carried out:

- Redevelopment on or close to a landfill site that received organic waste;
- Where nuisances due to an adjacent/on-site landfill are evident (e.g. die-back or odours);
- Where fires or explosions have occurred due to the presence of a landfill;
- Where other sources of gas exist (e.g. marshy areas, peat); and
- Where there is an option for utilisation of gas.

This guidance includes some specific recommendations on site investigation techniques, including the use of initial and detailed site investigations, building up knowledge of the ground gas regime with a medium to long-term monitoring programme.

Although this guidance is relevant, it is generic and needs further development in order to be used in a site-specific manner.

BRE Report 212 (1991) "Construction of New Buildings on Gas Contaminated Land"

This document focuses on gas control measures in buildings, with no specific recommendations for investigation of sites at risk from ground gases. The problems with determining 'trigger' levels for methane are recognised, with the following points being noted:

- Gas concentrations vary greatly over time depending on prevailing conditions;
- Risks relating to explosive properties of methane are difficult to calculate; and
- Methane is generally present in variable background concentrations (as is carbon dioxide).

BRE Report 414 (2001) "Protective Measures for Housing on Gas Contaminated Land"

This document is designed as a practical guide to good practice for the detailing and construction of passive soil gas protection measures for new and existing residential development. The document is designed for use after a detailed site investigation has been carried out when there is high confidence that the worst temporal conditions for the site have been established and that the ground gas regime is has been fully characterised.

Individual sections show ground gas protection measures for the most common forms of foundation and floor used on residential developments. Of particular relevance within the document are construction details to identify the principal components of each ground gas protection measure and a list of 'Watchpoints', which offer practical information for installation and buildability highlighting where particular attention is required to the detail drawings and during the on-site construction. The most common ground gas entry routes into buildings will be significantly reduced if the Watchpoints for each ground gas protection method are followed.

Ground Engineering (February 1999) "Reliability and Risk in Gas Protection Design"

GB Card and SA Wilson

This paper comments on the widespread use of the gas concentration parameter in determining the requirements for remedial work on gas-impacted sites. Consideration is often not given to issues such as gas flow rates, gas source and generation rate and quality of survey data. There is much inconsistency in specifications for gas protection systems, which may result in designs that are not sufficiently safe. The paper assesses the use of gas concentrations, borehole flow rates, surface emission rates and nature of gassing source in determining the site ground gas regime. A table is provided that characterises gas situations based on a variety of parameters, including concentration, borehole flow velocity and borehole gas volume flow. Comparison is made between the characteristic gas regimes given in CIRIA 149 and the Partners in Technology regimes.

An important fact to note with this article is that Table 5 has missing footnotes regarding the proposed length of times. However, this has been updated by CIRIA Report 659 as a Revised Wilson and Card Classification as discussed within Section 11.10.5 of this report.

Passive Venting of Soil Gases Beneath Buildings

Ove Arup Partners in Technology (September 1997)

This document was produced as reference material for practitioners and regulators requiring information on the design of buildings on or near sites producing low concentrations of gas, where passive venting systems are considered appropriate. Computational fluid dynamic modelling was used to assess the performance of different ventilation methods under differing conditions. Design recommendations for different scenarios are included, with the advantages and disadvantages of each passive venting technique being discussed.

Department of the Environment (1986) "Waste Management Paper No. 26: Landfilling Wastes"

This document includes data specifically relating to the design, operation and restoration of landfill sites. Some mention of closed landfill sites and a discussion on site investigation are also included. Key points are:

- The potential for building on shallow landfill sites greater than 20 years old [however, this may not represent current thinking];
- The main components of a site investigation (desk study, trial pits and boreholes followed by gas monitoring);
- Assessment of geotechnical factors and a review of all potential hazards, including chemical influences, gas and leachate migration, toxicity and potential for explosions; and
- The safety of buildings and future occupants is vital, and designs on gassing sites should ensure this.

The document generally does not provide the type of information necessary for developing on brownfield gassing sites, and its main use is in providing background information on gas behaviour.

Department of the Environment (1991) "Waste Management Paper No. 27: Landfill Gas" (Edition 2)

This document gives guidance on monitoring and control of landfill gas, and is often applied incorrectly in any number of scenarios. Monitoring of gas at landfill sites is a key section of the report; risk issues are included, again focussing on landfill sites.

Department of Transport, Local Government and the Regions and the Welsh Office (April 2004) "The Building Regulations: Approved Document C – Site Preparation and Resistance to Contamination and Moisture"

This document is specifically concerned with measures used in developments to resist moisture. Guidance is provided on the ingress of contaminants such as ground gas, including requirements

for further investigation and gas ingress preventative measures recommended based on the methane and carbon dioxide levels recorded. The new revision of this document includes comments on the use of an objective risk assessment to ensure that the lower explosive limit (for methane) or toxic levels (for other gases) are never reached. This document does not include any specific information for post-construction monitoring of protective measures, but it does state that actively ventilated systems are generally not appropriate for private housing.

DoE Circular 21/87, Development of Contaminated Land (1987)

The principal aim of this guidance is to advise developers and local authorities on the options for redeveloping contaminated land. A number of relevant points are covered, including:

- Information on the cost-benefit balance of redeveloping a site;
- The local authority responsible for a specific site has the duty to decide which policies and practices are applicable for their area;
- The presence of (or potential for) contamination at a site should be considered as part of the planning process;
- The degree of contamination may restrict the future uses of a site;
- Sites must all be considered individually, as so many variables exist;
- The developer should take responsibility for assessing whether the land is suitable for the intended end use;
- Where remedial measures are required, these should be identified by the developer and approved by the local authority; and
- Planning permission may be granted where there is evidence that contamination is likely to be fairly low.

This guidance document is not specific to contaminated land and, although relevant to ground gases, is not aimed particularly at these issues.

Department of the Environment (1989) "Circular 17/89 – Landfill Sites: Development Control"

This circular notes that where gas is present, or suspected to be present, an investigation should be conducted to classify the ground gas regime and determine any necessary remedial measures to minimise the risk.

Interdepartmental Committee on the Redevelopment of Contaminated Land (8th Edition, 1990) "ICRCL 17/78: Notes on the Development and After-Use of Landfill Sites"

This document specifically addresses development on former landfill sites, and states that a site investigation is necessary in all cases, except where sufficient knowledge of the site is already held. The key components of the site investigation are the desk study, intrusive phase and laboratory sampling.

Environment Agency (July 2003) "Consultation on Agency Policy: Building Development on or within 250m of a Landfill Site (Background Information)"

This document states the position of the EA to be that a risk-based assessment should be adopted to determine the impact of emissions for an authorised landfill on the proposed development. Where the landfill is unlicensed, the Agency may provide information, but will not make recommendations.

It is noted that upon surrender of the landfill licence, the site is not necessarily safe for development and additional or active control measures may be needed.

Environment Agency (September 2004) "LFTGN-03: Guidance on the Management of Landfill Gas"

This document, which updates WMP 27, was prepared to give guidance on the management of landfill gas from landfill sites and, therefore, is aimed principally at landfill operators. The legislative requirements of the recent Landfill Regulations, PPC Regulations, Waste Framework Directive and current good practice are all considered. Future revisions are planned that will further develop Best Available Techniques for landfill gas utilisation.

A structured approach to the management of landfill gases generated principally from landfills is presented. It covers the assessment of landfill gas impacts, the implementation of control measures and the monitoring required to demonstrate proper performance of the control measures.

The document consists of three parts:

- **Part A** – Regulatory framework under which landfill gas is to be managed;
- **Part B** – Legislative requirements for landfill gas management and the role of risk assessment; and
- **Part C** – Technical information and details of current best practice on landfill gas management.

APPENDIX B: FLOW CHART OF EXAMPLE GROUND GAS INVESTIGATION

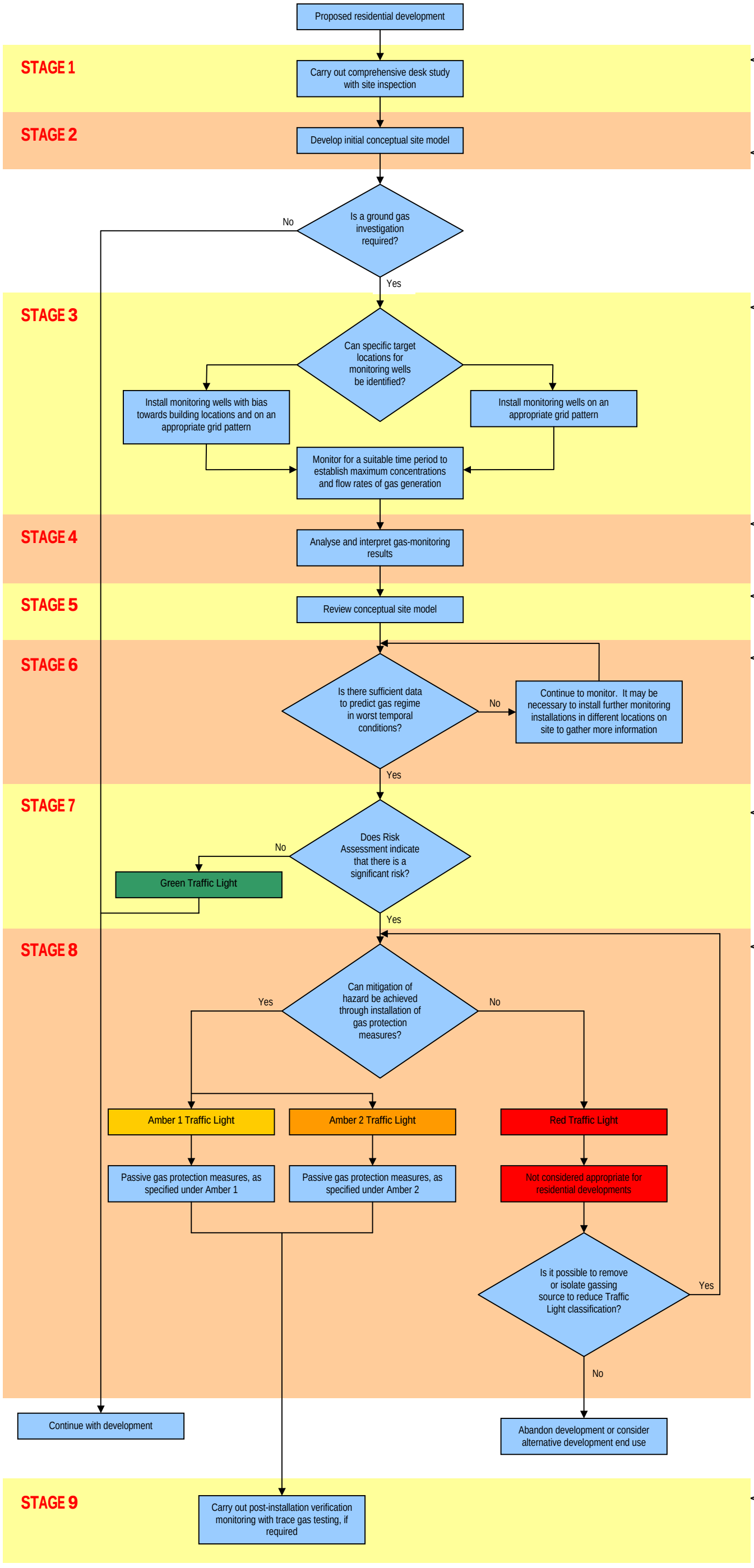
Appendix B: Flow Chart Of Example Ground Gas Investigation

The flow chart outlined within Figure B1 included in this Appendix is intended to be an easy-reference staged list of the steps that should be followed during a site investigation and risk assessment for development on a site with a potential to emit ground gases. The flow chart provides step-by-step details listing the necessary actions that are required, starting with the identification of a gas issue, leading onto the consideration of remedial measures to be incorporated in the new development and post-construction monitoring, if required.

Each step of the flow chart is clearly referenced to the section of this document where further details can be found, and also to other published guidance and reports.

Figure B1: Ground Gases Investigation Flow Chart

(Based upon CIRIA Report 150, 1995)



Report Section (appropriate CIRIA guidance)	
Section 7 (CIRIA 131, 150 & 659)	The Preliminary Risk Assessment should aim to identify, at least, the historical use of the site and surrounding area, former contaminative uses and contamination incidents, coal mining, quarrying, worked, infilled and made ground identification, any neighbouring landfills, geology, soil type, hydrology and hydrogeology, possible tidal influences, and any other pertinent information.
Section 8 (CIRIA 151 & 659)	The Conceptual Site Model must consider all information gathered within the PRA and identify ALL potential sources, pathways and receptors of ground gases, preferably in a diagrammatical form. In addition, ALL potential S-P-R linkages should be indicated, even if these are unconfirmed. The CSM should also identify how various temporal effects could influence the affect the S-P-R linkages and the ground gas regime.
Section 10 (CIRIA 131, 150, 151 & 659)	Design of a ground gas-monitoring investigation, based on the PRA, should be undertaken to establish the validity of the S-P-R linkages within the CSM. The primary aim of any investigation is to provide data for the risk assessment. As a result, it is important that the worst-case scenario of the ground gas regime at the site is established. In order to do this, monitoring must be undertaken during the worst temporal conditions that a site may experience (i.e. after rainfall and during falling barometric pressure events).
Sections 5, 6 & 9 (CIRIA 150, 151, 659)	The levels of interpretation achievable depend on the quality of the information gathered, which ultimately depends on the quality of the investigation and the appropriateness of the response zones of the monitoring installations. Equipment limitations, together with meteorological information recorded at the time, should always be considered when assessing the results and before any risk assessments.
Section 8 (CIRIA 151 & 659)	The CSM should be updated and refined as information is gathered during the investigation and monitoring exercises before any risk assessments.
Section 11 (CIRIA 659)	Risk assessment cannot be carried out until ALL S-P-R linkages, as shown in the CSM, present at a site have been both identified and characterised. Therefore, a sufficient quantity of reliable high quality data must have been gathered during some of the worst temporal conditions that a site may experience. If this is not carried out, risk assessment will be based on an inaccurate interpretation of the ground gas regime.
Section 11 (CIRIA 152 & 659)	Risk assessment should consider the safe concentrations of ground gas(es) that will be present in the building. As such, at the very maximum, it must ensure that the lower explosive limit (LEL) for methane (5%v/v) and the 10-minute operational exposure limit (OEL) for carbon dioxide (1.5%v/v) can never be reached. The impact of the development on the ground gas regime should also be considered.
Sections 12 & 14 (CIRIA 149 & 659)	Risk assessment should be carried out for all S-P-R linkages identified within CSM. And all hazards to the site users must be fully established. This will allow for the most appropriate ground gas protection measures to be determined. For low-rise residential properties, reference to the TRAFFIC LIGHTS should be made for designing the control measures, as reproduced below. For a flatted or commercial development, the Revised Wilson & Card Classification as presented within CIRIA Report 659 should be used.

TRAFFIC LIGHTS	
Green	Ground gas protection measures are not required.
Amber 1	Low-level ground gas protection measures are required, using a membrane and ventilated sub-floor void that creates a permeability contrast to limit the ingress of gas into buildings. Gas protection measures are to be installed as prescribed in BRE 414. Ventilation of the sub-floor void should be designed to provide a minimum of one complete volume change per 24 hours.
Amber 2	High-level ground gas protection measures are required, creating a permeability contrast to prevent ingress of gas into buildings. Gas protection measures are to be installed as prescribed in BRE 414. **Membranes used should always be fitted by a specialist contractor and should be fully certified** (see Appendix E). As with Amber 1, ventilation of the sub-floor void should be designed to provide a minimum of one complete volume change per 24 hours.
Red	Standard residential housing is not normally acceptable without further Ground Gas Risk Assessment and/or possible remedial mitigation measures to reduce/remove the source of the ground gases. In certain circumstances, active protection methods could be applied, but only when there is a legal agreement assuring the management and maintenance of the system for the life of the property.

Section 13 (CIRIA 149 & 659)	Post-installation verification is rarely possible. Therefore, it is essential that the ground gas protection measures designed are adequate and fit for the purpose with appropriate conservancy. This means that the site investigation, interpretation and risk assessment must all have been carried out using the ground gas regime identified during the worst-case temporal conditions that a site may experience.

APPENDIX C: EXAMPLE PRO FORMA FOR RECORDING SITE-BASED GROUND GAS MONITORING DATA

Appendix C: Example Pro forma For Recording Site-Based Ground Gas Monitoring Data

Two example pro formas for recording site-based ground gas monitoring data are contained within this Appendix, both of which have been partially filled out with example comments. The first pro forma (Table C1) is for use with multiple monitoring installations at a site, whilst the second pro forma (Table C2) is for use with only one monitoring installation. For Table C1, the peak and steady state concentrations of methane, carbon dioxide and oxygen should be recorded, together with the ranges of flow rate detected. Table C2 sets out set times from initial (zero seconds) to 600 seconds (10 minutes), although the monitoring may require substantially more or less time than this on a site- and monitoring installation-specific basis.

The monitoring steps (as also presented within Section 10.4) should generally be completed as both pro formas are read from left to right, top to bottom, which is also in the order as listed below:

1. Site and job/reference number, together with the time and date of monitoring;
2. The reference number of the monitoring point being monitored;
3. Ground gas flow in litres per hour (l/hr). For Table C1, the initial flow rates should be recorded and a note made of what the steady flow decreases to, together with what the steady flow rate is. For Table C2, the flow rates should be recorded at the set intervals.
4. Borehole pressure in Pascals (Pa). It is often possible to record at the same time as flow rate (Item 3);
5. Concentrations of methane, carbon dioxide and oxygen as follows:
    A. Methane in percentage by volume (CH_4 %v/v) and as a percentage of the Lower Explosive Limit (CH_4 % LEL), the latter of which can be worked out back at the office. For Table C1, both the initial and steady states should be recorded, together with the time it takes to become steady. If the concentration does not become steady, record the length of time monitoring occurred, which should typically not be less than 10 minutes. For Table C2, the concentrations should be recorded at the set intervals.
    B. Concentration of carbon dioxide in percentage by volume (CO_2 %v/v). For Table C1, both the initial and steady states should be recorded, together with the time it takes to become steady. If the concentration does not become steady, record the length of time monitoring occurred, which should typically not be less than 10 minutes. For Table C2, the concentrations should be recorded at the set intervals.
    C. Concentration of oxygen in percentage by volume (O_2 %v/v). For Table C1, both the initial and steady states should be recorded, together with the time it takes to become steady. If the concentration does not become steady, record the length of time monitoring occurred, which should typically not be less than 10 minutes. For Table C2, the concentrations should be recorded at the set intervals.
6. Concentration of other ground gases, usually carbon monoxide (CO) and hydrogen sulphide (H_2S) in parts per million (ppm). The exact components of ground gases that may be required to be measured may vary considerably if the source gas identified within the PRA and ICSM is a nearby landfill. As a result, this will affect the equipment used;

7. Depth to water in metres below ground level (m bgl). It is imperative that the depth to water is recorded after the ground gas flow rates and concentrations, as this involves removing the monitoring well bung, which will release all ground gases to the atmosphere;
8. Name and position of the person carrying out the monitoring;
9. Atmospheric pressure (millibars, mb) at the time of monitoring. Also record the range if it changes during the monitoring at the site, together with if it is rising or falling;
10. The weather conditions, including, for example, wind, precipitation, frost, etc.;
11. The temperature in degrees centigrade (°C), noting the operating range of the equipment in use (for infra-red gas monitors it is typically between -10°C and +40°C);
12. The equipment used and the next date of calibration;
13. Any visible signs of vegetation stress at the site, especially within the vicinity of the monitoring point;
14. The reference numbers of the monitoring points sampled for submission to an analytical laboratory; and
15. Any other comments and/or observations deemed pertinent.

Several of the more important parameters are discussed in greater detail within Section 10.4.1 of this report.

Site: _____

Job No.: _____

Table C1: Ground Gas Monitoring Round Pro Forma One

Borehole	Gas Flow (l/hr)	Borehole Pressure (Pa)	Methane (%v/v)		Methane (% LEL *)		Carbon Dioxide (%v/v)		Oxygen (%v/v)		Other Gases (ppm)			Depth to Water (m bgl)
			Initial	Steady	Initial	Steady	Initial	Steady	Initial	Steady	PID	H_2S	CO	
BH1					0	0								
BH2					0	0								
BH3					0	0								
BH4					0	0								
BH5					0	0								
BH6					0	0								
BH7					0	0								
BH8					0	0								
BH9					0	0								
BH10					0	0								
BH11					0	0								
BH12					0	0								
BH13					0	0								
BH14					0	0								
BH15					0	0								

Notes:
Monitoring order is from **left to right** across table.
Monitoring should be for **not less** than 3 minutes. However, if high concentrations of gases initially recorded, monitoring should be for up to 10 minutes
* LEL = Lower Explosive Limit = 5%v/v

Relevant Information At Time Of Monitoring				
Monitored by (name, position):	e.g. A. N. Other, Stores Technician			
Atmospheric Pressure (mB):	e.g. 989, falling to 985			
Weather:	e.g. Intermittent rain, overcast with sunny intervals			
Temperature (°C, between -10°C to +40°C only):	e.g. 12, falling to 11			
Equipment Used (RSK Reference No.):	Infra Red Gas Analyser		**Last calibrated:**	
	Mass Balance Transducer		**Last calibrated:**	
	MiniRAE PID		**Last calibrated:**	
Visible Signs of Vegetation Stress:	e.g. Slight browning of grass around BH4			
Other Comments / Observations:	e.g. BH1 peak flow <20 seconds			
Boreholes Sampled For Laboratory Analysis:	e.g. BH1			

Site: _____

Job No.: _____

Table C2: Ground Gas Monitoring Round Pro Forma Two

Borehole	Time Seconds (Minutes)	Gas Flow (l/hr)	Borehole Pressure (Pa)	Methane (%v/v)	Methane (% LEL *)	Carbon Dioxide (%v/v)	Oxygen (%v/v)	Other Gases (ppm)			Depth to Water (m bgl)
								PID	H_2S	CO	
BH1	0				0						
	15				0						
	30				0						
	45				0						
	60 (1)				0						
	90				0						
	120 (2)				0						
	180 (3)				0						
	240 (4)				0						
	300 (5)				0						
	360 (6)				0						
	420 (7)				0						
	480 (8)				0						
	540 (9)				0						
	600 (10)				0						

Notes:
Monitoring order is from **left to right** across table.
Monitoring should be for **not less** than 3 minutes. However, if high concentrations of gases initially recorded, monitoring should be for up to 10 minutes
* LEL = Lower Explosive Limit = 5%v/v

Relevant Information At Time Of Monitoring				
Monitored by (name, position):	e.g. A. N. Other, Stores Technician			
Atmospheric Pressure (mB):	e.g. 989, falling to 985			
Weather:	e.g. Intermittent rain, overcast with sunny intervals			
Temperature (°C, between -10°C to +40°C only):	e.g. 12, falling to 11			
Equipment Used (RSK Reference No.):	Infra Red Gas Analyser		**Last calibrated:**	
	Mass Balance Transducer		**Last calibrated:**	
	MiniRAE PID		**Last calibrated:**	
Visible Signs of Vegetation Stress:	e.g. Slight browning of grass around BH4			
Other Comments / Observations:	e.g. BH1 peak flow <20 seconds			
Boreholes Sampled For Laboratory Analysis:	e.g. BH1			

APPENDIX D: PRINCIPAL GROUND GAS PROTECTION MEASURES

Appendix D: Principal Ground Gas Protection Measures

Table D1: Principal Ground Gas Protection Measures

Available Technique					
Type			Description	Comments	Costs
Removal of source		Excavation and disposal	If source of gas is relatively small, for instance a thin layer of made ground, removal will render the site hazard free.	Must ensure that such material is indeed the source of ground gas emissions and that no residual gas remains in the ground. Can be impractical on very large sites, if source is at depth or if a large quantity of source material present.	Increasing due to increases in landfill tax and disposal charges.
Gas monitoring and alarms		Gas monitoring	Either periodic or continuous monitoring can occur of ground gases, depending on the nature and use of the building and concentrations of gas. The frequency of gas monitoring may be reduced after a period of time if it is shown that the gas risk is low.	Does not provide physical protection against the hazards of ground gases. Is not considered a replacement for permanent protection measures. It is generally agreed that this technique alone SHOULD NOT be installed in residential developments due to the extreme sensitivity of the receptor to even minor fluctuations in gas concentrations and flow rates.	
		Gas alarms	Gas detectors can be installed into buildings near the likely points of gas ingress and confined spaces (e.g. sub-floor voids and cavities). If pre-set gas concentrations are exceeded, an automatic audible alarm sounds to prompt building evacuation.	Does not provide physical protection against the hazards of ground gases. Is not considered a replacement for permanent protection measures. It is generally agreed that alarms SHOULD NOT be installed in residential properties due to the general apathy of residents and maintenance issues.	
Barriers	Buildings	Design and construction of ground slabs/foundations	Impermeable gas barriers are constructed on top of a high permeability layer, from which ground gas can be extracted in a controlled manner (e.g. concrete slab overlying gravel layer). No barrier is completely impermeable to the passage of ground gas; however, the technique relies upon the barrier providing a greater resistance to gas migration than the surrounding ground so that gases are encouraged to migrate in another direction away from the building.	The permeabilities of many materials, particularly clays and cements, can vary due to changes in pore size and pore distribution caused by changes in the ground (e.g. decreased or increased water content). The design of any barrier should take into account these effects and allow for potential changes in permeability of either the surrounding ground or the barrier itself.	

Available Technique						
Type				Description	Comments	Costs
		Membranes		Membranes work on the same principle as barriers, except a polyethylene, LDPE or modified bitumen/LDPE layer is installed to prevent gas ingress on top of a high permeability layer. The minimum recommended standard of membrane is 300 micrometers (1200 gauge) (BRE 212). A single membrane, if carefully designed and selected, may satisfy both the requirements of a damp proofing course and gas protection.	Membranes are usually installed in conjunction with passive or active venting. Of concern is whether the membrane can withstand the construction process because, once torn or damaged, the membrane will cease to operate as an effective barrier. Adequate quality control during the laying of the membrane is extremely important and the membrane should be protected.	
Barriers (Continued)	In-ground	In ground barriers	Vertical barriers	Vertical barriers are used to prevent lateral gas migration towards the development. A high permeability trench should be installed on the gassing source side of the vertical barrier to ensure gases are vented to the atmosphere and do not build up. Vertical barriers are only suitable where a low permeability material horizon is present at depth, where the vertical barrier is 'keyed' in. In some situations, the groundwater table can be considered to be an effective impermeable horizon to prevent ground gas migration. Vertical barriers can be constructed to surround a gassing source or, if the source is remote, in between the source and development to prevent and intercept migration.	The barrier has to remain in place for a considerable time period (50 or even 100 years) and the integrity of the barrier used must be complete. If concrete materials are to be used, the ground regime should be understood and the presence of concrete aggressive materials should be pre-designed for. Tolerance to ground movements (e.g. from mining subsidence) should also be guaranteed. If the groundwater table is identified as a suitable impermeable horizon, care should be taken to ensure that all fluctuations in its level are identified so that gaps between the groundwater and vertical barrier are not created, which could allow ground gas migration to occur. Vertical barriers could induce changes in the groundwater regime (e.g. flow direction), which could result in groundwater level rises upstream of the barrier. This could also alter the ground gas regime upstream, which could increase ground gas generation and affect existing or future development design. The presence, location and depth of the horizontal barrier should be made known so that any future services installed do not pass through and render it obsolete.	

Available Technique						
Type				Description	Comments	Costs
			Horizontal barriers	Horizontal barriers are used to prevent ground gas migration from sources directly beneath the development. The barrier, which can be constructed from a range of materials including clay, mass concrete or synthetic liners, is carefully placed and sealed around services, foundations and structures. Usually, a venting blanket or gas drainage layer will underlie the horizontal barrier. Injection or jet grouting can also provide horizontal barriers to prevent gas migration through a low permeability horizon at depth beneath a site, which is known as 'bottom sealing' or 'under sealing'.	The barrier has to remain in place for a considerable time period (50 or even 100 years) and the integrity of the barrier used must be complete. If concrete materials are to be used the ground regime should be understood and the presence of concrete aggressive materials should be pre-designed. Tolerance to ground movements (e.g. from mining subsidence) should also be guaranteed. Suitable drainage measures should be built into the ground above the horizontal barrier to prevent the areas becoming a quagmire. The presence, location and depth of the horizontal barrier should be made known so that any future services installed do not pass through and render it obsolete.	
Dilution and Dispersion	Buildings	Passive or natural venting		This technique relies on the natural movement of air through buildings and/or structure fabric by the action of natural climatic conditions by the processes of gas diffusion and advection. Therefore, passive venting is suitable in situations where precise control over the air quality and volume flow rate of fresh air is not critical to dilute gas concentrations to safe acceptable levels. Passive venting to a development that is affected by ground gases can be applied in two ways: • Dilution of gas within the building fabric by providing adequate volume flow rate of fresh air to disperse gas; and • Dilution of gas before entering the building, i.e. reducing the concentration to safe acceptable levels so that ingress of gas into the building fabric, if any, will have no adverse affect.	Dispersion will not necessarily reduce gas concentration since gas may still be present or continue to arrive from a gassing source. Indeed, by providing an easier flow path the rate of gas entry may increase in gas concentration if the rate of release to the atmosphere is low. Other protection measures may have to be considered to either replace or supplement a passive venting system. It is generally considered good practice in the absence of reliable gas monitoring information to assume that active venting is required for gas protection measures until proven otherwise. Gas diffusion beneath or within the confined space of a building can be extremely slow and generally cannot be relied upon to provide adequate dilution and dispersion. Therefore, passive venting is normally designed on the basis of advection and the application of a pressure gradient to cause gas dilution and dispersion.	

Available Technique						
Type				Description	Comments	Costs
		Active venting	Mechanical extraction / natural supply	This is the simplest form of venting system and comprises one or more fans, usually of the propeller type, installed in outside walls or in the roof. Air is extracted from the confined space of a building so to draw in fresh air.	It is essential that provision for replacement air is made and consideration given to the location and size of the inlet. Too high a flow rate of gas ingress may cause excessive heat loss within the building. All mechanical and electrical components should be intrinsically safe. It is generally agreed that mechanical techniques SHOULD NOT be installed in residential properties due to maintenance issues.	
			Mechanical supply / natural extraction	This system is similar to mechanical extraction but arranged to deliver fresh air in the building. Such a system necessitates provision for the discharge of foul air by natural means. The system works better with a more controlled movement of air if a ducted system is installed.	An air-cleaning device and air heater with automatic temperature control will normally be required. Too high a flow rate of gas ingress may cause excessive heat loss. All mechanical and electrical components should be intrinsically safe. It is generally agreed that mechanical techniques SHOULD NOT be installed in residential properties due to maintenance issues.	
			Combined mechanical supply and extraction	This system combines the other active venting systems discussed above and comprises supply and exhaust ductwork systems or may employ a fan with fresh air inlet on the low-pressure side of the building.	These systems are generally not suitable for gas protection since they could potentially involve the recirculation of gases. Locating the inlet and outlet vents on opposite sides of the building could possibly alleviate this, although detailed design would have to ensure this. All mechanical and electrical components should be intrinsically safe. It is generally agreed that mechanical techniques SHOULD NOT be installed in residential properties due to maintenance issues.	

Available Technique					
Type			Description	Comments	Costs
Dilution and Dispersion (Continued)	In-ground	Passive venting	Passive venting is the controlled release and dispersal of gas from the ground to atmosphere via a preferential pathway through diffusion and advection of gas to surface outlets to release ground gases to the atmosphere away from sensitive areas of a site. Such preferential pathways may be venting trenches, venting walls and drainage layers. Passive venting is generally of a relatively simple construction and can be: • Low maintenance; • Effective for a long time; and • Installed with minimal intrusion within a development.	Passive venting should be designed to allow gas migration under all circumstances, irrespective of fluctuations in concentration or the emission rate of the gas or changes in the ambient atmospheric conditions, i.e. wind speed, temperature, barometric pressure and rainfall. Detailed knowledge of these variable parameters is required so that the ventilation system can be designed confidently. In addition, comprehensive site investigation and gas monitoring data will be required.	Relatively low cost.

Available Technique					
Type			Description	Comments	Costs
		Active abstraction	Gas is collected via a system of perforated pipes laid on or in the ground and through installed wells by mechanical pumps. The pumps create an artificial pressure gradient in the venting system to draw the gas from the ground, which is then either released to the atmosphere via surface outlets away from sensitive areas of a site or is flared off if the abstracted gas is potentially combustible. Active abstraction is most effective in situations of high and variable gas concentrations and/or rates of emission.	A trial pumping exercise should be undertaken in order to establish: • The mechanical pump capacity required • The zone of abstraction of individual gas wells (generally not more than 30 to 50m) • Spacing of gas wells. The system must be as airtight as possible (generally, a low-permeability material covers the pipework), because if air is drawn into the system from the ground surface it can result in: • Loss of suction of ground gas and a diminished effectiveness of the abstraction system; and • A potentially flammable gas mixture and the potential risk of explosion within the system or even the ground. As a result, the active abstraction system can take a long time to design and install. In addition, it is rarely adequate as a sole means of protection.	Medium cost to install, but ongoing running and maintenance costs.

Available Technique				
Type		Description	Comments	Costs
Miscellaneous techniques	Chemical or biological	Such techniques may rely on chemical (e.g. formaldehyde, methanol, ferric iron salts) or biological control to inhibit gas generation, which in turn prohibits gas migration. Temporary inhibition of methanogenesis may be a useful and practical tool, especially in an emergency, before more permanent gas control measures can be installed.	Difficulties in the process include: • Difficulty in efficient and uniform dispersal; • May only be partially effective; • Chemicals may themselves be degraded and turned into ground gases and increased leachate generation; and • Impact on environment by adding toxic substances to ground.	Can be very expensive.
Note: Techniques shaded in red generally **SHOULD NOT** be installed in low-rise residential properties and are considered only here for the sake of completeness.				

APPENDIX E: INSTALLATION OF A VENTILATED SUB-FLOOR VOID WITH MEMBRANE

APPENDIX E: INSTALLATION OF A VENTILATED SUB-FLOOR VOID WITH MEMBRANE

The use of an airbrick ventilated sub-floor void with a membrane is the most common ground gas protection method employed at the current time within low-rise residential properties and, as a result, requires further discussion. This is particularly the case due to the ease of which the protection can be damaged during and after installation, which can render the development unprotected and potentially at risk from either an explosion of accumulated methane or that an occupant may die of asphyxiation from accumulated carbon dioxide.

E1 CORRECT INSTALLATION OF GROUND GAS MEMBRANES

BRE Report 414 (Johnson, 2001) presents various Watchpoints offering practical information for installation and buildability to highlight where particular attention is required to the detail drawings and during the on-site construction. The most common ground gas entry routes into buildings (see Section 5.3 and in particular Figure 5.1) will be significantly reduced if the Watchpoints for each ground gas protection method are followed. To follow on from these, several areas where particular importance should be applied are presented below. The membrane should cover the whole plan area of the structure to all external faces to seal both the ground slab and also any cavity walls and voids in hollow concrete block work. Figures E1 to E4 provide typical principal construction details for use with a membrane with ventilated sub-floor void.

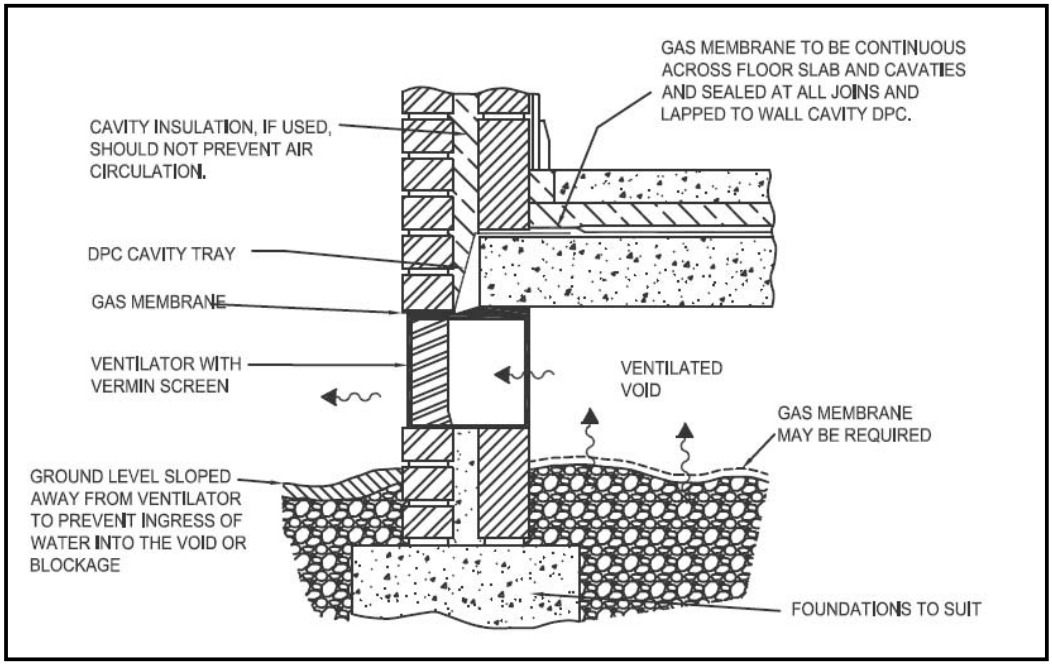


Figure E1: Example Venting Arrangements for Sub-Floor Void – Detail at Junction of Floor and External Walls

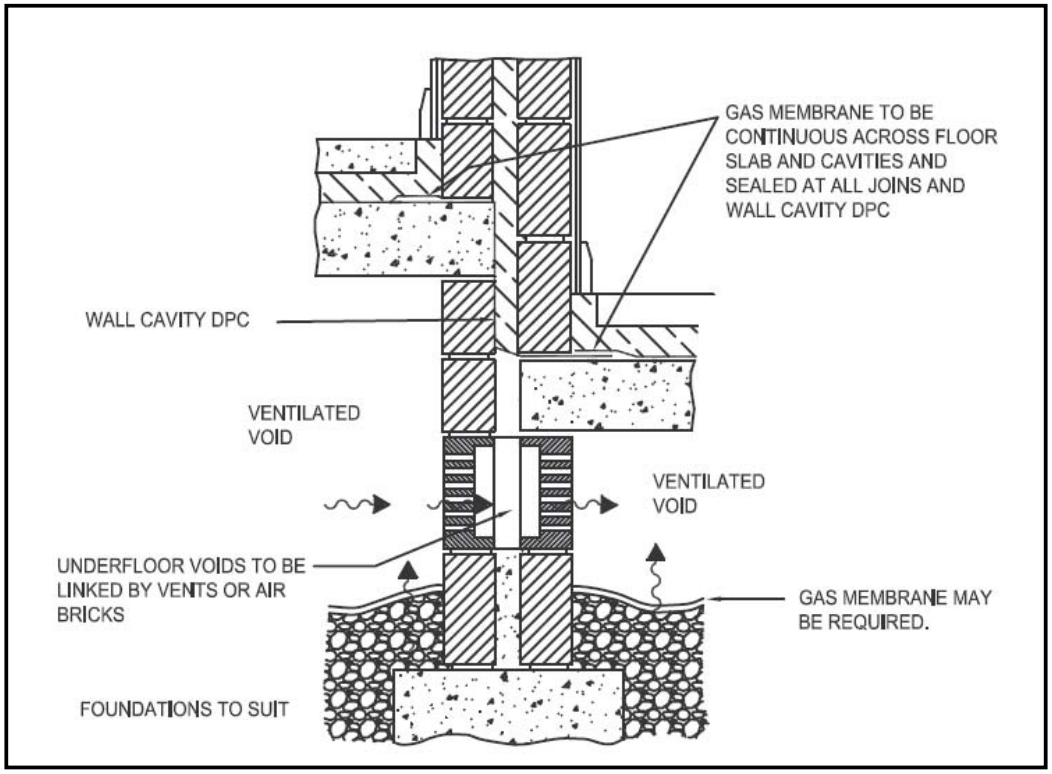


Figure E2: Example Venting Arrangements for Sub-Floor Void – Party Wall Detail at Change of Level

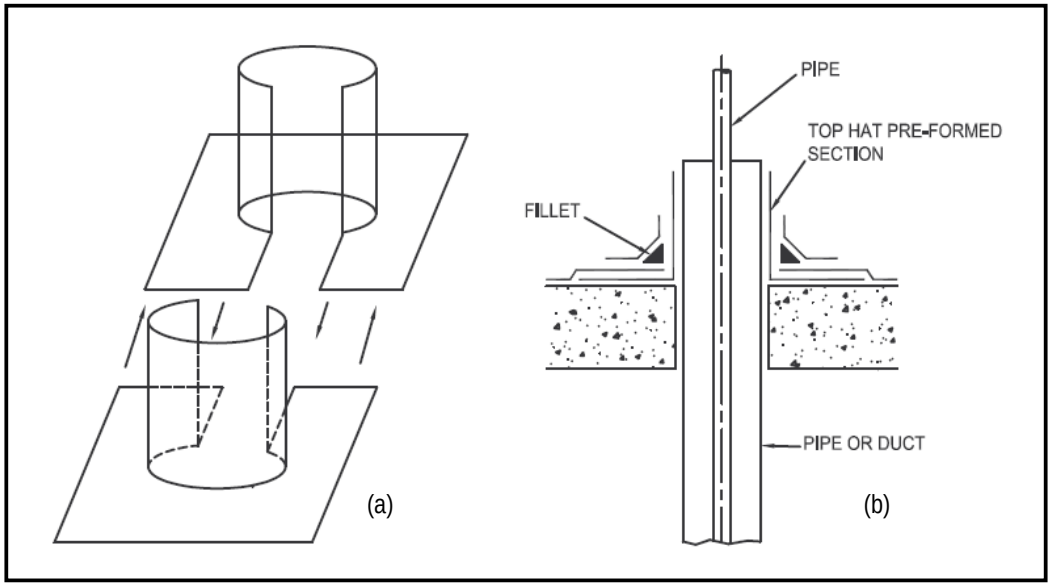


Figure E3: Example Pre-Formed Membrane Sections for Service Entry Points; Collar or "Top Hat" Preformed Section (a) or Bonded Collar to Membrane (b)

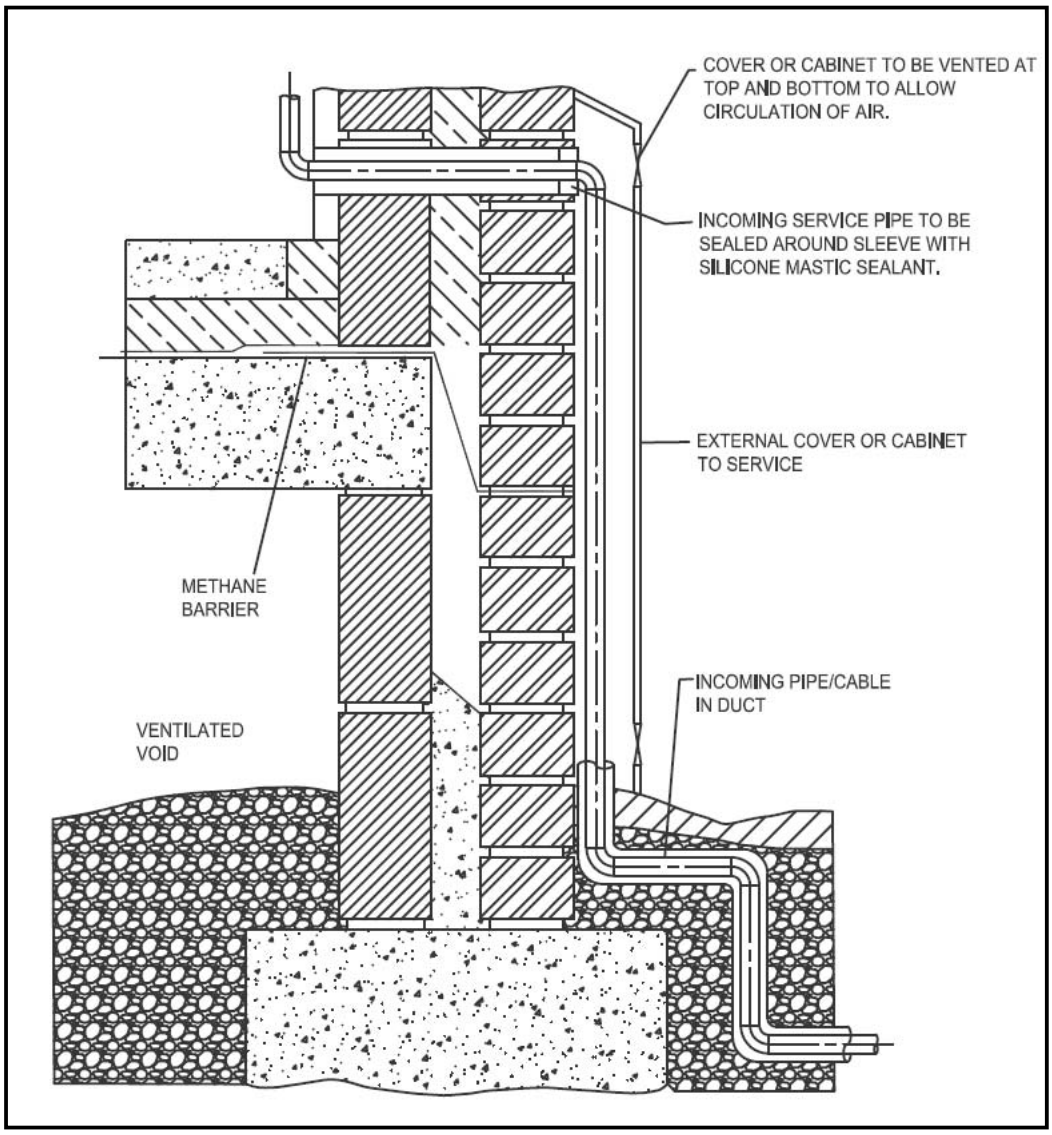


Figure E4: Example Pre-Formed Membrane Sections for Service Entry Points

To reinforce these points, Section E2 presents a series of photographs from a particularly poorly installed sub-floor void with membrane that has had to be extensively replaced at significant cost to facilitate adequate protection of the buildings and occupants. The site where these photographs were taken was determined as Part IIA contaminated land by the Local Authority in accordance with the Environmental Protection Act 1990.

Manufacturers of membranes provide instructions on how to properly lay and install gas proof membranes and should be consulted prior to installation of any membrane. The principal considerations when installing a membrane are given below:

1. Adequate quality control is very important when laying a membrane to ensure that no damage occurs.

2. Membranes should be protected from overlying trades either by the use of temporary boards or sheeting over the whole area, or by immediate laying of the upper slab or floor screed. Protection of the underside of membrane may also be required in certain situations, e.g. when using a granular blanket or double impacted geocomposits as the ventilation layer. A no fines concrete blinding layer of minimum thickness of 50mm or a suitable geotextile should be used.

3. All membranes should be continuous over the whole plan area of the structure. Cavity walls, voids formed in hollow concrete block walls, etc, should be sealed to avoid gas accumulating in them. Careful consideration of the detailing of the gas impermeable damp proof course should be undertaken to avoid creation of slip planes in construction.

4. Continuity of membranes can be achieved by joining separate membrane panels by either overlapping (for self adhesive membranes), taping or welding.

5. For membranes to be overlapped or taped, the separate panels should be overlapped in accordance with the manufacturer's instructions. The joint should have at least the equivalent gas transmission properties as the surrounding membrane.

6. When using thermal fusion/melt bonding on polyethylene membranes, the degree of heat applied needs to be carefully controlled. Too little heat results in poor seam strength and too much weakens the membrane. Particular care also needs be applied in using thermal fusion/melt bonding on thin membranes containing aluminium in order not to completely melt through the polythene layers and damage the aluminium sheet.

7. Elongation of the membrane should be avoided. Aluminium in particular has a very low coefficient of elasticity and will rupture if the membrane elongates, even slightly. The use of HDPE grids and multi-layer LDPE sheets will reduce the ability of the membrane to elongate. If unreinforced membranes containing aluminium are used, then they should be bonded to the slab to prevent elongation.

8. Edges and corners around floor slabs, ground beams, columns and service pipes should ideally be sealed with preformed membrane sections that are either welded to the underlying membrane or fixed with adhesive. Additional protection can be achieved by using a bitumen-based or equivalent sealing tape, to secure the preformed section. Advice on the minimum overlap required to ensure a reasonable gas tight seal should be sought by consultation with membrane manufacturer.

9. If the gas membrane is separate to the damp-proof course, the two membranes should be joined in such a way so as not to affect the frictional resistance of the damp-proof course.

10. Service penetration should enter the building above the sealed floor slab; where this is not possible, the penetrations should be kept to a minimum. Where services need to penetrate the ground slab and membrane, they should be sealed into a slab using a suitable sealant and the membrane should be completely sealed around the protruding service.

11. Prior to laying the upper slab or floor screed, the membrane should be inspected to ensure that no damage has occurred during installation. Any damage should be

repaired to ensure a gas tight seal. Inspection and repair of the membrane should be carried out by either the membrane manufacturer or a qualified installation contractor. This inspection may also constitute a statutory notification to building control.

E2 INCORRECT INSTALLATION OF GROUND GAS MEMBRANES

To reinforce the BRE 414 Watchpoints reproduced within Section E1, photographs E1 to E4 were taken of a particularly poorly installed sub-floor void with membrane that has had to be extensively replaced at significant cost to facilitate adequate protection of the buildings and occupants. The site where these photographs were taken was determined as Part IIA contaminated land by the Local Authority in accordance with the Environmental Protection Act 1990.

Figure E5: Membrane Edges Overlapped, but not Sealed (Note Debris Underneath – see Figure E6)

Figure E6: Debris Underneath Membrane Causing Pressure Points, which may Rip Membrane

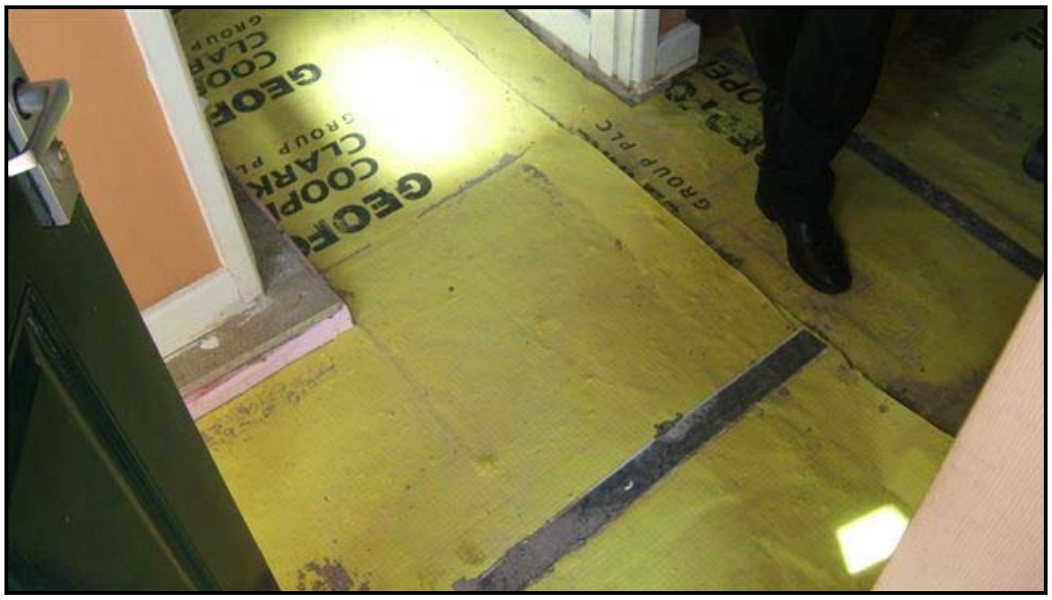


Figure E7: Odd Snippets of Membrane used up, but not Sealed

Figure E8: Crumpled Membrane near Rear Patio Door with no Sealing

Figure E9: Partially Blocked Air Vents within Sub-Floor Void

Figure E10: Water Pipe Entry not Sealed

E3 INTEGRITY TESTING TO ENSURE THE CORRECT INSTALLATION OF GROUND GAS MEMBRANES

The Amber 2 Traffic Lights require the correct installation by certified professionals who should carry out appropriate integrity testing. The most effective post-installation test method is to pressurise the underside of the membrane with an appropriate tracer gas and then sweep the top surface with a suitable gas-detection device (BRE 414). The advantage of this method is that the whole membrane including joints are tested. It has been demonstrated that this test method can detect even very small gas migration routes in the membrane. Any leaks found in the membrane or the joints should be sealed before construction continues.

APPENDIX F: DERIVATIONS OF GAS SCREENING VALUES USED WITH TRAFFIC LIGHTS

APPENDIX F: DERIVATIONS OF GAS SCREENING VALUES USED WITH TRAFFIC LIGHTS

F1 MODEL LOW-RISE RESIDENTIAL DEVELOPMENT

The model low-rise housing development is based upon a model low-rise house as shown in Figure 1. The property has a floor plan of 8.00m x 8.00m, giving a floor area of 64m^2. Continuing the assumption that an individual 50mm internal diameter borehole relates to an approximate area of 10m^2 (proposed by Pecksen (1985) and further expanded by Ove Arup & Partners (1996)), this, therefore, represents 6.4 boreholes for the floor plan of the house.

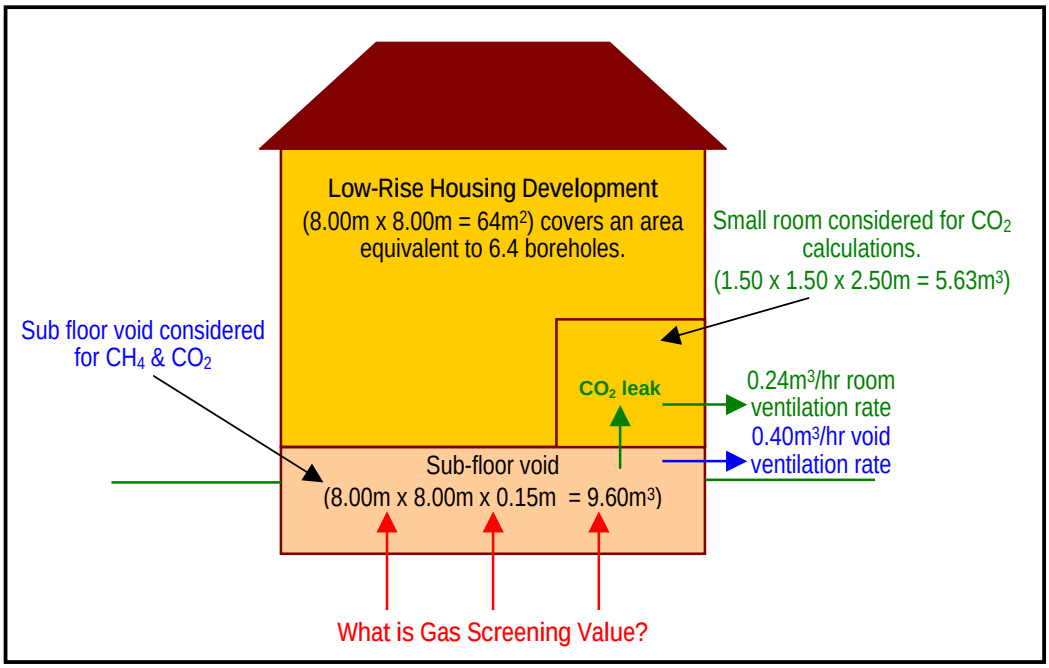


Figure F1: Model Residential Property Developed for Calculating Maximum Permitted Equilibrium Gas Concentrations within the Sub-Floor Void

The model low-rise house was given the minimum recommended sub-floor void height of 0.15m as specified in The Building Regulations 'Approved Document C' (Department of the Environment and the Welsh Office, 2004 edition), which produces a sub-floor void space of 9.60m^3. As a worst-case scenario, it was considered that the ventilation rate within the sub-floor void was subject to a complete volume change every 24 hours, which is considered to be highly conservative. The ventilation rate, therefore, is 9.60 / 24 = 0.40m^3/hr.

For methane, the equilibrium concentration of gas within the sub-floor void is important as a stray ignition source (e.g. dropped cigarette or match) could ignite any accumulated methane, which could seriously affect life and property.

For carbon dioxide, however, it is not considered to be a problem how much gas is contained within the sub-floor void, as humans will not be entering into it. What is of

concern is if the membrane and/or floor above the sub-floor void are accidentally or otherwise penetrated, which would allow for a release of carbon dioxide into the house. Therefore, for carbon dioxide a leak of gas from the sub-floor void into a small room (e.g. downstairs toilet with soil pipe potentially passing into sub-floor void) of dimensions 1.50m x 1.50m x 2.50m with a total room volume of 5.63m^3 was considered. Again, as a worst-case scenario, it was considered that the ventilation rate of the room was subject to a complete volume change every 24 hours, which is again considered to be highly conservative. The ventilation rate within the room is, therefore, 5.63 / 24 = 0.24m^3/hr. The leak from the sub-floor void was assumed to account for ten percent (0.024m^3/hr) of the small room ventilation rate, which is considered to represent a significant leak. Therefore, this is considered to be highly conservative in its approach.

F2 METHANE GAS SCREENING VALUE DERIVATIONS

F2.1 Introduction

When the concentration of methane in air is between the limits of 5.0%v/v and 15.0%v/v, an explosive mixture is formed with normal concentrations of oxygen. The Lower Explosive Limit (LEL) of methane is 5.0%v/v, which is equivalent to 100% LEL. The 15.0%v/v limit is known as the Upper Explosive Limit (UEL), but concentrations above this level cannot be assumed to represent safe concentrations.

The maximum concentration of methane that could possibly be permitted in any sub-floor void, therefore, is 100% LEL (5.0%v/v). However, these concentrations were considered by the NHBC (Boyle and Witherington, 2006) to represent an undesirable maximum and a more conservative maximum permissible equilibrium concentration of 2.5%v/v methane (50% LEL) within the sub-floor void was proposed. This still allows worse ventilation rates to rise from those assumed on extremely still days. 2.5%v/v methane was considered to represent the upper threshold limit for development (Red Traffic Light) and equilibrium concentrations above this would indicate that a standard low-rise housing development with passive ventilation systems would not be acceptable. A lower limiting equilibrium concentration of 1.0%v/v methane within the sub-floor void was taken for the transition between Amber 1 to Amber 2.

The GSVs for methane are derived below.

F2.2 Amber 2 to Red Gas Screening Value

At equilibrium, the maximum concentration of methane considered allowable within the sub-floor void with protection prescribed in Amber 2 to Red is 2.5%v/v. The maximum equilibrium rate of methane entering the sub-floor void is the same as the methane exiting the void, which is 2.5% of 0.40m^3/hr = 0.01m^3/hr = 10l/hr.

Assuming that the house occupies an area equivalent to 6.4 boreholes, the GSV for Amber 2 to Red Traffic Lights is:

- 10 / 6.4 = 1.56l/hr.

The Typical Maximum Concentration for Amber 2 to Red Traffic Lights is 20.0%v/v.

If the GSV of methane is exceeded, it would cause a Red Traffic Light and development should not continue, unless the gassing source can be removed or reduced, or agreement can be reached with the NHBC regarding other detailed protection measures with full legal agreements to cover maintenance and other issues have been addressed.

The Typical Maximum Concentration may be exceeded if the GSV indicates it is safe to do so or a site-specific GSV can be derived.

F2.3 Amber 1 to Amber 2 Gas Screening Value

At equilibrium, the maximum concentration of methane considered allowable within the sub-floor void with protection prescribed in Amber 1 to Amber 2 is 1.0%v/v. The maximum equilibrium rate of methane entering the sub-floor void is the same as the methane exiting the void, which is 1.0% of 0.40m^3/hr = 0.004m^3/hr = 4l/hr.

Assuming that the house occupies an area equivalent to 6.4 boreholes, the GSV for Amber 1 to Amber 2 Traffic Lights is:

- 4 / 6.4 = 0.63l/hr.

The Typical Maximum Concentration for Amber 1 to Amber 2 Traffic Lights is 5.0%v/v.

If the GSV of methane is above this value, it would cause an Amber 2 Traffic Light and development should include protection measures as prescribed in Amber 2. The Typical Maximum Concentration may be exceeded if the GSV indicates it is safe to do so or a site-specific GSV can be derived.

F2.4 Green to Amber 1 Gas Screening Value

If a sub-floor void were to be present, the maximum equilibrium concentrations of methane considered allowable would be 0.25%v/v. The maximum equilibrium rate of methane entering a hypothetical sub-floor void would be the same as the methane exiting the void, which is 0.25% of 0.40m^3/hr = 0.001m^3/hr = 1l/hr.

Assuming that the house occupies an area equivalent to 6.4 boreholes, the GSV for Green to Amber 1 Traffic Lights is:

- 1 / 6.4 = 0.16l/hr.

The Typical Maximum Concentration for Green to Amber 1 Traffic Lights is 1.0%v/v.

If the GSV is not exceeded, no gas protection measures are considered necessary for methane. However, if the GSV of methane is above this value it would cause an Amber 1 Traffic Light and development should include protection measures as prescribed in Amber 1. The Typical Maximum Concentration may be exceeded if the GSV indicates it is safe to do so or a site-specific GSV can be derived.

F3 CARBON DIOXIDE GAS SCREENING VALUE DERIVATIONS

F3.1 Introduction

The UK Health & Safety Executive (HSE) has published information ('EH40: Occupational Exposure Limits 2002', 2002) relating to concentrations of carbon dioxide that humans may be exposed to, which uses concentrations contained in the Control of Substances Hazardous to Health (COSHH) Regulations 1999. These are the Long Term Exposure Limit (8 hour period) and the Short Term Exposure Limit (15 minute period), which are 0.5%v/v and 1.5%v/v carbon dioxide, respectively.

In an unknown penetration of the membrane above the sub-floor void occurred, continued release of carbon dioxide into the small room may happen. If this were to occur, the maximum permissible concentration of carbon dioxide within this room is considered to be at equilibrium 0.5%v/v. It has been assumed that the leak from the sub-floor void will account for 10% of the air in the small room, which is considered to represent a significant leak. Therefore, this is considered to be highly conservative in its approach.

The GSVs for carbon dioxide are derived below.

F3.2 Amber 2 to Red Gas Screening Value

At equilibrium, the maximum concentration of carbon dioxide considered allowable within the sub-floor void with protection prescribed in Amber 2 to Red is not known. However, it is known that the maximum equilibrium concentration of carbon dioxide permissible within the small room is 0.5%v/v.

As previously stated, it has been assumed that the ventilation of the small room is 5.63 / 24 = 0.24m^3/hr and that 10% (0.024m3/hr) of this comes from the leak in the sub-floor void. At equilibrium, the carbon dioxide entering the small room is the same as the carbon dioxide exiting the small room, which is 0.5% of 0.24m^3/hr = 0.0012m^3/hr. Therefore, the maximum concentration of carbon dioxide entering the small room is 5.0%v/v (0.0012 / 0.024 x 100%).

If the maximum carbon dioxide concentration entering the small room is also 5.0%, the equilibrium concentration of carbon dioxide within the sub-floor void must also be 5.0%, which is also the concentration of carbon dioxide exiting the sub-floor void. 5.0%v/v of 0.40m^3/hr = 0.02m^3/hr = 20l/hr.

Assuming that the house occupies an area equivalent to 6.4 boreholes, the GSV for Amber 2 to Red Traffic Lights is:

- 20 / 6.4 = 3.13l/hr.

The Typical Maximum Concentration for Amber 2 to Red Traffic Lights is 30.0%v/v.

If the GSV of carbon dioxide is exceeded, it would cause a Red Traffic Light and development should not continue, unless the gassing source can be removed or reduced, or agreement can be reached with the NHBC regarding other detailed protection measures with full legal agreements to cover maintenance and other issues have been addressed.

The Typical Maximum Concentration can be exceeded if the GSV indicates it is safe to do so or a site-specific GSV can be derived.

F3.3 Amber 1 to Amber 2 Gas Screening Value

For the Amber 1 to Amber 2 Traffic Light, it is considered that the maximum tolerable concentration of carbon dioxide within the small room is 50% of the Amber 2/Red concentration, which is 0.25%v/v. Thus, from the Amber 2/Red calculations, the maximum concentration of carbon dioxide entering the small room is 2.5%v/v. Therefore, the carbon dioxide exiting the void is 2.5%v/v of 0.40m3/hr = 0.01m3/hr = 10l/hr.

Assuming that the house occupies an area equivalent to 6.4 boreholes, the GSV for Amber 2 to Red Traffic Lights is:

- 10 / 6.4 = 1.56l/hr.

The Typical Maximum Concentration for Amber 1 to Amber 2 Traffic Lights is 10.0%v/v.

If the GSV of carbon dioxide is above this value, it would cause an Amber 2 Traffic Light and development should include protection measures as prescribed in Amber 2. The Typical Maximum Concentration may be exceeded if the GSV indicates it is safe to do so or a site-specific GSV can be derived.

F3.4 Green to Amber 1 Gas Screening Value

If a sub-floor void were to be present, which would allow CO_2 to leak into a small room, the maximum equilibrium concentrations of carbon dioxide considered allowable within the small room would be 25% of the Amber 2/Red concentration, which is 0.125%v/v. Thus, from the Amber 2/Red calculations, the maximum concentration of carbon dioxide entering the small room equates to 1.25%v/v of 0.40m3/hr = 0.005m3/hr = 5l/hr.

Assuming that the house occupies an area equivalent to 6.4 boreholes, the GSV for Green to Amber 1 Traffic Lights is:

- 5 / 6.4 = 0.78l/hr.

The Typical Maximum Concentration for Green to Amber 1 Traffic Lights is 5.0%v/v.

If the GSV is not exceeded, no gas protection measures are considered necessary for carbon dioxide. However, if the GSV of carbon dioxide is above this value it would cause an Amber 1 Traffic Light and development should include protection measures as prescribed in Amber 1. The Typical Maximum Concentration may be exceeded if the GSV indicates it is safe to do so or a site-specific GSV can be derived.