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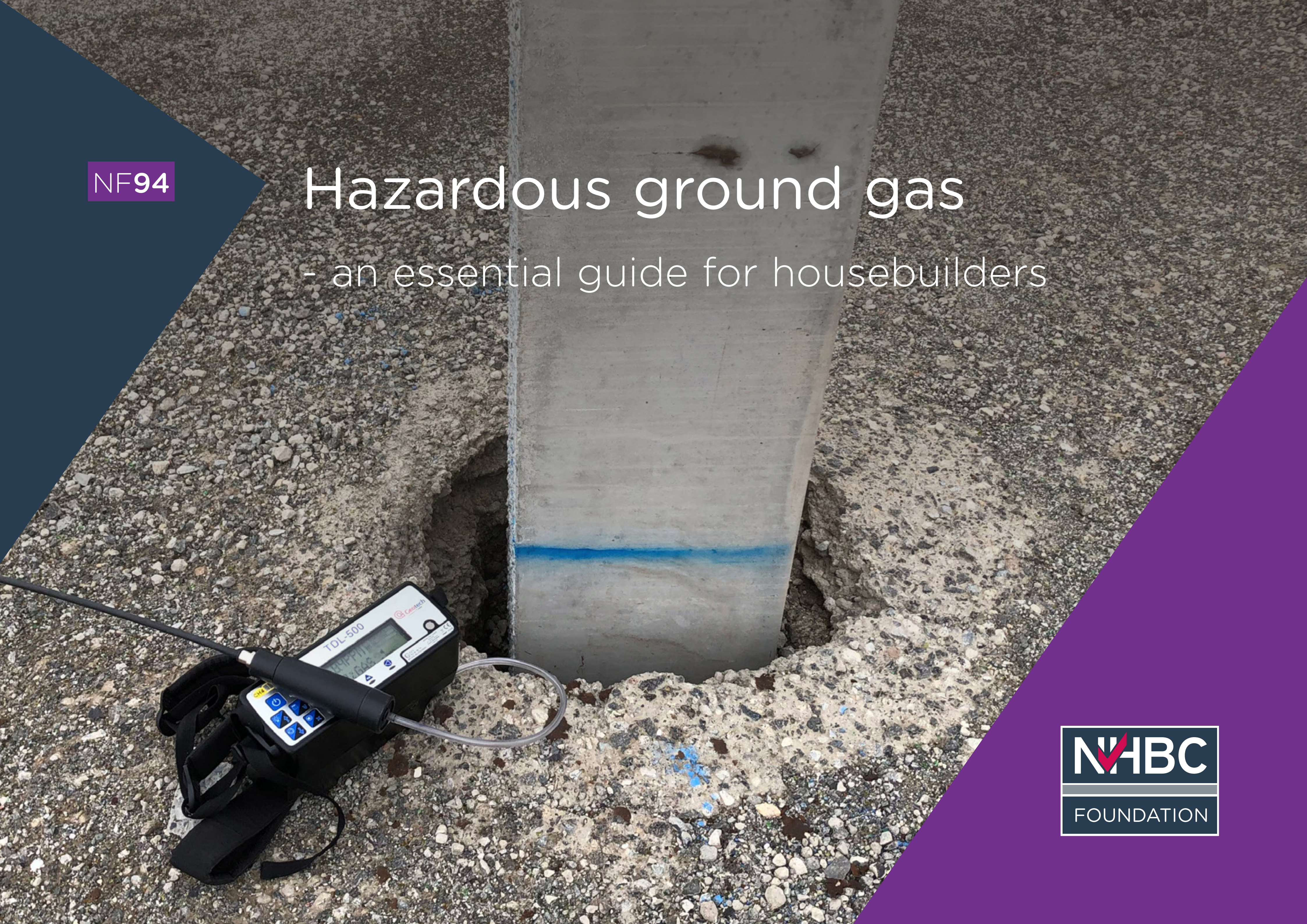
Hazardous ground gas

- an essential guide for housebuilders



NHBC FOUNDATION

Hazardous ground gas
- an essential guide for housebuilders

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Summary

Purpose

The overall aim of this Guide is to provide updated good practice guidance on ground gas issues and housebuilding. The advice ranges from initial investigations and assessment of ground gas regimes to the application of gas protection measures and is structured to reflect the six stages of the hazardous ground gas management process. It applies to housing of construction types typically employed by NHBC's major builder customers. Adoption of these good practice procedures will result in improved quality of advice and construction practice, in cost savings, and in raised awareness of some key issues specifically in relation to detailing, construction and verification.

Competence

Throughout the Guide and at each Stage, reference is made to competence. The quality of the work carried out at all stages of the process depends hugely upon the competence of the individuals and the organisations involved. This competence is also important when reports are submitted to support or enable the discharge of Planning or NHBC Conditions, where the regulators are encouraged by Government policy statements to ensure that any such work is carried out by appropriately competent persons (having appropriate knowledge, skills, experience and qualifications).

Stage 1. Desk study and preliminary risk assessment

A desk study relates to collecting information about a site and its surroundings and a preliminary risk assessment involves critical interpretation of that information. The collection of data for any desk study should be rigorous, comprehensive and critical and should always include a site walkover survey. A dynamic assessment of data quality and uncertainty and a multiple lines of evidence approach should be taken. A preliminary risk assessment should be carried out for all the potential contaminant sources (including hazardous ground gas) and all receptors (current and future) identified in the conceptual site model. The preliminary risk assessment should be logical, transparent and repeatable.

Stage 2. Investigation and monitoring

The investigation and monitoring stage of a project must focus upon obtaining data specific to a site and its surroundings (i.e. the definition of the conceptual site model). The data must be obtained using good practice so that all parties are able to recognise its reliability, whilst also understanding its uncertainty. The investigation should follow a multiple lines of evidence approach related to the initial conceptual site model (described by the Stage 1 Desk Study).

Stage 3. Risk assessment

The risk assessment stage of a project is about the rigorous, transparent and repeatable assessment of the potential risks. That assessment should be based on all the data obtained in Stages 1 and 2 giving due consideration and understanding of the reliability, uncertainty and limitations associated with the data. Disassociating the data from the conceptual site model and looking only at the data in a spreadsheet, can only ever lead to flawed risk assessment. There are four approaches by which a quantitative assessment of gas risk and be carried out (the most appropriate determined from the results of Stage 1 and Stage 2) and these are described in the Guide. Including a gas membrane into the design of a building where it is not required is not an acceptable solution to a poor quality investigation or risk assessment.

Stage 4. Design and detailing

The design and detailing of gas protection measures requires more than just adding up points in the BS8485 screening system and providing standard details for membrane installations. The process should be systematic and commence with a general description of the gas protection system necessary to mitigate all of the potentially significant risks. The design of the gas protection system should include consideration of the protection inherently provided by the building construction and any conflict between the building design and gas protection measures. BS8485 advises that the gas protection design should be summarised in a design report and site specific design drawings should be provided. The report should: identify the key assumptions made in the design, justify the points assigned (if using the points system), justify the choice of products including gas membrane specification (not just gas transmission rate), provide ventilation calculations (site specific calculations to demonstrate performance), and include any other specific requirements.

Stage 5. Material specification

The specification of the various elements of a gas protection system is the responsibility of a competent designer. It should not be left to the architect or structural engineer, nor to installers or material suppliers. The specification may be developed at the same time as the design and detailing determined in Stage 4. All products used should be checked to ensure they are fit for purpose, and capable of delivering the design. This should be followed by a check of particular materials against the design parameters with respect to ventilation and the gas barrier. Depending upon the proposed measures, the specified materials should be checked against the planned verification to ensure appropriateness and adequacy.

Stage 6. Construction, installation and verification

The construction and verification of a gas protection system in a project depends upon the awareness and professional implementation of the gas protection measures as designed. Those works must be properly defined and communicated well to all of the relevant workforce. This awareness is critical if the specified protection is to be installed and survive intact the construction process. Irrespective of whether gas protection system is being installed by a specialist installer, by a groundworker or by a general builder, the staff undertaking the work should have been provided with adequate training to ensure that the system is installed correctly, in accordance with good practice, the design drawings, the specification and the manufacturer's guidance. Once completed, all relevant parties should be able to be confident that the gas protection measures have been installed and will perform as designed and specified. Such confidence can only be gained by an appropriately rigorous programme of verification and publication of a report presenting comprehensive and robust lines of evidence.

Introduction

Purpose

The overall aim of this document set out by the NHBC Foundation, is to provide updated guidance on ground gas related issues. This advice ranges from initial investigations and assessment of ground gassing regimes to the application of gas protective measures. It applies to housing of construction types typically employed by NHBC's major builder customers. In particular, this report up-dates and supersedes the NHBC guidance[1] published in 2007 as best practice and provides concise "how to" guidance for the NHBC registered developers and builders (as well as their advisors and regulators).

There is a substantial body of existing information and guidance related to hazardous ground gas, notably the NHBC guidance[1] and CIRIA C665[3], both published in 2007. Although much of the guidance in these documents remains entirely relevant, the approach to the assessment of risk has changed over the last 15 years. This can and does lead to uncertainty and confusion. Accordingly, this current and up-dated guidance published by the NHBC Foundation advises that the approach should now be as described in the current British Standard (BS8485[4] (and set out in detail here in Chapter 3). It also provides a clear road map (Section 7.1) which allows the reader to use / refer to the all the other guidance documents effectively. The full list of publications referred to in the report is presented in Section 7.2.

Adoption of the good practice procedures described here will result in improved quality of practice and advice, in cost savings, and in raised awareness of some key issues specifically in relation to detailing, construction and verification. The guidance will assist all members of the target audience (i) to recognise the high risk sites (and thus take appropriate action), and (ii) to avoid unnecessary gas protection on low/ minimal risk sites. It is applicable to all sites, small and large, straightforward or complex and everything in between. It recognises that small sites can be complex and large sites can be simple. However, cost savings by sensible assessment and design of mitigation measures on larger development sites can be significant (and equally so can the cost of getting it wrong). The guide therefore places emphasis upon the need for the work at each stage of the process to be carried out by competent professionals with appropriate qualifications and experience.

This guidance:

- will help NHBC registered developers and builders appoint appropriate competent professionals at the right stage
- emphasises the critical importance of understanding and reflecting the conceptual site model at all stages
- promotes the value of a well-executed Phase 1 Desk Study and Preliminary Risk Assessment
- provides advice on ground investigation and monitoring programmes to ensure appropriate and cost-effective delivery
- provides advice on the complete process of assessment, design, implementation, and verification, and
- advises on monitoring strategies that are relevant to the size, complexity and gas risk of the subject site.

This guidance has been prepared to provide advice primarily with respect to the hazardous ground gases, methane, carbon dioxide and to depleted oxygen. Elements of this advice may also be relevant to other gases/ vapours (such as radon or VOCs). However, there are particular issues with respect to the investigation, assessment and remediation of VOCs and radon, which must be addressed by reference to the relevant specific guidance and by appropriately competent and experienced personnel.

This guidance also provides advice on the inherent gas resistance that is present in current "typical designs" (for example from an underfloor ventilated void or from waterproof concrete construction). It provides advice on assessing gas risk and designing mitigation measures and considers evolving approaches to housing construction such as modular construction, timber frames and new materials. It addresses the current (and frequently encountered) "gap" between the conclusions and recommendations of ground investigation reports and the structural design of buildings (where recommendations for gas protection measures may fail to be incorporated).

Structure

This report is structured to reflect the six phases of the hazardous ground gas management process (see Figure 1 overleaf). Following this Introductory chapter, the subsequent chapters present the guidance relevant to each phase / Stage of activity, namely;

Stage 1. Desk Study and Preliminary Risk Assessment

Stage 2. Investigation and Monitoring

Stage 3. Risk Assessment

Stage 4. Design & Detailing

Stage 5. Specification of Materials

Stage 6. Construction & Verification.

Hazardous Ground Gas
Overall Procedure

Stage 0
Inception

Define
Site,
Project,
Objectives

Stage 1
Preliminary
Risk Assessment

Carry out
Desk study

Describe
Initial conceptual site model

Undertake
Preliminary risk assessment

Prepare
Desk study report

Stage 2
Investigation and monitoring

Define
Objectives and scope of investigation

Prepare
Specification

Tender
Invitation and award

Implement
Ground investigation
Post investigation monitoring programme

Prepare
Factual ground investigation report

Stage 3
Risk Assessment

Collate
And assess data

Update
Conceptual site model

Carry out
Generic Quantitative Risk Assessment (GQRA)

Carry out
Detailed Quantitative Risk Assessment (GQRA)

Define
Level(s) of risk

Identify
Need for gas protection

Prepare
Risk assessment report

Stage 4
Gas Protection - Design and Detailing

Describe
Gas protection system

Design
Ventilation

Design
Barrier and detailing

Verification
Plan

Stage 5
Gas Protection - Specification

Product
Consideration
Fitness for purpose
Performance
Vulnerability

Ventilation
Adequacy
Airflow

Barrier Specification
Data sheet review
Permeation
Durability
Strength
Thickness

Verification
Plan
Scope
Testing

Stage 6
Construction, installation and verification

Preconstruction
Kick off meeting

Define
Verification programme & activities

Installation
Gas protection system

Implementation
Verification activities

Prepare and Publish
Verification report

Figure 1 The phased procedure of hazardous ground gas management

Each of the report's six chapters is structured in the same way. They each start with a Figure illustrating the process applicable to that stage. This is followed by brief comment upon; competence, roles and responsibilities, the current state of the art (derived mainly from responses from the industry to a questionnaire - see below). Key watch points addressing the identified issues then follow and this forms the bulk of the advice and is supported by figures etc. as appropriate. The final chapter includes the full list of references, for which there are citations at key points within the main text. It also presents a matrix of key reference documents for ground gas protection, illustrating at which of the Stages, 1 to 6 that form the structure of this document, they are applicable. Additional information is provided in the Appendices.

Appendix A – Responses to Questionnaire

Appendix B – Bibliography

Appendix C – Standard Details

Appendix D – Example ventilation calculations

Appendix E – Sealing of membranes

Appendix F – Example Verification Plan

Target audience

The target audience for this guidance is primarily NHBC registered developers and builders but it will also be useful for their professional advisors (architects, environmental / engineering consultants etc), contractors and regulators. Recognition of this wide audience is important because problems associated with hazardous ground gas occur because of poor procurement practices and/or a lack of understanding of where appropriate expertise may lie (for example by consulting with product suppliers for advice on ground gas risk assessment). It is also important because the wider industry often relies on advice provided in NHBC documents, even if not using NHBC insurance or Building Control services. This wide range of technical understanding in the target audience has resulted in the document being focused and straightforward avoiding jargon, simplifying procedures by the use of visual methods (e.g. flow charts and drawings) and by appropriate cross referencing to key guidance.

Competence

The quality of the work carried out at all stages of the process depends hugely upon the competence of the individuals and the organisations involved. This competence is also important when reports are submitted to support or enable the discharge of Planning or NHBC Conditions, when the regulators are encouraged by Government policy statements to ensure that any such work is carried out by appropriately competent persons. The authority of reports can also be enhanced by their preparation and submission under recognised schemes such as the National Quality Mark Scheme (NQMS)[6]. It is also important to recognise that the skills or expertise required will change as a project progresses through the stages from the initial investigations, risk assessment and remediation appraisal and design, through to construction and verification. Commentary about the particular skills and competence necessary at each Stage of the process is presented chapter by chapter. It is important to recognise that the competency required will change through the phases of the project. Few people are likely to be competent for all aspects of all Stages.

Box 1 Definition of competence

Competent persons are defined in the National Planning Policy Framework (NPPF)[7] as persons "with a recognised relevant qualification, sufficient experience in dealing with the type(s) of pollution - - - and membership of a relevant professional organisation". This definition is referred to in the Environment Agency's Land Contamination: Risk Management (LCRM) guidance[8] which also explains how practitioners should have appropriate knowledge, skills, experience and qualifications in the relevant aspect of land contamination/ the type of contamination being addressed (hazardous ground gas in this instance).

The LCRM[8] provides examples of how competency may be demonstrated. Reference is made to qualifications and experience in specific technical or scientific disciplines (including multidisciplinary) and to application. Examples cited are:

- A Suitable Qualified Person (SQP) under the NQMS
- The SoBRA (Society of Brownfield Risk Assessment) accreditation scheme (for ground gas and VOCs this would require accreditation for permanent gases and vapour intrusion respectively)
- A SiLC (Specialist in Land Condition)
- Membership of a professional organisation relevant to land affected by contamination
- A GPVS (a specialist registered under the gas protection verification scheme)
- A proven track record of dealing with land affected by contamination (with further detail provided in LCRM).

Chartership with a relevant professional organisation (such as the Institute of Civil Engineers, Geological Society, Institution of Environmental Sciences, or Chartered Institution of Water and Environmental Management) is important in demonstrating competence; not just because it demonstrates that individuals have reached a certain level of technical ability but also because they will be signed up to a code of conduct which should prevent them from providing advice outside of their area of expertise.

Preparation and submission of reports under recognised schemes such as the NQMS can provide increased confidence and ensure the reports are of the expected quality. The declaration signed by the SQP included / submitted with the report will verify that factual and interpretative information meets the required standards and that the work has been carried out by appropriately capable people. A similar scheme is available for the verification of gas protection which is overseen by CL:AIRE (**https://www.claire.co.uk/projects-and-initiatives/gpvs**). A declaration can be made for verification reports that are prepared by a Specialist in Gas Protection Verification (SGPV).

Research carried out

An industry consultation was completed as part of the production of this guide. Engagement with industry was completed primarily by an online questionnaire. The survey was open to all, and responses were requested via email distribution lists, and by direct targeting of specific industry groups and representatives. The purpose of the consultation was to gather feedback on the existing issues being encountered in terms of poor practice in ground gas protection over all stages of investigation, assessment, design, construction and verification. The outputs from the survey have informed the selection of the "Watch points" that have been highlighted in each of the numbered chapters. Full details of the questionnaire and gathered responses are included in Appendix A. The NHBC Foundation is grateful to all respondents to this consultation.

Authors

This guidance has been prepared by Amy Juden and Steve Wilson (The Environmental Protection Group Limited) and by Hugh Mallett (Buro Happold) with advice from the NHBC and in consultation with the industry (developers, consultants, and regulators see Chapter 2) and with particular contribution and advice from Mr Neil Salvidge. The NHBC Foundation is grateful to all of the respondents.

Stage 1 - Desk Study and Preliminary Risk Assessment

1.1 Process and chapter structure

It is important to understand that a desk study relates to collecting information about a site and its surroundings and a preliminary risk assessment involves critical interpretation of that information. The collection of data for any Desk Study should be rigorous, comprehensive, and critical and should not rely solely on a set of environmental data and historical maps obtained from a commercial provider.

The overall process and steps necessary for completing a desk study and preliminary risk assessment is illustrated in Figure 1.1 overleaf. This is followed by comments on particular aspects related to desk studies and preliminary risk assessments, namely; competence (section 1.2), a summary of current issues arising from the industry consultation (Section 1.3), advice on a series of the key watch points related to those issues (Section 1.4) and followed by case studies (Section 1.5).

Stage 1

Preliminary Risk Assessment

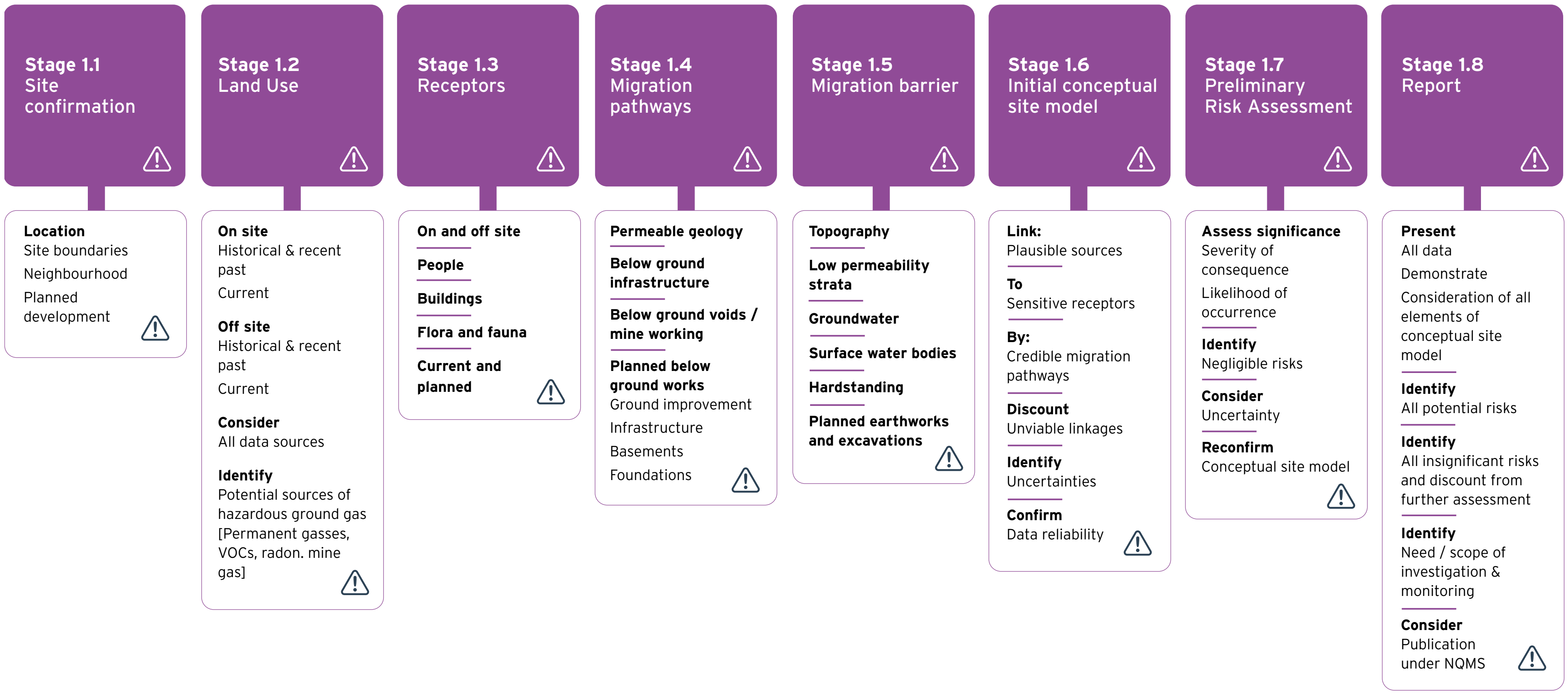


Figure 1.1 Desk study and preliminary risk assessment process

1.2 Competence, roles and responsibilities

It is important to ensure the appropriate expertise of people engaged in preparing desk study reports and carrying out Preliminary Risk Assessments. This is a critical first stage, where errors can have potentially significant consequences (time and money) in later stages. The personnel undertaking and reviewing this work must be able to demonstrate competence, training and experience in the understanding of site geology, in the potential for ground gas generation from pollution sources, backfill and geological strata, and of the factors affecting the potential for gas migration through the ground and into homes or other structures. In addition to engineering / environmental consultancies, the relevant skills and experience are also held by some housebuilders / contractors and also by the NHBC Land Quality Service.

Evidence of the necessary competence of personnel within all of these organisations would include relevant academic qualifications (e.g. earth science degrees) and training / experience. The work, assessment and published reports should all be overseen and reviewed by competent professionals (see Box 1).

1.3 Current state of the art

Based on the industry consultation survey responses the Preliminary Risk Assessment stage was where problems were least often encountered by practitioners compared to other stages of the process. However, the need for improved practice is still recognised as the modal response was that problems are "often" encountered, with this as the response by 32% of respondents.

The top causal factors for problems encountered in ground gas projects at the preliminary risk assessment stage were identified as "lack of competence" (69 respondents) and "lack of training" (54). "poor data quality" (29) and "lack of funds" (27) were also frequently identified as causal factors. Causal factors such as definition of responsibly (14) and the procurement process (11), and existing published guidance (3) were less often identified as being relevant at this stage of the process.

The key issues identified by survey respondents at the desk study stage were counted and grouped. The most frequently identified issues related to:

1. Lack of data sources gathered in the desk study assessment, including missing walkover survey or Local Authority records not gathered (see Section 1.4.1)
2. The Conceptual Site Model (CSM) and recognition of gas migration pathways, including geological and those altered or created by the development proposals (see Section 1.4.2)
3. Factors affecting generation potential of gas sources not being fully understood including age of fill, depth, distance to buildings or natural alluvial soils being miss-identified as a high risk source (see Section 1.4.3)
4. Failure to identify unconventional gas sources, including potential for vapours and coal mine gases (see Section 1.4.4)

Over conservatism, failing to determine that certain gas sources are low risk, or that the CSM means they are not relevant for the site (see Section 1.4.5) and conversely, failure to recognise high risk factors (see Section 1.4.6)

1.4 Watch points

1.4.1 Desk study and data gathering

All of the relevant guidance including British Standards[4,9] and the NHBC Standards[10] state that you must start with a desk study / preliminary risk assessment. It is important to recognise that a desk study is not just obtaining historical data and maps from a commercial supplier (nor is it a client's insurance policy). A desk study is a critical and essential first step in understanding the ground conceptual site model and should be carried out with reference to all of the relevant guidance.

Arguably the most important step in the preliminary assessment is the information gathered to inform it. The bullet point list below summarises the main sources of relevant information. The assessment can only be as good as the evidence available. A dynamic assessment of data quality and uncertainty should be undertaken during the preliminary assessment and building the conceptual model. A multiple lines of evidence approach should be taken, with multiple sources consulted to conclude the actual/predicted site conditions. If data sources provide conflicting evidence this should be explicitly stated in the assessment, and the reliability of the sources compared/assessed.

- Walkover survey with site reconnaissance (required)
- Previous ground investigation records, if available
- Commercial environmental search report
- Historical maps and aerial photographs (Groundsure, Landmark, Google Earth, British Library etc).
- Internet searches (of the site name, local area, land uses etc.)
- BGS maps, published reports, and borehole records
- Coal Authority records
- Opensource data (**www.data.gov.uk**) including current and historic landfill boundaries
- Local Authority records: manual search of planning portals and/or paid contaminated land search reports
- Local history records, Historic England, National Archives
- Existing topographical surveys and Google Earth photos and elevation profiles.

Information used in the assessment can be presented in full in appendices to the report. The main body of the document should reference the information sources (not reproduce them) and provide the professional interpretation of the data in terms of a description of the site conditions, and the conceptual model. At this initial stage it is also extremely helpful to set out all of the available information about the proposed development (e.g. development type and layout, proposed earthworks and ground levels (current and proposed formation levels) and basements etc.). If this information is not known, this should be stated clearly in the report and reflected in the risk assessment and recommendations for subsequent work.

Box 1.1 Walkover survey

A walkover survey is required as a part of any Desk Study. It is not an optional "nice to have". Internet searches of publicly available information, including local authority planning records should be used to supplement other information sources. BGS has published regional geology and hydrogeology guides for many regions that might contain useful information to refine the conceptual model.

1.4.2 Initial Conceptual Site Model and Preliminary Risk Assessment

Based on the data gathering, the conceptual site model details the sources, receptors, and pathways for ground gas for the site and the development. If plausible ground gas contamination linkages are identified, these should be specific to identified sources of gases in the ground, either on or off site. For a linkage to be present there must also be a plausible pathway for gas migration linking the source and receptor(s). An assessment of the pathways for ground gas needs to be done in three dimensions in space, and as such it is good practice to present drawings showing the sources, pathways and receptors, both in plan, and in section.

Factors affecting plausibility and significance of the potential gas pathways that are often missed include:

- topography (particularly relevant for off-site sources)
- whether a landfilled area was placed above original ground levels, rather than in a former quarry or pit excavation
- The presence of plausible mine gas sources, both shallow workings and deep workings (if un-flooded and/or linked to the site by preferential pathways). Further information on mine gases is given in section 1.4.6 and the relevant CL:AIRE good practice guidance[11]
- presence of groundwater and/or surface water that can act as a barrier to gas migration and/ or groundwater which can contain dissolved gases (see section 1.4.5)
- impermeable surface coverings
- permeability of soil strata and distance (vertical and or lateral) through which migration would need to occur
- geological structures (faults, joints, fissures, bedding planes etc.) which can act as preferential migration pathways
- inherent mitigation to ground gas ingress in proposed construction (i.e. raft foundation)
- changes to ground conditions and topography due to the development (e.g. earthworks or basement excavations)
- generation potential of the source materials (see section 1.4.3).

Further guidance on conceptual site models for potentially contaminated sites is provided in BS EN ISO 21365[12].

Box 1.2 Sketch the conceptual site model

It is always helpful to sketch a cross-sectional conceptual site model diagram as part of your Preliminary Risk Assessment. Include consideration of topography, ground conditions, groundwater levels, lateral distances and all details of the proposed development that are available. Try and draw it approximately to scale. This will help you imagine the site in three-dimensions and identify if there are credible ground gas pathways. The diagram and associated plans may also help you design the most effective ground investigation.

A preliminary risk assessment should be carried out for all the potential contaminant sources (including hazardous ground gas) and all receptors (current and future) identified in the conceptual site model. The preliminary risk assessment should be logical, transparent and repeatable. There is likely to be significant uncertainty at the end of the preliminary risk assessment stage and both the results of the assessment and this uncertainty will inform the need for, scope and design of any Phase 2 intrusive investigation.

The intrusive ground investigation should be designed and targeted to the conceptual model to gather the further data required to reduce the uncertainty and provide key parameters for use in the risk assessment. The data relevant to the ground gas risk assessment is not limited to ground gas monitoring. It is likely to also be concerning the source materials (e.g. soil testing for total organic carbon (TOC), forensic TOC, depth of fill, delineation of organic Made Ground, estimation of degradable materials) or the potential pathways (e.g. permeability analysis, groundwater levels, location of mine shafts). Further information on designing intrusive investigations is given in chapter 2.

1.4.3 Factors affecting gas generation and migration potential

The key factors to be considered when assessing the risk associated with ground gas emissions from potential sources are:

1. **Organic content.** The organic content determines the maximum volume of gas that can be generated over the life of the source. As gas is generated the source is used up so with time the source will reduce (and so will gas generation). Most soils have some organic carbon content, typically up to 1% TOC[13] although some soils / rocks such as Mercia Mudstone around Bristol can have up to 2% TOC with no risk of significant gas generation.

2. **Available degradable material proportion.** Many materials contain high concentrations of organic carbon but will still not degrade to produce ground gas in hazardous quantities. For example, asphalt, ash and clinker, plastic etc. Potentially degradable materials include wood and timber, but their ability to degrade very much depends on the form (i.e. timbers can be treated with preservatives which will considerably reduce the potential/speed of degradation, sawdust will be readily degradable) and conditions in the soil (see iii below). Readily degradable material such as fresh vegetable matter and food waste are the key indicators of a high generation potential that can cause hazardous quantities of gas. Note that newsprint is often not readily degradable, and it is not unusual to find old newspapers in 1960s landfills that are still readable.

3. **Nature of the fill material.** In addition to the organic / degradable properties discussed above consideration should also be given to the depth, volume and nature of the source material and how these properties may affect the potential to generate gas and to influence its migration. Deep fill has a greater potential for significant volumes of gas to be generated than thin layers. Cohesive fill materials with low permeability will limit the rate at which gas can escape. Waterlogged/ saturated source materials will also limit gas generation. If fill materials are particularly dense or stiff (rather than loose or soft) this is also a good indication that there is lower potential for gas to be generated.

4. **Age of materials.** As gas is generated the source material is used up. Therefore, over time the volume of the source reduces along with the more easily degraded material and the rate of gas generation and potential for emissions falls. For geological alluvium which has been deposited hundreds or thousands of years ago the generation rates will be negligible. The highest gas generation potential is with more recent domestic landfill materials. Older landfills from the 1960s and earlier, typically contain mainly non-degradable items (e.g. ash, clinker etc.) and their age means that any easily degradable material has normally been used up. 1970s waste would have originally contained an increasing amount of degradable material as the decade passed. However, such landfilled wastes are now up to 50 years old and gas generation will be declining from these sources. 1980s and 1990s landfill is probably the most critical in terms of potential development sites (later sites are not likely to be suitable for residential development).

5. **Distance from receptor.** The greater the distance between the source materials and the building(s), the less potential there is for a gas hazard to exist for a development. As gas is generated it will tend to migrate both vertically (to atmosphere) and laterally. The lateral distance the gas is capable of migrating will depend upon many factors, all of which must be identified (in the conceptual site model) and considered. The nature of the gas generating source (see i to iv above) is the most significant factor. Substantial lateral migration will usually only occur for active sources which are generating gas under pressure. Older landfills typically retain residual levels of gas within the waste, but pressures / flow rates are normally minimal so there is much less potential for lateral migration. However, driving pressures to promote migration of gas can also be provided by falling atmospheric pressures. This is particularly relevant for low generation rate sources, where there is also preferential pathways (see vi below), a permeable reservoir, or void for gas to collect in in the ground. Migrating gas will always take the path of least resistance, so will often preferentially migrate vertically, rather than travel long distances in the ground. The exception is if the pathway is interrupted by shallow impermeable layers of soil or surface coverings, which can trap gas in the ground and encourage longer migration distances (within limits).

6. **Presence of preferential pathways.** Lateral migration of hazardous ground gas is normally via permeable soils (such as sand and gravel) or "preferential pathways". Preferential pathways include open fractures or fissures in bedrock and below ground service infrastructure with granular backfill. The presence of such features (if they do actually link the source and receptor) can significantly increase the distance over which gas migration can feasibly occur, and will very much increase the risk of migration from low gas generation potential sources (diffusive flow). Without such pathways gas migration in the ground, even from high gas generation potential sources (with pressure driven advective flow) is unlikely to occur over any significant distance, and will only be relevant to adjacent or close-by receptors.

Box 1.3 Factors to be considered in risk assessment

The Preliminary Risk Assessment for ground gas should include assessment of all the factors (1 to 6) listed above for each potential ground gas source which is identified.

1.4.4 Non-landfill sources of hazardous ground gas

Where biodegradable materials are present in the ground, microbial activity produces methane and carbon dioxide and a number of other trace gases (and also results in depleted oxygen). These commonly known bulk gases (methane, carbon dioxide and depleted oxygen) are typically associated with landfill sites, but can also be derived from many other sources, which should be identified and assessed at the desk study stage. Previous uses of brownfield land (on or offsite) may also give rise to contamination that could be a source of ground gases, both bulk gases and other trace gases (e.g. hydrogen sulphide) and/or volatile organic compounds (typically petroleum hydrocarbons or chlorinated solvents).

- Degradable materials within a soil matrix of Made Ground, are normally fairly low risk source of bulk gases, except where there is a high proportion or readily degradable material in a deep layer of fill (i.e. unregulated landfill).
- Organic silts in docks, rivers and alluvial deposits are low risk sources of bulk gases.
- Peat and other natural geological strata (e.g. Chalk) can lead to elevated concentrations of bulk gases, but are low risk sources that cannot generate gas at a significant rate.
- Chemical storage and spillages leading to general petroleum hydrocarbon or chlorinated solvent pollution in the soil, groundwater, and/or vapour phase, can give rise to volatile organic compounds (VOCs), which require specialist assessment due to their chronic toxicity. Hydrocarbon vapours will also degrade to generate methane, but this is not normally the risk driver on these sites.
- Contaminated leachate migrating from landfills can contain toxic and potentially volatile contaminants and dissolved methane. But the methane will diffuse out of solution and therefore is unlikely to pose a significant hazard.
- Landfilled plasterboard or natural gypsum deposits are the primary sources of hydrogen sulphide gases in the ground. These may pose a significant risk where these materials are present in significant quantities.
- Shallow or deep mine workings are potential sources of bulk gases (mine gas). Mine gas can be a high risk source of gas generation, because of the potential for large volumes to be collected in open voids in the ground and the potential for preferential pathways to be present. Specific guidance on the assessment of risks from mine gas is provided in the 2021 CL:AIRE guidance[11].

1.4.5 Over-conservatism and identification of low risk sources

It may be possible to discount ground gas sources from the conceptual site model at the preliminary risk assessment stage and determine that they are not credible, or do not pose a credible risk of gas migration and ingress to the development. There are numerous sources of ground gas that can cause elevated gas concentrations in monitoring wells. This does not mean that they necessarily pose a hazard to above ground development, and it may be possible to discount these as a credible risk at the conclusion to Stage 1. Such low risk sources that may be discounted include:

1. **Buried topsoil** – a typically thin layer of topsoil present below a building is not likely to present a credible risk of gas emissions.

2. **Unworked Coal Measures** – the presence of unworked coal measures in the ground is not a credible source of ground gas that could impact a building (although it may need to be verified that the seams are not worked, as there is the potential for unrecorded shallow workings, which could be a potentially high risk source).

3. **Limestones and Chalk** – due to the extremely slow rate of degradation in all normal circumstances, Chalk or Limestone bedrock are also not credible sources of hazardous gas emissions.

4. **Groundwater** - Methane is often dissolved in groundwater plumes (see Figure 1.2), especially where there is hydrocarbon contamination and degradation is occurring. In any event the dissolved phase gas does not normally present a hazard to above ground development unless the water level is extremely close to the underside of a slab or water is entering a deep basement where the dissolved gas can then come out of solution. The dissolved gas is normally in equilibrium with the soil gas in the unsaturated zone and it diffuses slowly to the surface. The high moisture content at the capillary fringe limits the rate of diffusion and provides good conditions for bacteria to oxidise the methane.

5. **Alluvium** - Natural alluvium or mud flat deposits, including geological peat, are very unlikely to be credible sources of ground gas on most sites. The organic material is locked in a low permeability matrix. The gas generation rates are incredibly low, except when oxygen is artificially introduced via borehole or ground disturbance. Card et al[5] advise that the gas that is measured in Alluvial soils is predominantly from historic generation and is effectively immobile in the ground because of the saturation and low permeability of alluvial soils. Methane is also adsorbed onto the organic material and is only mobilised when a well is drilled into it.

6. **Made Ground** - Made Ground soils are not inherently a significant source of hazardous ground gas. Typically, substantial proportions of putrescible materials such as vegetation, food waste, paper, cardboard, wood are required to be a source of gas in the ground. The likely source of Made Ground on site needs to be considered when determining if it is a credible source of gas. Shallow Made Ground comprising predominantly construction and demolition waste is not a credible source. Made Ground comprising reworked natural soils is very unlikely to be a significant source of gas. The type of organic material is also relevant, ashy Made Ground may have a high TOC, but it is not readily degradable. Infilled features can be sources of ground gas, but small natural ponds filled a long time ago are unlikely to be a significant source, due to the limited volume and age of any backfill.

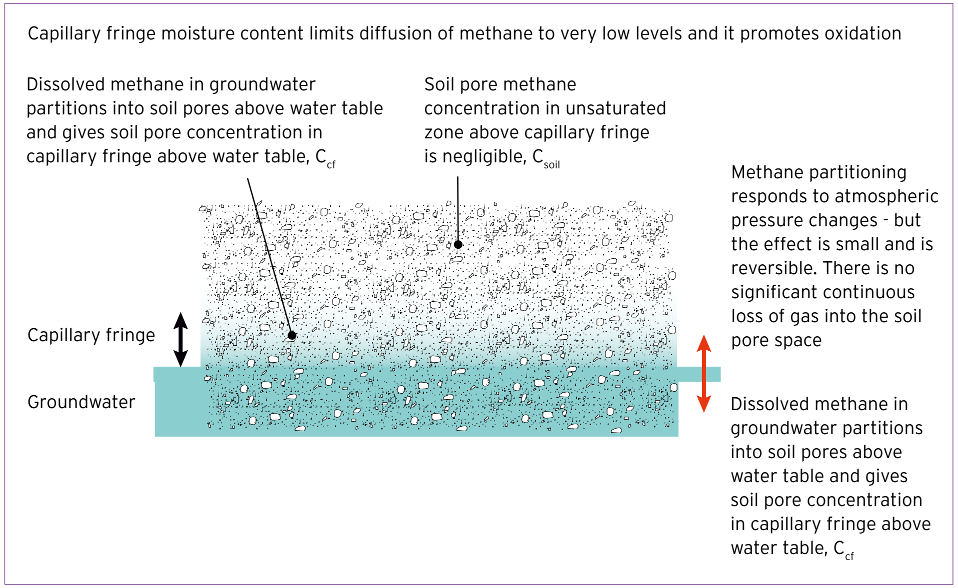


Figure 1.2 Methane dissolved in groundwater

Box 1.4 Consideration of gas generation potential

Backfill materials should not be treated equally when it comes to gas risk assessment.

Made Ground comprising mostly soil without significant proportions of degradable materials is not likely to be a significant gas source. The likely gas generation potential of fill materials should be determined at the desk study stage and verified during intrusive investigations. This is one of the most important lines of evidence of any ground gas risk assessment.

1.4.6 Identification of high-risk scenarios

Key factors to consider when determining if a ground gas potential pollutant linkage might be high or very high risk are the gas generation potential of the source, and the presence of preferential pathways.

In all cases where ground gas ingress incidents have occurred advective flow, generally (but not always) caused by drops in atmospheric pressure, has caused hazardous flow of gas from the ground into buildings. Therefore, the key to identifying high risk sources is to determine whether there is (or could be in the future) sufficient volume of gas under pressure to support advective flow into a building. If the limiting factor is diffusive flow through the ground and there are no significant preferential pathways then the risk will be low.

Three key high-risk scenarios are summarised below:

1. Advective flow from a landfill with a high gas generation rate to properties directly above, or close-by with migration through the ground.
2. Diffusive flow in the ground, migration via preferential pathway, accumulation in a permeable reservoir or void very close to a building and subsequent pressure drop causing ingress to a property.
3. Mine gas flow via preferential pathways.

For buildings located on landfill sites that are still in the active gas generation phase it is likely that sufficient gas is being generated to support pressure driven flow of gas through the ground towards the underside of the building and into it (Figure 1.3). This is a high risk scenario. Whether this occurs will depend on the gas generation rate and the presence of any low permeability layers in the ground such as capping layers.

High generation rate landfills with pressure driven flow are also the most likely to cause lateral migration of ground gas. Where development is within the zone that pressure driven flow is occurring, or can occur, the landfill gas risk will potentially be high. This zone is likely to be quite small, and without any significant preferential pathways may only extend to within 100m of the landfill perimeter. Head losses in the soil outside the landfill mean that the pressure quickly dissipates, and flow then occurs by diffusion. The distance over which significant gas migration will occur therefore depends on head losses outside the landfill. Head losses will be greatest in fine grained soils (shorter migration distance) and least in fractured rock with preferential pathways along open joints (longer migration distance).

It is possible for lateral gas migration to occur over very significant distances (>400m), but these scenarios are rare and must include migration along low head-loss preferential pathways that are also sealed over with an impermeable layer to prevent venting to atmosphere between source and receptor.

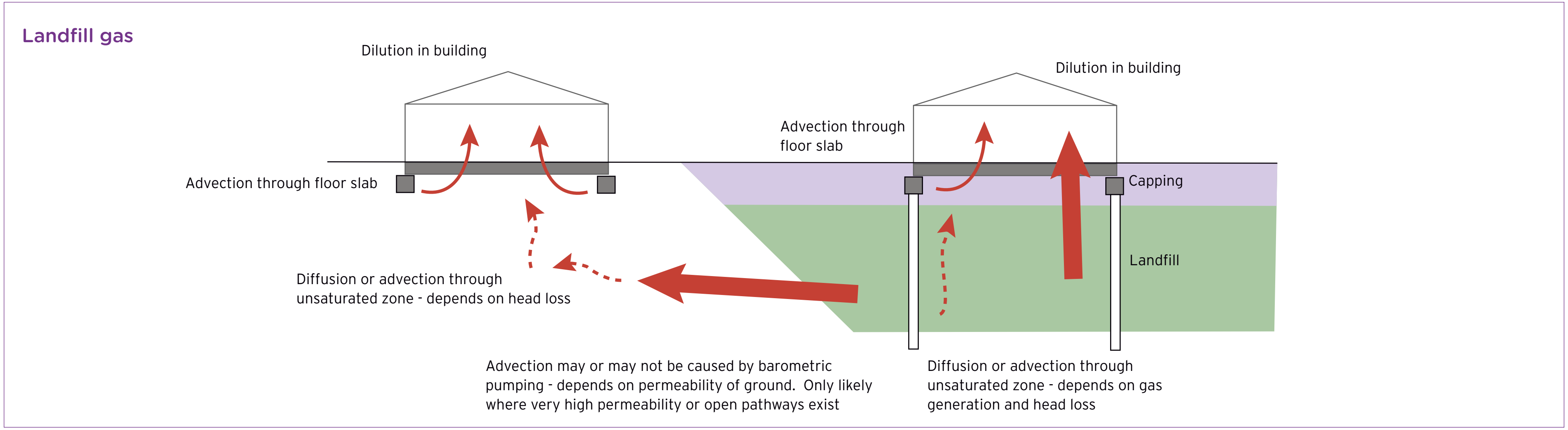


Figure 1.3 Diffusive and advective flow - landfill gas

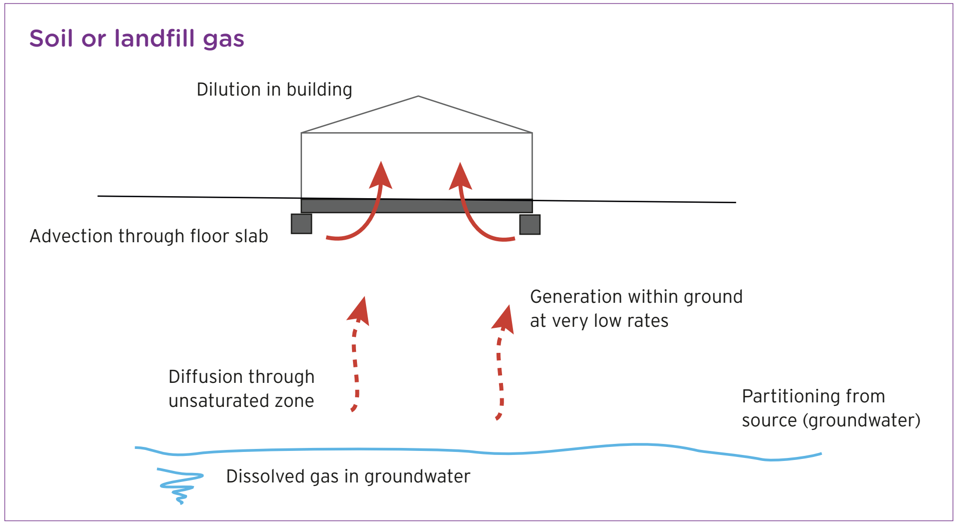


Figure 1.4 Diffusive flow - soil or landfill gas

Soil gas within the zone of influence of a building will be sucked into it by pressure driven flow across the floor (see Figure 1.3 and Figure 1.4). This occurs because of the slight negative pressure inside the building and the flow rate will respond to changes in barometric pressure.

If generation rates are low (for example older or inert landfill sites) the flow may be driven by diffusion and ground gas risks will be lower. This is likely to be the case for 1950s and 1960s landfill sites and may be the case for some 1970s sites. Diffusive flow of gas through the ground will be the limiting mechanism for low generation rate sources such as soil based Made Ground with limited degradable material, Alluvium and similar materials. This is also the case where the source is dissolved gas in groundwater.

Gas flowing by diffusion through the ground may migrate to the underside of a floor slab. However, if gas flow in the ground is diffusion driven the risk of ingress to the building is still likely to be low (Figure 1.4). This is the same conceptual model as used in vapour intrusion assessments for VOCs. Therefore, the analytical models used to assess vapour intrusion can be used as basis for assessment of any ground gas where diffusion is dominant driver for gas flow to the underside of the slab (methane, carbon dioxide, radon, etc).

Although diffusive flow is normally indicative of a low risk situation, under specific circumstances, involving preferential pathways there are exceptions to this. Where a large highly permeable reservoir or void (i.e. open fractured rock, soakaway, stone columns) is located close to the underside of the building, it is possible for a significant volume of gas to accumulate over time, and then be driven into the structure during an atmospheric pressure drop. Gases generated naturally by diffusion limited processes are unlikely to be present in significant enough volumes for this scenario to be feasible (i.e. alluvial soils, biological respiration in soil, dissolution from groundwater) but where a landfill (even an older landfill) or mine gas source is involved and connected to the building via a suitable pathway this high risk scenario could exist.

Shallow mine workings or entries to deeper workings are potentially high risk scenarios due to the significant reservoirs for gas to accumulate in the ground and the open preferential pathways (see Figure 1.5). The risk should be assessed following the relevant CL:AIRE guidance[11]. Advective flow of gas from the ground can occur directly into buildings via either fractured rock with open joints or mine entries themselves. Other similar scenarios are where shallow workings are intercepted by stone columns or old open and unsealed site investigation boreholes. There are also similar situations where shale gas or oil bearing rocks underlie parts of Scotland (e.g. in the Gullane Formation below Edinburgh which was previously known as the Lower Oil Shales). This is a high risk scenario for ground gas where there are open unsealed site investigation holes or other pathways that penetrate the overlying drift deposits.

Mine gas

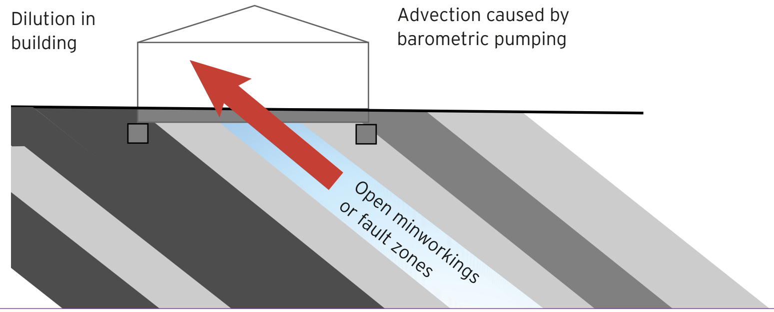


Figure 1.5 Open mine workings or fault zones

Box 1.5 High risk scenarios

High risk ground gas scenarios are likely to involve domestic landfill or mine gas sources.

High risk gas flow is via advection where significant volumes of gas migrate under pressure.

If flow is by diffusion the scenario is likely to be lower risk, but the presence of significant open pathways and potential gas reservoirs in the ground (e.g. fractured rock, drainage systems or mining shafts or adits) can increase this risk.

1.5 Case studies

1.5.1 Case Study 1. Inadequate desk study

Proposals for the construction of a new housing estate were put forward on derelict / disused land. No desk study was carried out and the limited ground investigation was focussed upon geotechnical properties and foundations. The site was developed in phases. During construction of Phase 3, substantial thicknesses of fill materials were encountered. Belatedly, some ground investigation and gas monitoring was undertaken and elevated concentrations of carbon dioxide and methane were recorded. Construction stopped and concerns were raised about the safety of the already developed phases. Investigations were instigated by the local authority, commencing with a desk study. This study identified historical activities on the site which included aggregate extraction, a saw mill and some land filling. Ground investigation on the developed phases included works in homeowners gardens, confirmed elevated concentrations of hazardous ground gas with associated elevated levels of risk and raised considerable alarm with homeowners (on the already developed phases of the development) faced with issues of blight etc. Remedial retro-fitting of gas protection measures (sealing service entries) eventually remedied the situation. The whole process was fraught. It involved considerable delay to the completion of the development, disruption to the lives of the residents of the developed phases and substantial costs for the developers.

A Desk Study at the start of this project would have identified the potential risks associated with hazardous ground gas and would have informed an appropriate ground investigation and monitoring programme. Gas protection measures would have been designed into the buildings from the outset. The complexities associated with the phased development would have been avoided. There would have been no delay to the build programme. No residents would have been put at risk. All of the disruption to people's lives and well-being and the financial uncertainty would have been avoided.

1.5.2 Case Study 2. Desk study demonstrates low risk of ground gas

A site was being redeveloped for housing within an existing area of housing in north London. The site was occupied by a large residential building since the 1950s and prior to that was parkland. The desk study indicated:

- the residential building did not have a basement
- there was no evidence of any previous industrial use of the site or surrounding area, and
- there was no evidence of previous quarrying or landfilling below the site or in the surrounding area.

The geological map indicated that the site was underlain by London Clay with no drift deposits present. Therefore, the desk study information indicated minimal risk from ground gas. At this point following the relevant good practice guidance[13, 14 and 4], it should have been apparent that the site was not at risk from ground gas and also that gas monitoring was not required as part of the site investigation. The gas risks could have been signed off at this point with no need for monitoring or protection measures.

Despite this the consultant installed gas monitoring wells in site investigation boreholes and completed gas monitoring. This was an unnecessary cost for the client. The design of the monitoring wells was also inappropriate in any event – see Case Study 3 in Section 2.

Stage 2 - Investigation and monitoring

2.1 Process and chapter structure

The investigation and monitoring stage of a project is all about obtaining data specific to a site and its surroundings. In terms of a conceptual site model, no two sites are ever the same and thus the data obtained for each site in terms of the hazardous ground gas regime will be unique. Accordingly, the collection of such data must be obtained using good standard practice so that all parties will recognise its reliability whilst also understanding the uncertainty associated with it. It is a well-rehearsed mantra that no ground investigation can ever determine absolutely the nature and variation of the geology, contamination, or hazardous ground gas regime on a site. But it is also true that the data that is obtained must be of quality, accurate and defendable and thus suitable for use in the Stage 3 risk assessment process.

The process and steps necessary for completing a programme of investigation and monitoring is illustrated in Figure 2.1 overleaf. This is followed by comments on particular aspects related to ground investigation and monitoring, namely; competence (section 2.2), a summary of current issues arising from the industry consultation (Section 2.3), advice on a series of the key watch points related to those issues (Section 2.4), followed by case studies (Section 2.5).

Stage 2
Investigation and Monitoring

Stage 2.1 Objectives

Identify
Objectives with respect to hazardous ground gas

Include
Geotechnical and geoenvironmental objectives

Exclude
Hazardous ground gas if discounted at Stage 1

Delineate
Source materials

Describe and test
Source materials

Determine
Hydrogeological regime

Measure
Gas composition and generation rate

Stage 2.2 Scope and methodology

Plan
Fully reflect the conceptual site model including development plan

Exploratory holes
Target sources & pathways

Spatial distribution/depth

Drilling method
Optimise installation quality

Optimise sample recovery

Design / install installations
Response zones

Headworks

Sampling & Analysis Plan
Soil, groundwater and gas/vapour

Test Methods

Limits of Detection

Gas and groundwater monitoring plan
Frequency & duration

Technique (spot/ continuous)

Stage 2.3 Specification

Reference
UK Specification for Ground Investigation

ICC Conditions of Contract for Ground Investigation

Include
Contract Drawings and Bill of Quantities

Define
Roles & responsibilities

Obtain
Relevant permissions

Stage 2.4 Tender invitation, evaluation and award

Prepare
Tender documentation

Define
Evaluation criteria (inc competence)

Provide
All relevant pre-construction information and specification

Evaluate
Based on defined criteria

Award
Best overall score - not lowest price

Stage 2.5 Intrusive works

Undertake
All site activities in accordance with specification & industry good practice

Appropriate site supervision

Note any deviations from specification

Logging
Accord with BS5930 and BS10175 and relevant good practice guidance

Consistent with drillers logs/ observations

Continuously review
Encountered ground conditions & vary implementation accordingly

Stage 2.6 Monitoring programme

Undertake intelligently
Appropriate time allowed [stabilised readings / suitable minimum period]

Reflect variable meteorological conditions

Check consistency with encountered ground conditions

Check consistency with laboratory analyses

Continuously review and vary accordingly

Stage 2.7 Collate and assess data

Collate
Data for all lines of evidence

Prepare / review factual report for ground investigation

Review
Uncertainties

Adequacy of data for risk assessment

Figure 2.1 Investigation and monitoring process

2.2 Competence, roles and responsibilities

It is important to ensure the appropriate expertise of people engaged in all stages of the investigation and monitoring process. The outputs from this Stage are the data upon which the risk assessments and the need for and scope of any gas protection measures will be based. Inadequate or erroneous data can result in both over-conservative / unnecessary protection measures, or a failure to recognise the need for such measures to mitigate significant risks. The personnel undertaking this work must be able to demonstrate competence, training, and experience in the understanding of all aspects of the ground investigation process (the construction of exploratory holes, sampling of soils, liquid and gas/vapour, monitoring (of gas and groundwater), physical and chemical analysis. There are often several organisations involved at the Stage of the process, each responsible for different elements of the work (described below). Therefore, it is important that at the planning stage of the investigation there are clearly defined roles, including a clearly defined process for checking the quality of the data.

The responsibility for the design of ground investigation, the supervision/oversight and contract management of its implementation, the interpretation of resultant data and the preparation of the interpretive report would usually be held by the consultant (may be, but not necessarily the same organisation responsible for the Stage 1 Desk Study).

The responsibility for carrying out the ground investigation intrusive works is likely to be held by a specialist ground investigation contractor. (Note: There are also organisations which can provide both the necessary consulting and contracting skills). The contractor would construct the exploratory holes, log soils, collect and transport samples to specialist laboratories, install the monitoring wells and prepare a report presenting all of the factual data. The laboratory testing (geotechnical and chemical) should be carried out by appropriately accredited laboratories. These may be a part of the ground investigation contracting organisation, but they may also be independent specialist laboratories. Either the consultant, ground investigation, or a specialist monitoring contractor (sometimes part of the testing laboratory) may carry out the monitoring. Whoever is completing the monitoring needs to be fully aware of the purpose of the work, the site conditions, the ground gas conceptual model, the installation details and the aims and objectives of the works.

Evidence of the necessary competence is required of all organisations commissioned to carry out the work and of their personnel. Ground investigation consultants and contractors should be members of relevant trade associations with defined Codes of Conduct and disciplinary procedures, namely the AGS (**www.ags.org.uk**) and the BDA (**www.britishdrillingassociation.co.uk**). Laboratories should be UKAS, accredited to ISO 17025, use MCERTS tests where available, and participate in relevant proficiency testing schemes (e.g. CONTEST, AQUACHECK).

Personnel within all of these organisations would be expected to hold relevant academic qualifications (e.g. earth science / geology degrees and NVQs) and training / experience. The work, assessment and published reports should all be overseen and reviewed by competent professionals (see Box 1).

2.3 Current state of the art

Based on the industry consultation survey responses the ground gas investigation and monitoring stage was in the middle in terms of the frequency of problems encountered by practitioners. The modal response was that problems are "often" encountered and was stated by 51% of respondents.

The top causal factors for problems encountered in ground gas projects at the ground investigation and monitoring stage were identified as "poor data quality" (73) followed by "lack of competence" (55), "lack of funds/ cost cutting" (53) and "lack of training" (48). "Poor quality assurance" (32) was also frequently identified as a causal factor. Causal factors such as definition of responsibly (14) and the procurement process (11), and existing published guidance (5) were less often identified as being relevant at this stage of the process.

The key issues identified by survey respondents at the ground investigation stage were counted and grouped. The most frequently identified issues related to:

1. Defining the ground investigation objectives and targeting investigation with reference to the CSM.
2. Gas monitoring well design: including the depth, target stratum, unsaturated zone.
3. Quality of well construction.
4. Volume and type of data collected. Sufficient monitoring data gathered over space and time, with consideration of use of continuous monitoring. Alternative data gathered for ground gas assessment in addition to monitoring in boreholes (ground conditions, forensic TOC, groundwater, surface emissions, permeability).
5. Gas monitoring data quality. Parameters to be recorded during monitoring. Intelligent monitoring practices where data quality is assessed at the point of collection. Feedback loops built into the monitoring process for collection of additional data to reduce uncertainty. Advantages of using automated continuous monitoring equipment.

2.4 Watch points

2.4.1 Investigation objectives and methods

A critical aspect in any ground investigation is the identification of appropriate objectives. The objectives must relate to the initial conceptual site model described by the Stage 1 Desk Study. Once the objectives are defined the methodology to achieve those objectives can be identified.

For example, if the Desk Study identifies a potential risk from hazardous ground gas associated with an area of infilled land then appropriate objectives would be; (i) To determine the presence, nature and extent of the infill material, (ii) to determine the ground gas regime. This would then inform the design of the investigation (location, method and depth of exploratory holes, positions of response zones, monitoring programme etc). If this was relevant to a mining area underlain by Coal Measures, then the objectives should be informed by circumstances particular to that situation as described in the recent CL:AIRE guidance[11].

Where the Desk Study does not identify any credible sources of hazardous ground gas at or close to the site there will be no requirement for investigation targeted specifically at ground gas sources or pathways. Any investigation (even purely geotechnical) will still provide information on ground conditions that will allow further refinement of the conceptual model and reduction of uncertainties around potential ground gas risk. If unexpected conditions are encountered it may be useful to revisit objectives during the investigation phase, adding in additional testing or monitoring.

Where a credible, but potentially low or very low risk, ground gas source has been identified in the Desk Study it may be possible to provide sufficient lines of evidence for the risk assessment without gas monitoring. Other data relevant to the ground gas conceptual model can be collected, both on the source materials (location, depth, extent, organic content) and the pathway for gas migration (permeability, groundwater table). Detailed soil descriptions, by an appropriately trained and experienced engineer are extremely important in the determination of the gas generation potential from Made Ground. The AGS guide[15] should be followed to provide appropriate high quality descriptions of fill materials. Guidance published by CL:AIRE[13] outlines an approach using forensic TOC testing that may be appropriate for low risk gas sources, without gas monitoring.

> **Box 2.1 Data requirements**
>
> A ground gas risk assessment cannot be completed from ground gas monitoring data alone. The ground investigation is required to gather information on all potential hazardous gas sources and pathways to help refine the conceptual model. Keep in mind the receptor and any development changes during investigation design.

Where credible or significant ground gas pollutant linkages are identified in the initial conceptual site model derived from the Stage 1 Desk Study, the objectives of the investigation should be aligned to obtain data on the sources, the potential migration pathways, and relevant receptors. In responding to these objectives, monitoring should be targeted on the source stratum on site, in areas where there are buildings, or to intersect credible pathway(s) between the source and the receptor. For instance, monitoring response zones will often be shallow soils on site, within or above a source under buildings, or on the boundary of the site to intercept the pathway for migration from an off-site source (further details on well design are provided in section 2.4.2). A monitoring plan should be prepared to take account of the advice in BS8576 (sections 8.6 and 8.7)[14] and summarised in Table 2.1 below. If continuous monitoring is proposed, reference should be made to relevant guidance[16]. Monitoring should not be completed in sources where there is no credible pathway (and where there is no potential for new pathways or receptors). The ground investigation objectives should be designed with the multiple lines of evidence approach in mind. Gas monitoring data is never sufficient evidence for a ground gas risk assessment in isolation. The objective of the ground investigation is to refine the conceptual model, collecting data on all components of the potential pollutant linkage.

Potential Source	Typical gas investigation / monitoring	Comment
No credible sources	Specific targeted ground gas investigation not required.	If unexpected conditions are encountered, then further investigation may be required.
Credible but very low potential sources	Gas monitoring unlikely to be required. Delineate source, detailed descriptions, TOC and/or FTOC testing.	Investigate barriers to gas flow in ground if relevant. i.e. low permeability soils, groundwater table etc.
Low to moderate potential sources	Gas monitoring (spot or continuous) including periods of falling atmospheric pressure. Delineate source, detailed descriptions, TOC and/or FTOC testing.	The burden of evidence required for different levels of gas hazard is different. For sites where the requirement for gas protection is borderline, strong lines of evidence with low uncertainty will be needed to demonstrate that no protection is required. Where there is the potential for high or very high risk gas sources (e.g. mine workings or high generation rate landfill), strong evidence is needed to ensure the risk is appropriately classified and adequate protection can be provided (i.e. the development is feasible). Where there is a low to moderate risk and gas protection is sure to be required in the development, there may be little benefit in gathering a large volume of data. In this case small refinements in the risk would be unlikely to change the details of the protection measures required, and as such the design would be able to accommodate a certain level of uncertainty.
Moderate potential sources	Gas monitoring required for an extended period, continuous monitoring is likely to be beneficial, to adequately characterise worst-case conditions and temporal changes to gas conditions, including potential meteorological drivers for gas emissions.	
High potential sources	Gas monitoring required for an extended period, continuous monitoring is likely to be beneficial. Consider collecting additional data to inform detailed quantitative gas modelling if required, i.e. soil porosity.	

Table 2.1 Summary of investigation / monitoring requirements against potential gas source(s)

2.4.2 Well design

If an objective for a ground investigation is to determine the ground gas regime, it is very important to design the monitoring installation so that detected gases are representative of that ground gas regime. Ideally, gas monitoring should be completed where installations have response zones wholly in the unsaturated zone away from the influence of groundwater.

Monitoring well response zones should be targeted to source materials, or potential permeable reservoirs for gas, or the zone should be within a permeable pathway for gas to migrate, for example the unsaturated zone directly beneath a building. Response zones in coal mining areas should be designed to reflect that particular conceptual site model[11]. For each gas monitoring well the logic for how the monitoring data is to be interpreted needs to be clearly set out. By installing wells with response zones isolated to a single stratum it is easier to determine where the gas that is recorded in the well is coming from.

Box 2.2 The focus of well design

Many very low risk gas sources can create high concentrations of methane and/or carbon dioxide in monitoring wells, but this does not mean that they necessarily pose a hazard of gas emissions into a building. Focus your gas monitoring and the well design on credible sources of hazardous gases, this will make interpretation of the data easier.

Deep groundwater monitoring wells should not be used for ground gas monitoring and no gas monitoring well should have a completely flooded response zone. Monitoring from partially flooded response zones may not be representative of the gas regime in the surrounding ground (depending upon the degree of flooding and the nature of any dissolved gas / vapour). Gas monitoring from wells with completely flooded response zones should not be undertaken where the objective is to determine the hazardous ground gas regime. A flooded response zone means that any gas in the well is trapped gas that is simply in equilibrium with the dissolved gas in the groundwater. Any gas recorded from monitoring will not be representative of the gas regime in the unsaturated zone. This is because in the surrounding ground the equilibrium in the well headspace is not reflected in the unsaturated zone because of oxygen ingress from the ground surface and potentially oxidation of methane. It is important to remember that the characterisation of a site using gas screening values is based on using data from the unsaturated zone and from wells that are not flooded.

Box 2.3 The rationale for monitoring

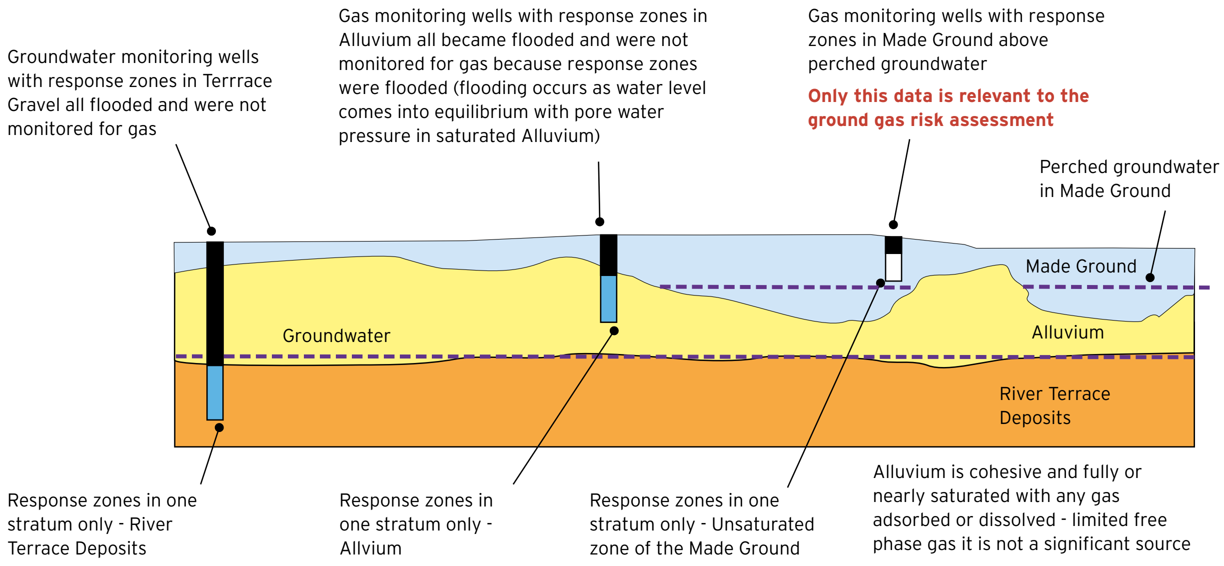
Gas monitoring data from wells with groundwater levels above the top of the response zone (flooded wells) is not representative and should not be used in gas risk assessment.

Do not install a gas tap on to a standpipe just because the pipe is there and then monitor that standpipe just because it has a gas tap on it.

Write down the rationale behind each gas monitoring well on a schedule: which gas source(s) is that well targeting? This will make it clear that you have a clearly defined strategy for your gas monitoring. Share this information with all parties involved: contractor, drillers, monitoring technicians.

Generally, fairly shallow gas monitoring wells are suitable for assessment of ground gas risks for most development sites. Deeper response zones can cause some issues when collecting and interpreting the data. Firstly, they are more likely to become water-logged. Long narrow standpipes can act as chimneys, inducing higher flow rates than are representative for the site. Monitoring wells with response zones at depth, will also require longer sampling periods to obtain a representative sample. For example, for a 50mm diameter, 10m deep unsaturated monitoring well pumping with typical gas monitoring equipment would take some 35 to 40 minutes to remove/ sample the standing volume of gas in the standpipe.

Keep in mind the details of the proposed development when designing your monitoring wells. For basements, or projects with significant cut and fill gas sources might be removed or altered during development works. There is no need to do a gas risk assessment on results from wells with response zones in material that will be removed from the site.



Installing appropriate wells and collecting appropriate gas data requires:
- good supervision on site to ensure gas wells are installed in one stratum and in the unsaturated zone
- observation of groundwater levels after gas monitoring - if the wells are flooded the results should not be used in the risk assessment (monitoring should not be continued if it is clear response zones have become permanently flooded)

Figure 2.2 Example response zones

If there is more than one source of hazardous ground gas then in order to ensure that the data from each of those potential sources is reliable, the monitoring installations and the monitoring programme will need to be designed to reflect that complex conceptual site model. In particular, with response zones specific for each of the potential gas sources. If this is not achieved, the monitoring data combined from a number of possible sources will be confused, the risk assessment will be flawed, and the determination of remedial action may not be appropriately targeted.

2.4.3 Well construction and decommissioning

2.4.3.1 Construction

Gas monitoring wells should be constructed to a high standard of workmanship (see guidance in BS8576[14]. In particular, the following key points should be taken into account when designing or constructing monitoring wells.

The installation of gas monitoring wells should be undertaken and supervised by appropriately qualified and experienced staff who should assess the geological profile encountered in a monitoring well and adjust the design of the installation on site so that it reflects the encountered ground conditions. A series of wells all constructed to a single pre-determined design are most unlikely to reflect the conceptual site model or to achieve the monitoring objectives.

The gas impermeable seals at the top (and bottom if required) of the response zone should be of sufficient length and installed correctly to ensure they function as required. Seals are generally formed using bentonite pellets, granules or a cement: bentonite grout mix. Bentonite pellets should be adequately hydrated with water and compacted down. Loose and/ or unsaturated bentonite pellets will not seal the installation and will not provide reliable data.

Dual response zones should be avoided if possible. Where response zones at different depths are required it is preferred to drill separate shallow boreholes adjacent to deeper ones (windowless drilling) with separate well installations. This avoids the issues of poor sealing between response zones and ensures there is no preferential pathway to the deeper response zone. If dual response zones are used in a single borehole the seals between them will also require grouting rather than using pellets.

Vapour monitoring implants (used to monitor VOCs via implants in a short sand filter with 6mm diameter tubing) should not be used in the UK for routine gas monitoring. In the UK, because of shallow groundwater and/or cohesive soils, the groundwater or porewater will tend to waterlog the response zone and this may not be apparent from monitoring. They can be useful to provide multi depth indicators of gas migration from an off site source, if they remain dry. However, flow rates from the implants should not be used to determine gas screening values.

2.4.3.2 Decommissioning

Gas (and groundwater) monitoring wells could provide preferential migration pathways from the source into buildings if located beneath building footprints and not appropriately decommissioned. Even if the headworks and near surface pipework are destroyed in the construction process, the pipework remaining at depth can provide an open conduit for the upward migration of gas into sensitive locations. This is particularly pertinent on mine gas risk sites where monitoring has been completed in worked coal seams at depth. It is therefore important that consideration is given to the decommissioning of monitoring wells – either at the conclusion of the ground investigation process or during enabling earthworks. The particular measures necessary should reflect the conceptual site model (e.g. the nature of the near surface soils) and reference should be made to the Environment Agency guidance[17] on decommissioning groundwater wells which contains useful and pertinent advice. It is recommended that a programme and responsibility for well decommissioning is set out on commencement of the ground investigation contract.

2.4.4 Data quality

In any monitoring programme there must be a focus upon data quality. There is no point in obtaining ground investigation or monitoring data if it is not reliable (in fact it may be worse than no data at all).

Data should be collected in line with best practice standards for investigation and monitoring works as outlined in BS8576[14] and BS10175[9]. One key factor for ground gases is to ensure that the monitoring equipment is always in calibration; and this should be stated in the data reporting.

It is also important to ensure that the complete record of monitoring is presented in the reporting (i.e. in the contractor's factual report and/ or the gas risk assessment sheets in an Appendix to an Interpretative Report). This must include for each well on each monitoring occasion the full time series of readings. This is important as it will provide a critical line of evidence justifying the selection of the steady state concentrations and flow rates that are used in the determination of the hazardous gas flow rates (and subsequently the GSVs). It will also support the identification (and discounting) of unreliable data – for example where there is an "instantaneous" flow of gas when the gas tap is first turned on, but which rapidly falls (10 – 30 seconds say).

One way to make the data quality check inherent in the assessment process, is to consider each set of data collected as a line of evidence. Do the lines of evidence generally agree or are they contradictory? If there is a conflict, which data source is the most reliable and has the lowest uncertainty? Desk study sources, information on site ground conditions, soil test data such as TOC and FTOC, and other gas emissions test data (e.g. surface emissions mapping, or flux box chambers) are all relevant additional or alternative lines of evidence to the gas monitoring completed in boreholes.

It may also be useful to support the data obtained from gas monitoring with the results from analysis of gas samples. In devising the sampling and analysis plan, consideration should be given to sampling the gas from wells where hazardous ground gas is not being detected during field monitoring as well as from those wells where elevated concentrations have been detected. Therefore, it is sensible to plan for confirmatory sampling and testing after the initial field data has been obtained and an appropriate selection of wells and sampling occasions can be determined.

2.4.5 Intelligent monitoring

Another key element of obtaining quality data about hazardous ground gas from ground investigations is that the monitoring is carried out intelligently and not as a mechanical, repetitive exercise in accordance with some pre-determined programme by personnel with no understanding or interest in the data obtained. Essentially, it is important that the monitoring is carried out in general accordance with the monitoring plan (see Section 2.4.1) relevant guidance[14, 16] but also in such a way to maximise the potential for the data to be representative of the conceptual site model.

In order to achieve this, it is necessary for the person undertaking the monitoring to be responsive to the data being obtained. For example, if unusual/ unexpected or potentially anomalous data is recorded whilst still in the field and collecting monitoring data thought must be given to such data, what it may mean in terms of source or generation. Such data should be queried, checked and confirmed or denied on site. For example, check that the instrument is functioning correctly, prolong the monitoring pump time, leave the gas tap open and remontoir later in the day etc. Consideration should be given to the number of minutes over which the monitoring is undertaken and whether this is sufficient for steady-state flow rates and concentrations to have been reached (particularly relevant for deeper wells as discussed above).

It is also highly beneficial to implement a monitoring programme in such a way to maximise the potential for "worst case" conditions to be recorded. The duration and frequency of the monitoring programme should reflect the conceptual site model. Strict adherence to a "monitoring at weekly intervals for 6 weeks" approach should be avoided. The monitoring programme must be planned but must also be responsive. For example, a programme of spot monitoring which takes place over a period of a few weeks should not be carried out at a set frequency (e.g. every Wednesday for 6 weeks), but at intervals that are responsive to weather and atmospheric conditions (e.g. on dry and wet days, on days with high, low and falling atmospheric pressures). The monitoring personnel should therefore keep the weather forecast under review during the monitoring programme and reflect that forecast in their implementation of the programme.

Monitoring technicians should therefore be appropriately trained and briefed about each site to ensure data quality and "intelligent" monitoring. Consideration should be given to the organisation and personnel entrusted to implement the monitoring. For example, a member of the consultant team, or a specialist technician is more likely to be fully aware of the need for quality data in a site specific context, rather than a non-specialist from the intrusive works contractor. The key aspect is that whoever is completing the monitoring needs to be fully aware of the purpose of the work, the site conditions, the ground gas conceptual model, the installation details and the aims and objectives of the works.

Using continuous monitoring techniques, bypasses much of the thought and strategy around when single gas readings should be taken. However, consideration should be given to the locations selected for continuous monitoring equipment to be deployed (often a sub-set, rather than all monitoring locations on a site) and the time period over which the monitoring is completed[16, 18]. The length of a monitoring period should be defined at the out-set and not open ended.

Box 2.4 Effective gas monitoring

Effective gas monitoring is most likely to be achieved by well trained staff that have some "skin-in-the-game" in terms of the quality of the data obtained, i.e. the same team as those who will complete the assessment.

If the monitoring is to be completed by technicians who are separate from the consultancy team, then effort should be made to ensure they are competent and fully briefed in terms of; the purpose of the monitoring, the conceptual model, site constraints, expected conditions and the anticipated ground gas regime. Good lines of communication with consultancy team throughout the monitoring programme will also improve quality of data collected.

2.5 Case studies

2.5.1 Case Study 1. Inappropriate monitoring programme and assessment

A development of large warehouse type buildings is located over a former landfill site: The geology comprises Langley Silt Member overlying River Terrace Deposits overlying London Clay Formation. Most of the Langley Silt Member and River Terrace Deposits were removed for sand and gravel extraction. Prior to landfilling many of the old gravel pits were flooded, indicating a shallow groundwater table. It was filled with predominantly inert waste (with some demolition and dredging waste). The filling was completed by the early 2000s.

Ground conditions comprise a mantle of topsoil and restoration soil, underlain by inert fill material which ranged in thickness between 3.0m and 6.0m. The inert fill material is underlain by remnants of the River Terrace Deposits, which varied in thickness between 0.1m and 4.0m. The London Clay Formation was present below this. The inert fill material matrix comprises predominantly gravelly sandy clay with flint, brick and concrete inclusions. There are occasional inclusions of chalk, ceramic, tile, clinker, fiberglass board, breeze block, bitumen and plastic. There are isolated occurrences of plant matter and wood fragments. A moderate to strong organic odour is frequently noted. The descriptions of the inert fill material are consistent with the operating permits of the landfills, i.e. the landfills accepted inert material (plus construction, demolition and dredgings) and importantly the log sheets do not indicate large quantities of degradable / putrescible waste to be present beneath the site.

Groundwater strikes outside the area of landfilling were typically recorded at around 3m depth, within the River Terrace Deposits. The groundwater strikes were generally observed to rise during the borehole construction period, indicating sub-artesian pressures within the River Terrace Deposits, confined by the overlying cohesive material of the Langley Silt. The water strikes typically stabilised at around 1m to 2m bgl, although locally were reported at / near ground level.

At this point if good practice had been followed the ground and groundwater conditions should have been considered during the site investigation at each hole location. This would have indicated that monitoring wells with response zones deeper than 1m would likely be flooded and would not provide representative data. The site was suitable for assessment using the TOC data combined with surface emissions and flux chamber testing which would have been a more suitable approach.

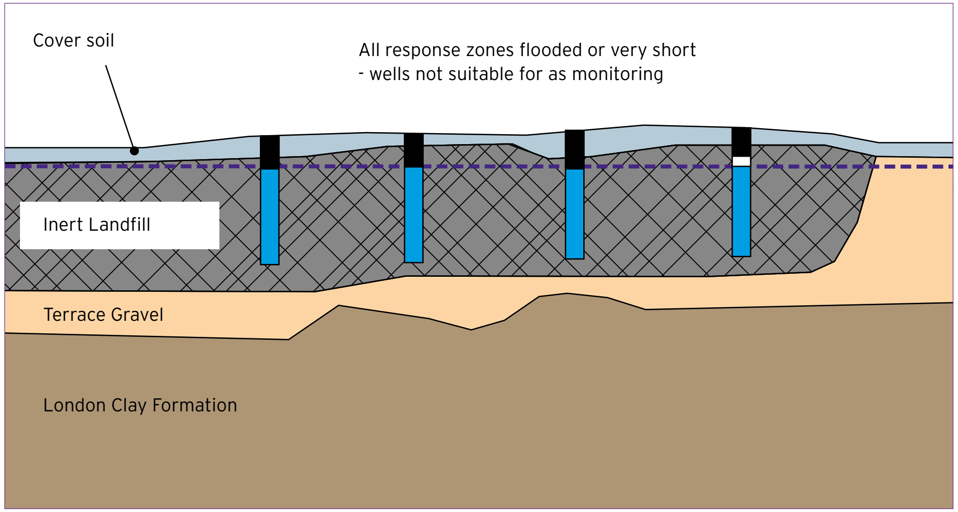


Figure 2.3 Illustration of inappropriate wells for monitoring

The indications were clear that the gas monitoring wells would be flooded so they should not have been installed. All the wells had response zones isolated in the Inert Landfill which is good practice as this is the only source of gas below the site.

Groundwater levels recorded on the first visit showed all the wells were flooded or had very short response zones. Good practice requires ongoing assessment of the data quality and again at this point it should have been determined that the gas data was not reliable. However, this was not done and gas monitoring was carried out in the flooded wells for six visits. In addition, despite the fact that the data would be unreliable, continuous gas monitors were installed in five flooded wells.

Furthermore, the data was not critically assessed. This resulted in a highly unrealistic and over-conservative categorisation of the gas regime as Characteristic Situation 4. In turn this caused unnecessarily cautious gas protection measures to be recommended to the client with significant cost implications.

Samples had been taken for TOC testing. Good practice in this type of site would require soil descriptions in accordance with the AGS guidance on the description of anthropogenic soils, samples taken at 1m depth intervals in the Made Ground for forensic descriptions and TOC tests.

All the TOC results were below the 1.5% limiting value quoted in BS8485 for a CS2 site (assuming the inert fill material has been in-situ for less than 20 years), i.e. consistent with a 'low' risk gas source.

Flux chamber tests were also completed and showed no methane or carbon dioxide emissions from the ground adjacent to boreholes that were recording high flow rates at the same time as the flux tests. This confirmed the site would not require gas protection to meet CS4 requirements and the buildings were simply provided with a gas membrane (no sub-slab venting) based on the more detailed assessment of the data.

2.5.2 Case Study 2. Reliable monitoring to inform risk assessment

A planned development comprised the phased construction of a number of residential blocks, ranging between 10 and 28 storeys, all of which contained single storey basements. The site had a history of previous extraction (Victorian brick pits), in-filling and industrial use (Iron Works, dyeing & cleaning works, cloak factory, engineering works and scrap metal yard).

Exploratory level ground investigations carried out prior to the planned redevelopment recorded some 3 to 8.5m of Made Ground underlain by superficial Brickearth and Terrace Gravels, followed by a substantial thickness of London Clay. Groundwater was perched within the Made Ground at varying levels.

A limited programme of gas monitoring was carried out across the whole of the site area. Methane concentrations in all wells were <1%, concentrations of carbon dioxide ranged between <0.1 to 15.1% and flow rates were generally very low. A Remediation Strategy was prepared for Phase 1 of the development, which based upon these data recommended the incorporation of a gas protection membrane into building footprints and these measures were incorporated into that Phase of the development.

The initial recommendation for gas protection measures was mainly a response to a limited data set, elevated readings of carbon dioxide and the need to adopt a cautious approach (in part to satisfy regulatory concerns and avoid delay). The need for gas protection on further Phases of development was not conclusive (assessment completed by a different consulting team appointed by the developer). That opinion reflected the initial variable thickness of the Made Ground, the removal of a portion of that Made Ground during enabling earthworks/ basement construction, the absence of elevated concentrations of methane and the low flow rates.

A supplementary ground investigation was designed to further assess the ground gas regime for the Phase 2 to 5 areas with its new post enabling works profile. The site investigation included; construction of fourteen exploratory holes to investigate and prove the base of the Made Ground, with detailed logging and installation of gas monitoring wells. Monitoring of ground gas (and groundwater) was carried out at daily intervals in all available installations during site work, followed by a 6 week programme of monitoring of all installations (by the consultant) with timing of monitoring visits flexible to ensure varying / worst case weather conditions were included and the emerging data kept under continual review and confirmatory chemical analysis of hazardous ground gas samples.

The ground investigation showed the residual Made Ground (still of substantial thickness in some areas) to be a slightly sandy, gravelly clay with the gravel comprised of various man-made fragments and with very limited evidence of any organic / biodegradable material). The monitoring data was subject to critical assessment in accordance with the British Standard and relevant good practice guidance). It was demonstrated that;

1. There was a sufficient set of data from the monitoring programme and site work period (although the ground investigation data was inevitably more sporadic, disparate and inherently variable it was generally comparable with the data obtained post investigation);
2. The monitoring data was generally consistent with the nature and extent of the source (Made Ground) which was now typically about 6m thick and contained some organic material (possibly re-worked natural superficial deposits etc.) but showed no evidence of substantial volumes of degradable materials, refuse etc.;
3. The response zones of all installations contained a suitable length of unsaturated element which allowed the ingress of ground gas from the target strata.
4. The monitoring was carried out during steady, rising and falling atmospheric pressure conditions, with atmospheric pressures less than 1000mb recorded on occasion.
5. Concentrations of methane at/ below 0.1% were recorded in the large majority of installations on the large majority of occasions (>90% of readings). Concentrations of methane above 1% were rarely recorded (<2% of readings) with a maximum recorded concentration of 2.2%.
6. Concentrations of carbon dioxide were recorded typically above the limit of detection (0.05%), with about 2/3 of readings <1%. Concentrations above 2.5% were recorded in some installation on various occasions (14% of readings). Occasional readings were recorded above 5% (during the ground investigation only) with the maximum recorded concentration being 10.9%.
7. Flow rates were consistently low, typically below/ marginally above the limit of detection (0.05 l/hr) the potential for ingress into the building was therefore primarily associated with the potential for a rapid drop in atmospheric pressure to drive gas from the ground to the underside of the basement slab.
8. The site characteristic GSVs for both methane and carbon dioxide were all well below (typically two order of magnitude) the 0.07l/hr "threshold" for Characteristic Situation 1.
9. However, occasional concentrations of carbon dioxide and methane above the "typical maximum" for CS1 were recorded. Accordingly a quantitative assessment was carried out (in accordance with advice in the British Standard and industry good practice guidance). The results of that assessment indicated that even with highly conservative assumptions regarding the potential for gas generation, migration and accumulation in a small basement space, there was no plausible potential for hazardous concentrations to result.

In summary the site characteristic GSV for CO_2 and CH4 were determined as falling with Characteristic Situation 1. The data was considered reliable, having been obtained from an appropriate number of installations, with appropriate response zones and under varying atmospheric conditions. The data was also consistent, both within the data set itself and with the observed ground conditions. The soil descriptions and the nature of the gas regime provided good lines of evidence that the source of the gas was the Made Ground, the nature and extent of which being well defined by investigations. The built development under consideration comprised a single level basement not used for habitation or any permanent or long term occupation by people. The basement slab was constructed to be waterproof (to accord with the relevant standard – BS8102) and were therefore at low risk of cracking. Occasional readings of hazardous gases above the typical maxima for CS1 were recorded. Accordingly, consideration was given to increasing the classification of the gas regime to CS2. However, on the basis of all of the information and the associated risk assessments it was clear that such an increase would result in a disproportionately high gas hazard prediction and an over-precautionary Characteristic Situation.

It was concluded by the consultant and agreed by the local authority, that the ground gas regime for the Phase 2 to 5 areas of the site had been demonstrated by an appropriate investigation and monitoring programme to fall within CS1. Accordingly, no special precautions are required to the building for gas protection purposes.

2.5.3 Case Study 3. Inappropriate response zones and risk assessment

This Case Study follows on from Case Study 2 in Section 1.5.2. The response zones for the wells were all at a depth of 1m to 3m within the London Clay. The new residential development also included a 4m to 6m deep basement. Therefore, even if there was a gas risk the response zones were not designed to be in the correct location - they were in material that would be removed for the basement construction. So (if actually required) the response zones of these wells should have been installed below the basement slab level. The gas monitoring did not detect any elevated concentrations of methane (all readings <0.1%) nor any elevated flow rates (all readings <0.1l/h). Slightly elevated concentrations of carbon dioxide (up to 11.5%) were recorded. All the hazardous gas flow rate values (Qhg) were less than 0.07l/h (i.e. Characteristic Situation CS1). However, the consultant increased the classification to Characteristic Situation CS2 on the basis that carbon dioxide exceeded 5%, without any consideration of the conceptual site model and source of the carbon dioxide. Carbon dioxide concentrations up to 21% are commonly encountered in the London Clay and Terrace Gravel Deposits (and also in the Made Ground) around London. In the absence of methane, the source of the carbon dioxide is biological respiration of small quantities of organic material in the natural soils or Made Ground. The turnover rate is many thousands of years, so the gas generation is insufficient to cause hazardous emissions from the ground. It is not necessary in this case to increase the site to CS2 (BS8485 only requires the risk assessor to consider an increase based on gas concentrations and it is not a mandatory requirement. The requirement is there as a sense check). There is no evidence of VOCs or a high risk gas source outside the basement that could cause lateral migration of vapour or gas into it.

In any event the ground around the wells was to be removed as part of the basement construction which was also not considered by the risk assessor. Therefore, even based on the gas monitoring data the site did not require any gas protection measures. Furthermore, it was to be used as a car a park and was constructed as a Type B waterproofing structural barrier (waterproof concrete). Therefore, even if there had been a slightly elevated gas risk, specific gas protection would still not have been required.

Note: Monitoring in the gas sources inside a basement may be appropriate if the same source material is to remain in place around the outside of the basement and it can also generate sufficient gas to cause lateral migration through the proposed wall construction. In this case, GSVs were not intended to be applied in this more complex scenario and they should not be used to assess the data (site specific assessment using quantitative methods will be necessary).

Basement project - London

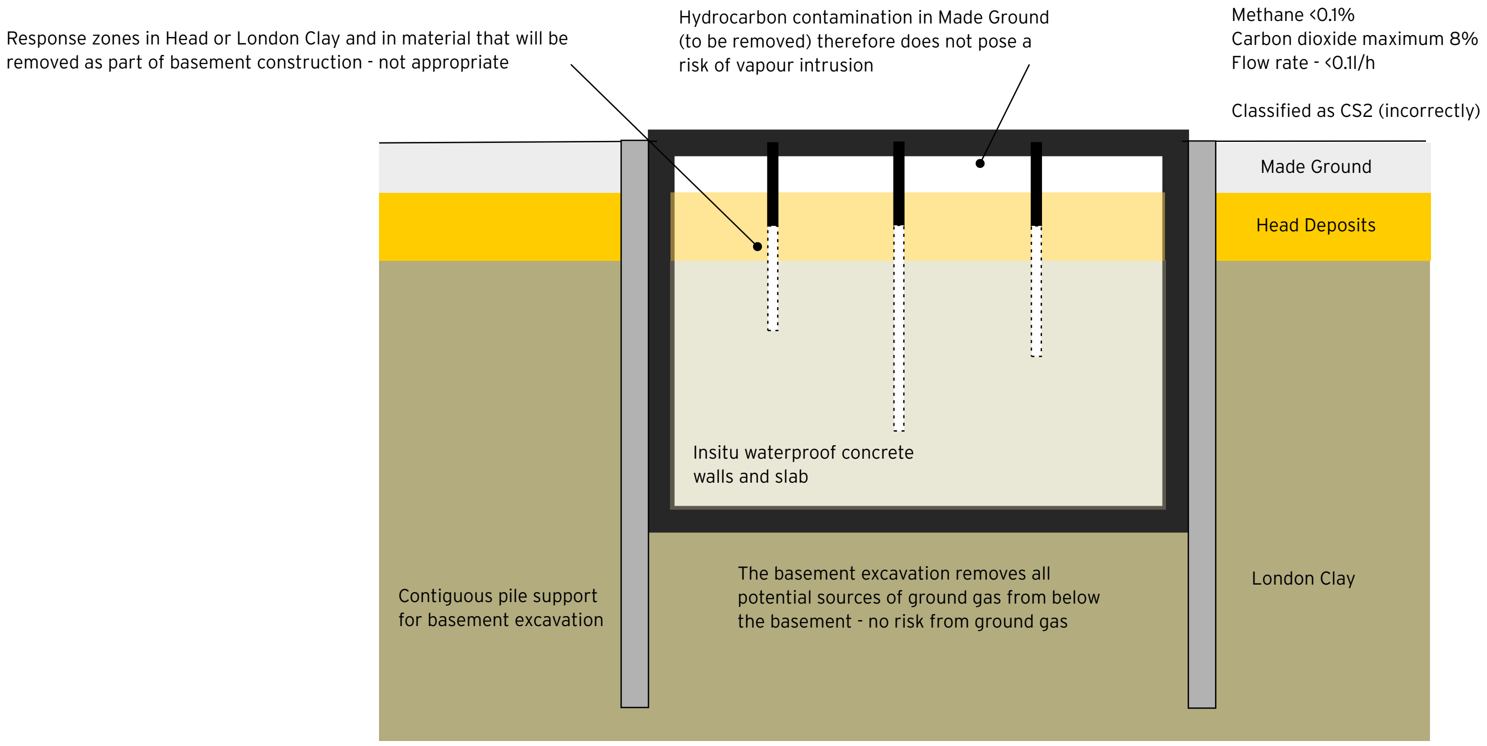


Figure 2.4 Simplified sketch of Case Study 3 conceptual site model

Stage 3 - Risk Assessment

3.1 Process

The risk assessment stage of a project is about the rigorous, transparent and repeatable assessment of the potential risks. That assessment should be based on all the data obtained in Stages 1 and 2. It must consider the planned development (its location, nature and scale etc). It must be based upon the specifics of the conceptual site model and consideration must be given to the various uncertainties that apply to the data, the source of the hazardous ground gas and the possible migration pathways. At this stage the Preliminary Risk Assessment undertaken in Stage 1 is re-evaluated based on the newly acquired data from Stage 2, initially by reference of that data to published relevant assessment criteria in a Generic Quantitative Risk Assessment (GQRA). If more detailed assessment would better define the level of risk and / or would inform the need for and scope of gas protection measures, then consideration should be given to a carrying out a Detailed Quantitative Risk Assessment (DQRA) which would require both particular detailed data and appropriately competent risk assessors.

The overall process and steps necessary for completing the risk assessment Stage is illustrated in Figure 3.1 overleaf. This is followed by comments on particular aspects related to risk assessment, namely; competence (section 3.2), a summary of current issues arising from the industry consultation (Section 3.3), advice on a series of the key watch points related to those issues (Section 3.4), followed by case studies (Section 3.5).

Stage 3
Risk Assessment

Stage 3.1
Data quality assessment

Evaluate
Uncertainties

Review
Conflicting lines of evidence

Weight
Evidence according to reliability

Determine
Data reliability and sufficiency for risk assessment

Stage 3.2
Refine conceptual site model

Refine
Gas generation potential of source materials based on findings

Initial ground model, based on ground conditions

Review
Viability of pathways for gas migration

Include changes to ground conditions related to planned development

Stage 3.3
Generic Quantitative Risk Assessment (GQRA)

Review
Data quality

Composition of ground gases / vapours

Flow rates

Assessment
Made on basis of all identified S-P-R linkages

Based upon multiple lines of evidence

Based on adequate / reliable data

Reflects potential changes to gas regime due to earthworks / development

Reference
Relevant assessment criteria

Stage 3.4
Risk review

Consider
Assessed risk(s)

If risks assessed as Low / Negligible;
i) Check adequate allowance made for uncertainty
ii) Discount hazardous ground gas as a source of potentially significant risk.
(iii) Report and exit

If risks greater than Low / potentially significant
(i) consider need for additional investigation data
(ii) consider whether DQRA would alter need for remedial design/action, if not
(iii) Prepare GQRA Report (Stage 3.6)

Stage 3.5
Detailed Quantitative Risk Assessment (DQRA

Carried out (if required) to further inform
Assessed level of risk

need for / scope of risk mitigation

Quantitative modelling
Gas flows in ground and into buildings

Diffusive or advective flow (evidence dependant)

Include building construction details (e.g. floor slabs)

Sensitivity analysis

Climate change
Consider effects on model assumptions

Stage 3.6
Risk assessment report (GQRA or DQRA)

Identify and describe
All potentially significant contaminant linkages with respect to hazardous ground gas

Confirm
Assessed level of risk

Define
Need for and scope of gas protection measures

Consider
Preparation and publication under NQMS

Figure 3.1 Risk assessment process

3.2 Competence, roles and responsibilities

As with the earlier stages it is important to ensure the appropriate expertise of people engaged in carrying out Risk Assessments. This stage requires critical thinking and not just the application of a particular formula or simple comparison of numbers against thresholds. Professionals engaged in Generic Qualitative Risk Assessments (GQRAs) should be able to demonstrate a proven ability to critically assess data sets, the uncertainties associated with such data and then apply these in an assessment which is rigorous, transparent and repeatable. For those undertaking Detailed Quantitative Risk Assessments (DQRAs) the requirement is to have particular background, skills and experience related to the hazardous ground gas or vapour in question (i.e. its nature, its potential to migrate or to degrade, its volatility etc.). It is entirely possible that no one individual may have all the necessary skills / experience to carry out a particular DQRA and personnel with different expertise may be required to successfully understand and quantify the risks associated with more complex gases and vapours.

Evidence of the necessary competence of personnel engaged in risk assessments would include relevant academic qualifications (e.g. earth science degrees) and training / experience. For DQRAs those qualifications / experiences should be relevant to the specific gas/ vapour in question and that detailed assessment would likely be carried out by a specialist risk assessor registered by the Society of Brownfield Risk Assessment (sobra.org.uk/accreditation). The work, assessment and reports should all be overseen and reviewed by competent professionals (see Box 1).

3.3 Current state of the art

Based on the industry consultation survey responses the ground gas risk assessment stage was in the middle in terms of the frequency of problems encountered by practitioners. The modal response was that problems are "often" encountered and was stated by 58% of respondents.

The top causal factors for problems encountered in ground gas projects at the risk assessment stage were identified as "lack of competence" (72) followed by "poor data quality" (70) and "lack of training" (54). "Poor quality assurance" (35) and "Lack of funds/cost-cutting" (34) were also frequently identified as a causal factor. Causal factors such as definition of responsibly (11) and the procurement process (8), and existing published guidance (8) were less often identified as being relevant at this stage of the process.

The key issues identified by survey respondents at the risk assessment stage were counted and grouped. The most frequently identified issues related to:

1. Poor data quality or lack of quality assurance
2. Lack of consideration for the conceptual site model
3. Quantitative assessments relying on calculated GSVs with a lack of multiple lines of evidence approach (for example, site categorisation being increased to CS2 based solely on a recorded concentration of CO_2 above 5%, without consideration of any other evidence
4. Overly conservative assessments on Low Risk sites.

Respondents also identified that there was some variability in available guidance, and some had experience of situations where guidance had been miss-applied or where there were conflicts between interpretations. One of the key purposes of this guide is to bring clarity to this and the relevant standards/ guidance to be applied to the risk assessment process are referenced as appropriate in the following key watch points and are outlined in Chapter 7 of this guide.

3.4 Watch points

3.4.1 Data quality check

Prior to undertaking an assessment of the risks (whether GQRA or DQRA) associated with hazardous ground gas it is important that the risk assessor(s) first consider and understand the uncertainty and limitations associated with the observations and records from the ground investigation and with the laboratory and monitoring data. It is important to recognise that the gas monitoring results need to be considered in combination with other lines of evidence (see 3.4.3.3). Disassociating the data from the conceptual site model and looking only at the data in a spreadsheet, can only ever lead to flawed risk assessment.

Box 3.1 **Data check**

Risk assessors should always carry out a "sanity check" of the data prior to undertaking the assessment itself.

Key things to check when reviewing the gas monitoring data in order to ensure that the data utilised in the risk assessment is reliable and that the inherent uncertainty is accounted for, are listed below (Note: most of these issues can be prevented by appropriate design and implementation of the intrusive works – see Chapter 2):

- Was the monitoring completed using best practice methods (BS8576) and using in-calibration equipment? If not, consider how this impacts the reliability of the data.
- Is the monitoring data from flooded wells? If so, discount it and do not use in the risk assessment to determine a GSV.
- Do the response zones span multiple strata? What is the significance of this for the risk assessment?
- Is monitoring data from deep boreholes that are forming an artificial pathway and flow rates that are not representative of ground gas emissions in the surrounding ground?
- Has gas monitoring data been obtained during falling atmospheric pressure? If not, what is the significance for the risk assessment?
- Is there limited gas monitoring due to access restrictions? If so, what is the significance for the risk assessment?
- Is the gas monitoring in soil that is due to be removed before development? If so, do not use the data in the risk assessment.
- Has gas monitoring been undertaken in combined groundwater monitoring wells installed into aquifers, not unsaturated zone? Consider whether the data is appropriate to the risk assessment.
- Is the monitoring data credible, consistent, and reliable? That is for example, do borehole dip measurements approximately match installation records on logs? Do atmospheric pressure readings match to forecast weather conditions on that day? Are multiple readings from the same location within a credible range? Do the readings show conditions vastly different from what was expected?

3.4.2 Assessment relevant to the conceptual site model

The appropriate description of the conceptual site model relies upon a competent determination of viable potential sources of hazardous ground gas which together with plausible migration pathways combine to result in a credible pollutant linkage to a defined receptor. In essence this means that the identified "source" must present a potential to generate hazardous ground gas at a rate that could give rise to hazardous volumes / concentrations.

Although the presence of very low risk (not credible) sources or potentially high risk scenarios should have been considered at Stage 1 (see sections 1.4.5 and 1.4.6), risk assessors should always carry out a review of the conceptual site model in light of the new Stage 2 data obtained before diving into the quantitative risk assessment process. This will ensure relevance and applicability and help avoid unnecessary work/ expenditure.

Box 3.2 Understand the source

Before undertaking any hazardous gas flow rate calculations first determine what your gas monitoring data (and other ground investigation data/ lines of evidence) is telling you about the likely sources of ground gas at your site.

For large or complex sites, consideration should be given to zoning a site if that assists in the definition of the conceptual site model. For example, if there are multiple potential sources of hazardous ground gas, or if parts of the site have variable shallow ground conditions, or if the source areas are distant from sensitive receptors.

Plotting gas concentrations on ternary plots can be useful in verifying that the data fits with the identified gas sources in the conceptual model. The ternary plot can help determine the signature of the gas. Figure 3.2 provides various zones on a ternary plot that indicate the potential source of gas. Some of the zones cover different sources and also overlap so the use of the plots should be combined with other evidence. The boundaries should not be considered as rigid and absolute.

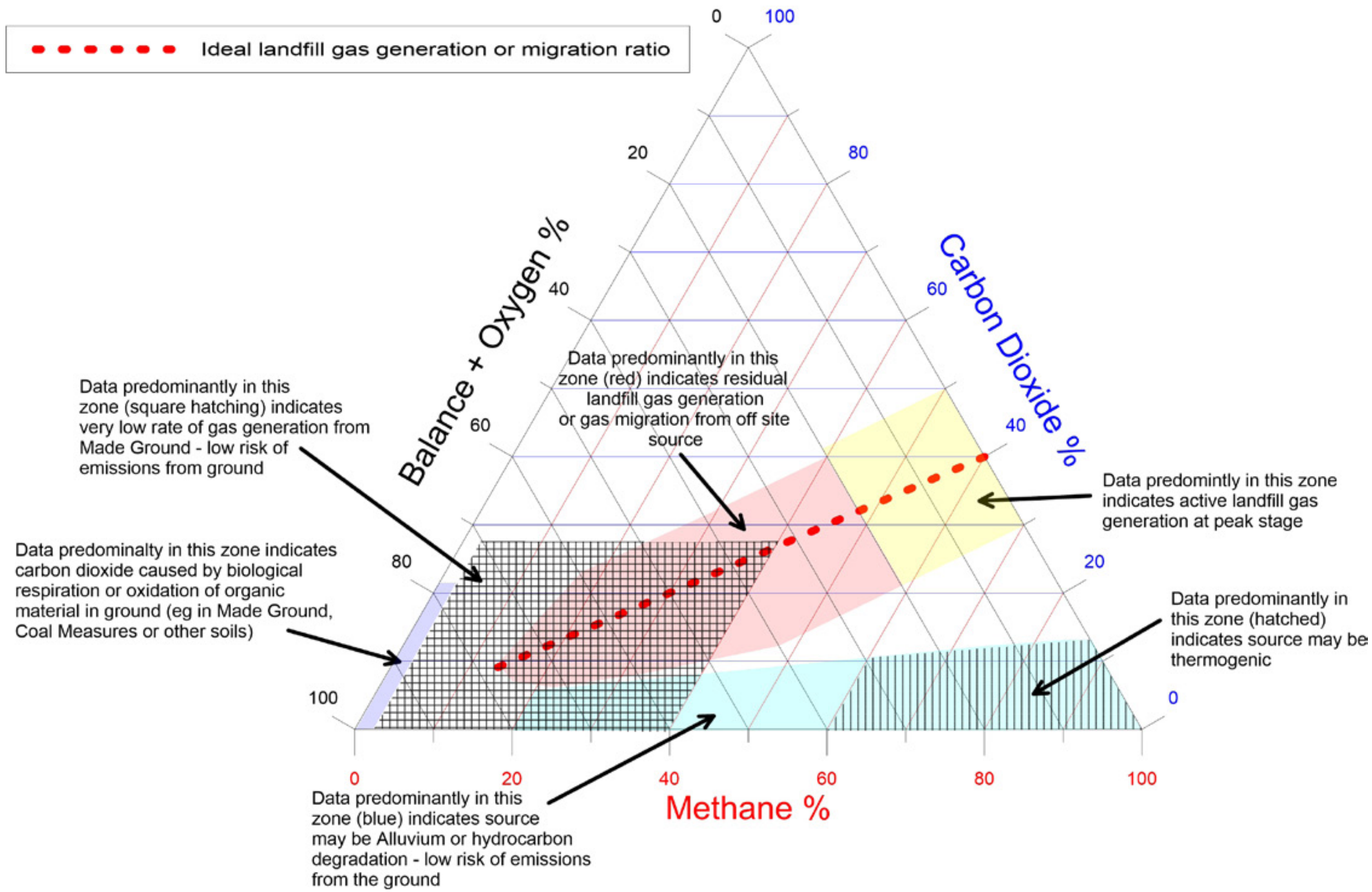


Figure 3.2 Ternary plot with zones indicating the potential gas source – Note this plot uses balance gas + oxygen on the z axis

A ternary plot is useful for deciding whether to increase a site's classification from CS1 to CS2 where there are elevated concentrations but low flow rates. For example, if there are concentrations from a single well or only occur occasionally that are in the purple, light blue, squared hatched and vertical hatched areas may indicate that there is no need to increase the classification. If there is some uncertainty around the gas source it is also possible to complete additional testing (isotopic or chemical analysis for other trace gases) to determine if gas is thermogenic (mine gas) or biogenic (decomposition), see CIRIA R151[19].

A ternary plot is useful for deciding whether to increase a site's classification from CS1 to CS2 where there are elevated concentrations but low flow rates. For example, if there are concentrations from a single well or only occur occasionally that are in the purple, light blue, squared hatched and vertical hatched areas may indicate that there is no need to increase the classification. If there is some uncertainty around the gas source it is also possible to complete additional testing (isotopic or chemical analysis for other trace gases) to determine if gas is thermogenic (mine gas) or biogenic (decomposition), see CIRIA R151[19]. Consideration should also be given to the potential for future changes to the conceptual site model, for example, groundwater rise, climate change, hard surface introduction or removal, disturbance and/ or aeration during earthworks/ construction, introduction of preferential pathways etc. associated with the development. The assessment must be site specific and not invent hypothetical considerations that are not relevant to the site. For example, if Made Ground is the source of the gas and is up to 4m deep, then changes in a deep groundwater level at 30m depth will have no effect on gas risk.

The potential for changes to the hazardous ground gas regime due to development or to earthworks must always form part of the assessment. This includes activities that could result in the removal (partial or complete) of the gas source or the creation or removal of migration pathways linking the gas source to the sensitive receptor. Another frequently overlooked element of the conceptual site model that can be critically important in gas risk assessment, is the protection from gas ingress into a building which is inherent in the building design, for example, suspended concrete floor slabs, raft foundations, sub-floor ventilated layers etc.

On most sites piled foundations will not provide a preferential pathway for gas migration[20] although there are specific situations where piles may form migration pathways when the extent to which this could change the gas risk should be assessed. In particular driven precast concrete piles are increasingly being used as a cost effective foundation solution. Gas monitoring around the top of the piles has demonstrated that they do not form a preferential pathway for gas migration when installed by modern driving equipment with in-cab monitoring systems.

3.4.3 The completion of quantitative risk assessment

3.4.3.1 Approaches

There is more than one approach by which a quantitative assessment of gas risk can be carried out. The most appropriate method should be determined site by site from the results of Stage 1 and Stage 2. BS8485[4] describes three different approaches for completing quantitative risk assessments with a fourth approach applicable to particular circumstances published more recently. These approaches are briefly summarised below:

1. The total organic carbon method or TOC screening level approach can be used if the sole source of hazardous ground gas is Made Ground or Alluvium. In such circumstances where the sources are intrinsically low risk, total organic carbon testing of the source can provide the data for the assessment in lieu of gas monitoring data (CL:AIRE RB17[13]). Initially TOC test data from waste acceptance criteria (WAC) testing is used to determine the Characteristic Situation. Where the TOC limits for the Characteristic Situations are exceeded, dissolved organic carbon (DOC) on 10:1 leachate samples (following WAC testing procedures) may be used to assess whether the TOC is degradable or not and thus allow an appropriate Characteristic Situation to be defined. (Note: TOC testing requires a minimum sample size of 10kg).
2. Using a Gas Screening Value derived from assessment of gas monitoring data obtained from either spot monitoring or continuous data as set out in BS8485[5] and described here in Section 3.4.3.2 below.
3. Detailed quantitative risk assessment (DQRA) can be carried out based on detailed modelling and assessment of gas generation and migration through the ground and into the building (described in sections 6.2.2 and 6.4 of BS8485[4]). It is also possible to complete probabilistic risk assessment for ground gas (CIRIA Report 152[21] and the Ground Gas Handbook[22]). Where DQRA is employed the results and models should be used to determine the appropriate scope of gas protection. It is important when using such methods to avoid multiplying numerous worst case assumptions as this quickly escalates to an unrealistic assessment of the risk. If completing a DQRA, GSVs should not be used (except to screen out any areas of low risk and thus not subject to DQRA), nor should reference be made to the Characteristic Situations or the BS8485 points system.

Since publication of BS8485, a fourth generic screening risk assessment has been published in Ground Engineering[5]. This method can only be used where there is sufficient continuous monitoring data to ensure robust assessment. Furthermore, it should only be used by appropriately qualified people where gas is from low to moderate risk sources such as Made Ground, Alluvium, older or inert landfill sites (not domestic landfill sites post 1970 or mine workings). It is useful as a screening tool where continuous monitoring data is available and avoids the complexity of a detailed quantitative risk assessment. The screening values referred to could also be adapted using the method described to suit different pumping rates, well response depths, etc. In addition, the background information is useful when interpreting any gas monitoring data.

The relationship between the four different methods and their applicability in terms of complexity and data requirements is illustrated below (Table 3.1). Any risk assessment should start using the simplest approach that is relevant to a particular site and its conceptual site model. Adoption of the next more complex approach should only be carried out if it is justified (e.g. the current approach appears to be providing an unrealistic assessment or unacceptable levels of uncertainty).

Semi quantitative approach using Total Organic Carbon (TOC) results for very low to low risk sites	Semi quantitative approach using Gas Screening Values (GSVs) for very low to moderate risk sites	Quantitative approach using continuous monitoring data and alternative GSVs for very low to moderate risk sites	Detailed quantitative risk assessment using numerical modelling for very low to high risk sites
Claire RB17	BS 8485	Ground Engineering 2019	BS8485
Increasing complexity and increasing data requirements →			

Table 3.1 Complexity and data requirements for risk assessment approaches

3.4.3.2 Appropriate selection of the GSV

The term Gas Screening Value (GSV) was originally used in CIRIA C665[3] and NHBC 2007[1] to describe the hazardous gas borehole flow rates (Qhg) described by Wilson and Card[2]. However, the definition of GSV has changed subtly (and importantly) over the last fifteen years. Although much of the guidance in CIRIA C665 and NHBC2007, remains entirely relevant, the approach to deriving a GSV should now be as described in BS8485[4] (Clause 6.3.1) and not as described in CIRIA C665 or NHBC 2007. This recommended current approach is summarised in the bullet points below and described in more detail in the following text;

- Borehole hazardous gas flow rates (Qhg) are calculated for each borehole standpipe for each monitoring event (with decisions made as to whether to use peak gas flow rates or steady state rates in each calculation);
- The reliability of measured gas flow rates and concentrations takes borehole construction into account and decisions are made about how to deal with any temporal or spatial shortages in the data; and
- Judgements are made regarding the site characteristic GSV in the assignment of the Characteristic Situation and for design purposes, taking all relevant information and the conceptual site model into account.

Calculation of borehole hazardous gas flow rate (Q_{hg})

Consideration must be given to both methane (CH4) and carbon dioxide (CO_2) concentrations as well as flow rates. The borehole hazardous gas flow rate (Q_{hg}) is obtained for each hazardous gas, by multiplying the relevant gas concentration by the flow rate . It is calculated for each gas, on each monitoring event in each well. Where flow or gas is not detected the limit of detection of the instrument is used in the calculations (typically <0.1l/h for flow and <0.1% for concentration).

The individual values of borehole hazardous gas flow rate (Qhg) obtained from several monitoring locations over a number of visits are considered collectively to establish a Gas Screening Value (GSV) for the site as a whole (a site characteristic GSV). This requires consideration of the results in relation to the conceptual site model.

Consideration of site characteristic Gas Screening Value (GSV)

If the data set is considered comprehensive and representative and consistent with the conceptual site model, the site characteristic Gas Screening Value (GSV) will normally be the maximum Qhg. However, it is not simply a matter of considering the maximum Qhg value. The location of any high results in relation to proposed buildings, the number of results at or close to the highest value and the stratum of the response zone(s) all need to be considered. Furthermore, if the data set is temporally or spatially limited, a "worst case" condition should be determined (see below) and this "worst case" Qhg may be adopted to determine the site characteristic GSV.

Determination of characteristic situation (CS)

The site characteristic GSV for both methane and carbon dioxide is then used to determine the characteristic situation (CS), with CS1 representing the lowest risk and CS6, the highest. Further consideration of the appropriateness of this Characteristic Situation should be given by reference to additional factors (e.g. recorded maximum concentrations and flow rates). BS8485 advises that there is a requirement to consider an increase from CS1 to CS2 if methane concentrations exceed 1% v/v or carbon dioxide concentrations exceed 5% v/v however, increasing the classification is not mandatory. It is only necessary to increase the classification where a high risk source of gas is present such as from domestic landfills and open mine workings, or where there are consistently elevated methane concentrations in a number of wells across a site in Made Ground. It is not normally appropriate to increase the classification when there are sporadic and isolated elevated methane results and the source of gas is Made Ground with limited organic content, Alluvium or similar sources. For example, natural carbon dioxide concentrations can be up to 30% and methane in Made Ground can be up to 30% with no risk to development and no requirement to increase from CS1 to CS2.

Worst case assessment

BS 8485 (Clause 6.3.7.4) describes the completion of a "worst case" assessment, but in any event, the assessor needs to determine if such an approach is "reasonable". For example, a reasonable approach may not comprise the multiplication of the site's maximum gas concentration by the site's maximum flow rate. BS8485 (Clause 7.7.3.4) advises that such a worst case assessment is appropriate where there is limited data (i.e. less than required by BS8576) and it should be calculated using reasonable worst case measurements in the same stratum. However, it also advises that to adopt the worst case as a site characteristic GSV, the assessor should be confident that it is prudent and reasonable to do so and does not result in unnecessarily conservative protection of the development.

A worst case assessment is also not appropriate where continuous monitoring data is available that covers the worst case zone of barometric pressure changes as defined in CL:AIRE TB17[16].

Box 3.3 The Gas Screening Value (GSV)

A GSV is not a simple multiplication calculation but is a value determined using professional judgement and should be made with reference to all other lines of evidence and the conceptual site model.

3.4.3.3 Multiple lines of evidence approach

Multiple lines of evidence approaches are described in CIRIA Report C795[23] and in the CL:AIRE Guidance on mine gas risk assessment[11]. Following a multiple lines of evidence approach requires the gas monitoring results to be considered in combination with other data for the site from the desk study, and from intrusive works, i.e. soil descriptions, TOC and hydrocarbon soil test results, gas sample test results, groundwater levels. Each line of evidence is considered and weighted and conclusions drawn from it on its own. Differences between different lines of evidence are discussed and understood.

Box 3.4 Selecting the GSV

The appropriate selection of the GSV must use a multiple lines of evidence approach. The GSV must not be determined by a simple multiplication of the worst-case flow rate and the worst-case concentration of each gas **without further consideration/assessment.**

This issue is closely related to the data quality check (see section 3.4.1), as conflicting lines of evidence need to be considered and judgement made about the most reliable data source, or uncertainty taken into account where it exists. Quantitative modelling of various scenarios (including worst case) may be used to examine the potential for gas ingress and accumulation to potentially hazardous concentrations in sensitive locations (e.g. small ground floor rooms) which can further inform the assessment of risk (see examples in CIRIA C665 – Appendix A5.3.3[3]).

3.4.4 Identification of low risk sites

In addition to financial motives, there are sustainability gains in designing out unnecessary remediation. Assessors may determine whether or not ground gas risks can be assessed as "Acceptably Low / Negligible" at an early stage in the risk assessment process (Stage 1). Or, if there are credible potential sources that warrant assessment, this conclusion may be drawn later, after sufficient investigation and consideration of multiple lines of evidence. Such an assessment must also conclude that there is no plausible potential for future change to the gas regime, such as from climate change effects. If there is sufficiently robust data, then it can be concluded that no mitigation (installation of gas protection measures) required. If uncertainty still remains, then further data gathering might be required to determine the correct classification of the site. If all gas monitoring wells are flooded, then TOC data combined with flux tests might be needed. Or if monitoring has not yet been completed during falling atmospheric pressure (and it is likely to be a driver for gas emissions) then further visits should be scheduled. Where all existing lines of evidence point to a negligible or acceptably low risk, but there is some remaining uncertainty or deficiency in the investigation data, this should be critically assessed to determine if it is likely to have a material impact on the risk classification.

Box 3.5 Gas membrane and low risk sites

Including a gas membrane and/or other protection methods into the design of a building on a "precautionary basis" with no justification is not an acceptable approach. Although it is "easy" for a designer to show a gas membrane on a drawing and the costs of materials is relatively small, the true costs of installation (expertise, programme, verification) can be significant. If the quality of the site investigation data is poor the risk assessor should assess the data gaps and uncertainty this causes in the risk assessment and then explain how the gas protection measures will adequately address the issues. The assessor should be sure that collecting more data or completing more detailed assessment is not likely to result in the scope of gas protection measures being greater than proposed.

3.4.5 Accounting for climate change in ground gas risk assessment

The global climate and future weather patterns are changing (**https://www.metoffice.gov.uk/weather/climate-change/effects-of-climate-change**) and these changes may influence the risk posed by the presence of gas or vapours in the ground and should be considered on a site specific basis. Ground gas risk assessment therefore needs to include consideration of the potential for:

- increased frequency of UK warm spells
- increased frequency of heavy rainfall events and increase in rainfall intensity and
- increased duration and/ or frequency of dry spells in summer.

Increased temperature and drier summers could, for example, increase the depth of desiccation in a landfill cap or clay confining layer or cause a drop in groundwater levels. These may expose a new migration pathway, potentially influencing off-site migration. Increased rainfall will increase flood risk and this could influence both gas generation and migration.

Increases in rainfall may also influence the extent and duration of ground saturation (the influence of which being dependent upon soil permeability) and may also cause a rise in groundwater levels. Particular attention would be required where groundwater is shallow and responds more quickly to rainfall (e.g. a site located in a valley where groundwater responds to rainfall in a large surrounding catchment, whereas groundwater at depth may be less sensitive to short intensive rainfall events). As always, critical consideration of the conceptual site model is required to inform a site specific assessment.

The effect of increased water infiltration on the ground gas generation processes should be assessed including consideration of the rate of gas generation or release and whether this is likely to change sufficiently to increase the risk from surface emissions. The key parameter in this respect is the total organic carbon and degradable organic carbon of the materials in the ground.

A site specific assessment of the impact of climate change should also consider whether the effects discussed above are likely to increase gas risk such that the planned level of protection is sufficient to keep risk acceptably low for the lifetime of the development. In many cases the effects from climate change will not significantly change the risk because the source generation rate or migration pathway is the limiting factor or alternatively the existing gas protection is sufficient to deal with any plausible change to the gas regime.

The effects of climate change of atmospheric pressure events is currently inconclusive. However, barometric pressure drops of at more than 20mb in 24 hours are not unusual in the UK at present and therefore this factor also needs consideration in any assessment incorporating potential climate change effects. The factors affecting the potential for an increase of gas emission from the ground caused by falling atmospheric pressure are:

- the greater the depth of the unsaturated zone, the greater the potential for increased emissions;
- the greater the permeability of the ground, the greater the reservoir potential;
- the greater the pressure drop, the faster and further emissions will migrate.

Climate change therefore needs to be considered in a site specific assessment which includes:

- a balanced consideration of credible and foreseeable events against hypothetical events that are not realistically likely to occur
- consideration of credible pathways considering what is known about the geology and hydrogeology, building construction and services layout, etc.
- site specific consideration of the impact of foreseeable events such as flooding, changes in groundwater level, extreme weather conditions and possible changes to the gas regime caused by future development
- where appropriate, quantitative assessment of any credible changes in gas regime and the impact this may have on the risk posed by hazardous ground gases.

Box 3.6 Consideration of climate change

Assessment of climate change effects should be site-specific and realistic.

There is normally a significant degree of conservatism already built into ground gas risk assessments and consideration of future changes due to climate change should determine if the likely changes are significant when compared to assumptions already accounted for in the baseline risk assessment.

3.5 Case studies

3.5.1 Case Study 1. Multiple lines of evidence approach

A site was to be redeveloped as housing blocks with commercial use at ground level. There were no housing units at ground level. The site is underlain by a thin layer of Made Ground (0.4m to 2.1m thick) comprising soil materials with occasional pieces of wood. The Total Organic Carbon content of the soil was 0.5% to 2.1% with an average of 0.8% (combined results from proportion of wood and TOC of soil). The site had no previous uses that could cause a significant source of ground gas (i.e. it was not a landfill, near mine workings or similar). The Made Ground was placed to level the site as part of previous commercial developments. It did contain low concentrations of hydrocarbon contamination but at levels such that vapour intrusion was not a significant risk. There are no other sources of ground gas below the site. There was no need for any gas monitoring and the site could have been classified as CS1 based on the soil descriptions and TOC results. However, because of the timescales, gas monitoring wells were installed during the site investigation as a precaution (in case the TOC results came back high) and the consultant subsequently monitored for ground gas.

Monitoring wells were correctly installed with response zones in the Made Ground. However, wells were also installed in the Glacial Till below the site and the deeper Chester Formation which is a sandstone. These were not necessary as neither is a ground gas source. The gas monitoring results are summarised in the figure below.

Three sets of monitoring wells

Response zone in Made Ground
Max CH_4 = 12%
Max CO_2 = 9%
Min O_2 = 0.1%
Max flow = <0.1l/h

Response zone in Glacial Till
Max CH_4 = 0.1%
Max CO_2 = 12%
Min O_2 = 9%
Max flow = <0.1l/h

Response zone in Chester Formation (groundwater wells)
Max CH_4 = 0.1%
Max CO_2 = 3%
Min O_2 = 19.2%
Max flow = 52.6l/h

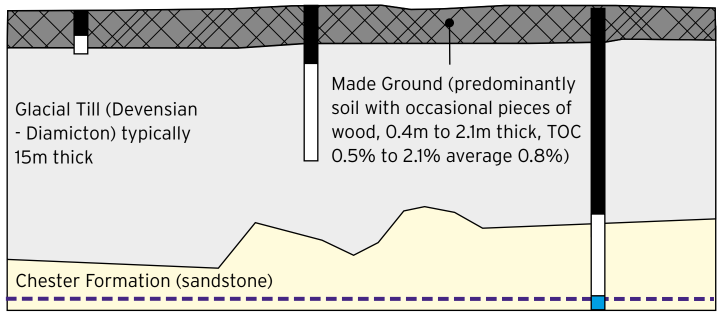
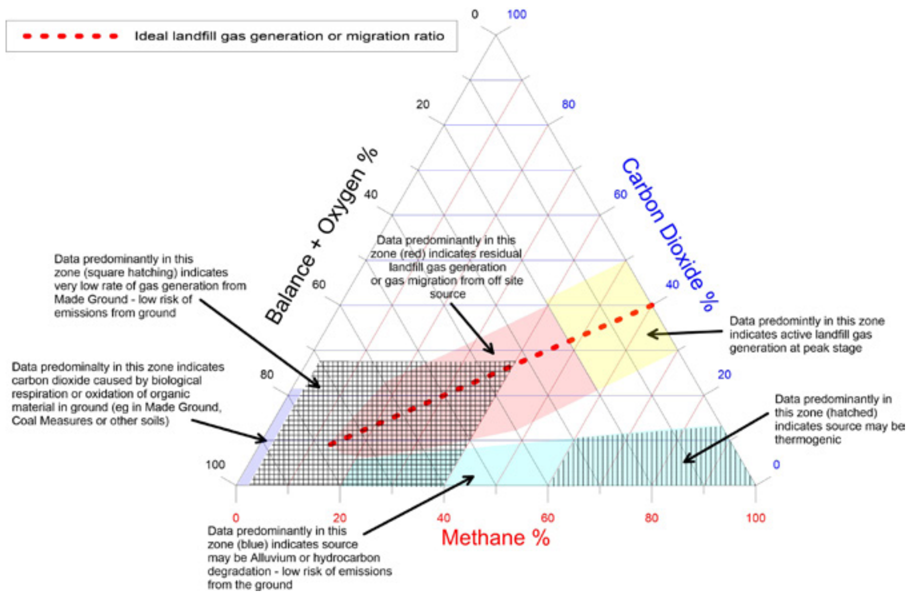
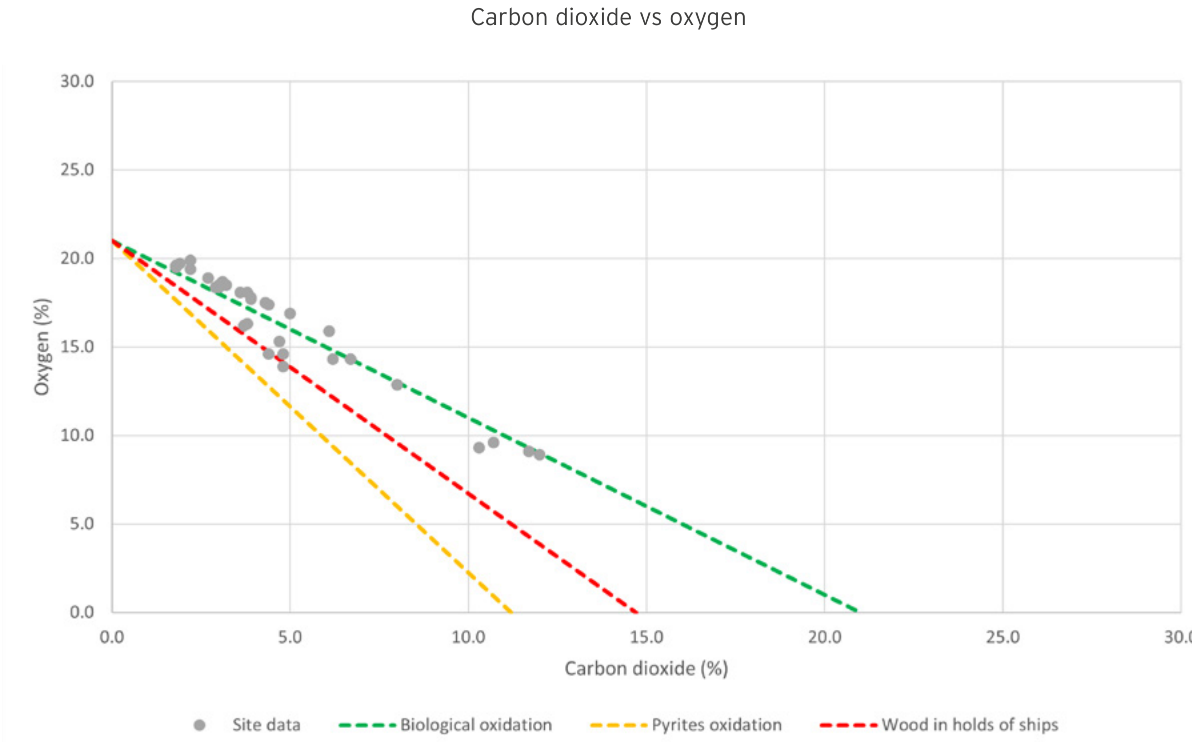


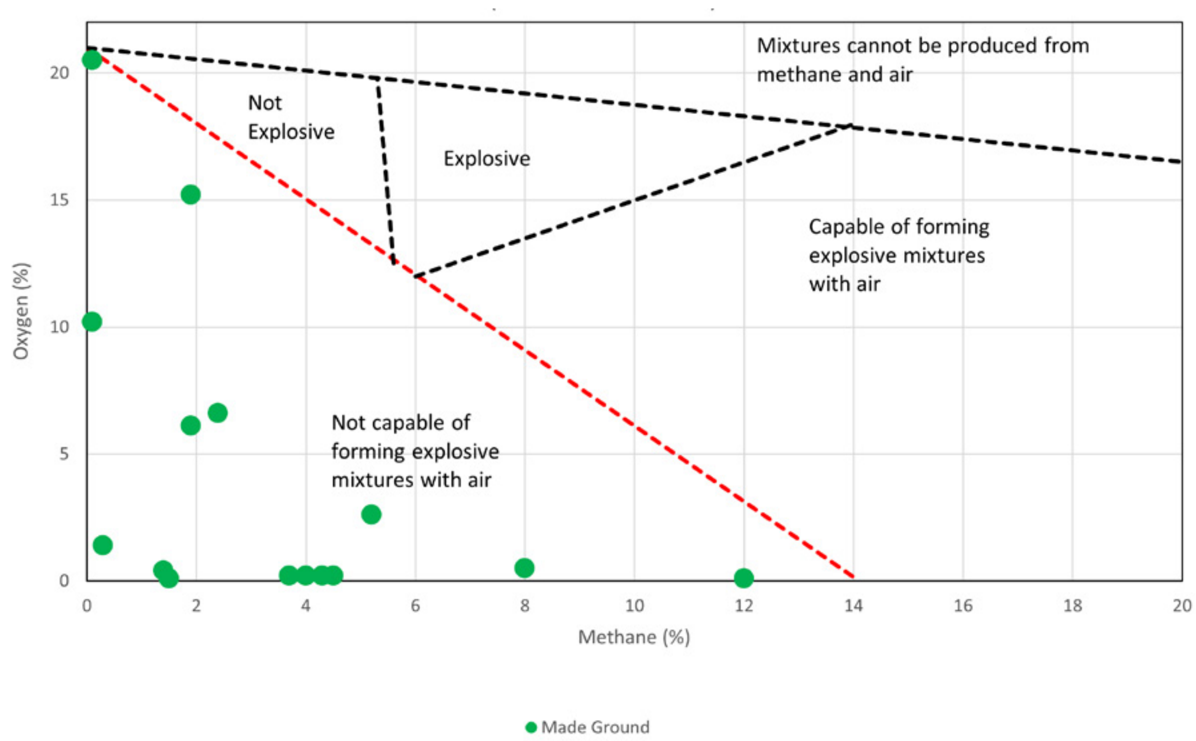
Figure 3.3 Monitoring wells at the case study site

The site was determined (incorrectly) to require gas protection measures comprising gas membranes and an active sub slab venting layer on the basis it was CS4. This classification was derived by multiplying the highest methane and flow rate regardless of the response zone (12% methane in Made Ground and 52.6l/h flow rate from Chester Formation). This was incorrect and BS8485 is clear that where a GSV is derived using worst case data it should use data from wells with response zones in the same stratum, not from different strata. The multiple lines of evidence approach that was subsequently adopted is described below.

Line of Evidence	Description	Risk
Desk study	The desk study has not identified any significant source of gas. It has a history of development and general Made Ground is to be expected but with a very low gas generation potential. Hydrocarbon contamination may be present at low concentrations. There is no evidence of excavations, infilled railway cuttings, quarrying, landfilling or mining.	Very low
Soil descriptions	Made Ground is predominantly soil with occasional wood. There is no evidence of highly degradable material which is consistent with the desk study. There is nothing to suggest high gas generation rates will occur. The TOC and DOC from waste acceptance criteria (WAC) testing results indicate very low gas generation rates. Hydrocarbons present in isolated pockets at low concentrations – hydrocarbons will degrade and produce methane but at very slow rates such that hazardous emissions are not likely. All the above indicate the risk of hazardous emissions into buildings is very low.	Very low
TOC results	The Total Organic Carbon content of the soil was 0.5% to 2.1% with an average of 0.8% (combined results from proportion of wood and TOC of soil). Defined as Characteristic Situation CS1 in accordance with CL:AIRE RB17[13].	Very low
Gas monitoring data	Worst Hazardous Gas Flow rates are: Made Ground – 0.012l/h (Characteristic Situation CS1) Calculating HGFRs for the Glacial Till and Chester Formation is not appropriate as they are not sources of ground gas that could pose a risk to the development. The ternary plot below and the plot of carbon dioxide vs oxygen below shows the carbon dioxide in the Glacial Till is caused by biological respiration which is a natural process and occurs widely in soils to produce elevated carbon dioxide. It does not pose a risk of hazardous emissions. The explosive limits graph and the ternary plot suggest that the methane in the Made Ground is caused by degradation of hydrocarbons. With the small volumes of hydrocarbon contamination, the methane cannot be produced at rates that will cause hazardous emissions. In addition, because the degradation process are consuming oxygen the methane could not form an explosive mix in air if it comes out of the ground. 	

Line of Evidence	Description	Risk
Gas monitoring data continued		Very low

<table>
<tr><th>Line of Evidence</th><th>Description</th><th>Risk</th></tr>
<tr><td>Gas monitoring data continued</td><td>
Relationship between compostition of mixture and air (ASTM E 2993 - 16)



For both methane and carbon dioxide there is no justification for increasing the site classification from CS1 to CS2 based on gas concentrations.</td><td>Very low</td></tr>
<tr><td>Generation and flow analysis</td><td>Not required on this site</td><td>N/A</td></tr>
<tr><td>Surface emissions survey</td><td>Not required on this site</td><td>N/A</td></tr>
<tr><td>Flux chamber tests</td><td>Not required on this site</td><td>N/A</td></tr>
<tr><td>OVERALL RISK</td><td>All the lines of evidence indicate a very low gas risk on the site.
Gas monitoring data indicates Characteristic Situation CS1</td><td>Very low - CS1</td></tr>
</table>

Table 3.2 Summary of lines of evidence

3.5.2 Case Study 2. Gas risk assessment for a residential development

An exploratory level ground investigation was carried out in two phases on a site of proposed residential redevelopment. The investigation was informed by a considerable body of existing information from previous investigations (both on site and on neighbouring land). The ground conditions at the site comprised two elements of Made Ground (a capping layer over historic fill with little degradable material) overlying Alluvium (clay with bands of sand, silt and peat), followed by Terrace Gravels. The focus of the initial phase of investigation was to assess the gas generated from the Alluvium with six monitoring wells installed across this stratum and the overlying Made Ground and monitoring carried out over a 6 month period. The associated report summarised the strata and groundwater encountered but did not include the detail of the response zones. The gas monitoring data was presented for each exploratory hole (graphical record plus brief text) but did not include information on response zones or depth to groundwater. An assessment of gas risk was provided in a simplified table which was potentially misleading, and this was used to support the determination of the Characteristic Situation (CS) based upon a statistical assessment of the gas screening value (GSV) which did not accord with the advice in relevant guidance or pay adequate attention to the reliability of the data (i.e. source(s) of the gas and the effects of groundwater). The report concluded that a gas protection system consistent with measures identified as "typical" for CS4 would mitigate the potential hazardous gas risks to an acceptably low level.

The local authority did not accept the report as suitable to discharge the relevant planning condition (or to adequately identify the need for / scope of gas protection measures). Accordingly, a second phase of ground investigation and monitoring (12 well installations) was carried out focussed upon the source(s) of hazardous ground gas. The monitoring data was presented but the nature of the response zones (six wholly flooded and four part flooded) was not considered. Maximum and mean hazardous gas flow rates were tabulated. The hazardous ground gas regimes were characterised as CS1/2 for the shallow Made Ground strata and CS5/6 for the deep alluvium (effectively ignoring the unreliable nature of the data from the flooded wells).

A third party consultant was commissioned to summarise all of the existing data and to re-assess the hazardous ground gas risk. That risk assessment commenced by detailed consideration of the response zones, groundwater data as well as the recorded concentrations of gas and flow rates (including continuous gas monitoring data). This demonstrated that;

- the principle source of hazardous gases was the deep Alluvium
- the recorded high concentrations of hazardous gas are predominantly associated with peat which is confined and does not readily migrate to the ground surface
- the Made Ground is a subordinate low risk source of gas
- flow rates generally are a response to changes in groundwater level and are an artefact of the presence of the borehole.

The conceptual site model was defined which included a clear identification of the main potential sources of hazardous ground gas (mainly the deep Alluvium together with the Made Ground) the (limited) potential for piles constructed for foundations to form preferential migration pathways and the identification of the main migration pathways pertinent to the proposed development as; service penetrations, cracking and joints in the floor slabs. The results of mathematical modelling which considered the potential for hazardous concentrations of ground gases in buildings via diffusion and advective flows (carried out in accordance with CIRIA C665) was then presented. The modelling adopted a number of conservative assumptions, and the results indicate a very low likelihood for the gases to reach even a fraction of hazardous concentrations in buildings. On the basis of all of the assessed data a Moderate level of risk associated with both diffusion and advective flow was determined, the designation of and CS5/6 was discounted (supported by the risk assessment) and detailed recommendations for a gas protection system (comprising a combination of; ground slab, membrane, venting and verification.

The detailed risk assessment was considered by the local authority to be entirely appropriate, consistent with the ground gas regime and the recommended gas protection measures.

Stage 4 - Design and Detailing

4.1 Process

The design and detailing of gas protection measures must comprise more than just adding up points in the BS8485 screening system and providing standard details for gas membrane installations. The process should be systematic and commence with a general description of the gas protection system necessary to mitigate all of the potentially significant risks identified during Stage 3. That description should include consideration of the gas protection that will be provided by the building construction and also any conflict between the proposed building design and the gas protection measures. Depending upon the proposed gas protection measures, a check should be made of the design details with respect to the ventilation measures (if any), the gas barrier (if any) and also the planned verification necessary to demonstrate successful installation / construction.

The overall process and steps necessary for the design and detailing of a gas protection system is illustrated in Figure 4.1 overleaf. This is followed by comments on particular aspects related to design and detailing, namely; competence (section 4.2), a summary of current issues arising from the industry consultation (Section 4.3), advice on a series of the watch points related to those issues (Section 4.4), followed by case studies (Section 4.5).

Stage 4

Gas Protection – Design and Detailing

Stage 4.1 Design report

Prepare report
To accord with BS8485

Define
Scope of measures

Design
Mitigate risks from all identified contaminant linkages

Specific to conceptual site model and design of new building(s)

Consider
Gas protection inherent to building design (e.g. floor slab)

Gas membrane

Ventilation

Potential conflict / adverse impacts between building and gas protection designs

Stage 4.2 Barrier design and specification

Identify and resolve
Conflicts between gas protection and other influences on construction

Review
Data sheets against specification

Provide
Detailing

Check
Constructability and build sequence

Stage 4.3 Ventilation design

Define
Performance level

Calculate
Gas flow from ground

Determine
Required air flow

Analyse system
Ensure sufficient ventilation

Consider no-wind conditions

Stage 4.4 Design changes

Re-visit
Risk assessment

Re-consider
Inherent building gas protection

Re-evaluate
Ventilation performance

Stage 4.5 Basements

Consider
Integration of waterproofing and gas protection

Stage 4.6 Verification Plan

Define
Scope of verification activities

Roles and responsibilities

Ensure
Compatibility of verification testing (if planned) with construction activities & programme

"Hold Points" – requiring verification before continuation of construction

Define
Required competence

Figure 4.1 Design and specification process

4.2 Competences, roles and responsibilities

The design of gas protection systems requires a thorough understanding of a wide range of disciplines including factors in the ground that can affect ground gas risk, foundation and building construction methods and materials, the performance and behaviour of reinforced concrete or other flooring materials, the properties of gas membranes and ventilation layers, and air flow theory. It should also be noted that the design process is more than just detailing up gas membranes onto drawings, which can be completed by competent technicians.

The design of the protection system cannot be divorced from the risk assessment process and a recent CIRIA Report[24] advises that the design of gas protection systems should be signed off by a Chartered Engineer or Geologist with appropriate experience. For example, one of the key aspects of design is providing a conceptual site model that includes gas migration pathways through the ground and also through the proposed building construction.

Box 4.1 Designers and competence

Designers of gas protection systems are required to be competent professionals with sufficient knowledge and understanding of both ground gas risks and the construction methods and materials.

For clients it is important that there is clear responsibility for the design of the gas protection system. The designer should be specifically appointed under a contract for design, and they should hold professional indemnity insurance that specifically covers them for the work. If a "design" is obtained from suppliers, manufacturers or installers, consultants can become responsible for that design if they transfer it onto their drawings and the supplier has not been appointed as the designer of the gas protection.

4.3 Current state of the art

Based on the industry consultation survey responses the design and detailing stage was in the middle in terms of the frequency of problems encountered by practitioners. The modal response was that problems are "often" encountered and was stated by 39% of respondents.

The top causal factors for problems encountered in ground gas projects at the design and detailing stage were identified as "poorly defined responsibilities" (56) followed by "lack of competence" (53) and "lack of training" (52). "Clashes with other site constraints/trades" (25) was also frequently identified as a causal factor. A broader suite of causal factors was identified than for earlier stages, with all factors being selected 14 or more times. Existing published guidance was the least often identified factor for problems for this stage of the process.

The key issues identified by survey respondents at the design and detailing stage were counted and grouped. The most frequently identified issues related to:

1. Responsibility for the design and who completes it.
2. Lack of detailed site-specific design and use of standard details which may not be applicable.
3. Constructability and build sequence for gas membranes and requirement for membrane protection. Specific gas membrane detailing issues: edges, thresholds, service penetrations, foundation design.
4. Ventilation calculations, pipe and sub slab ventilation layer (vent mat) layouts.
5. Design changes and poor quality drawings.
6. Issues associated with basements, waterproofing and gas protection
7. Lack of verification plans (see section 6.4.2).

It was also identified that there was a lack of standard details applicable to modern non-traditional building techniques, or that these details were spread across a range of sources. This stage of the process was also one where competence or understanding of requirements by practitioners, regulators and clients was most frequently commented on, and a need for further education and training has been highlighted.

This guide provides some standard details (Appendix C) that will be useful to NHBC's major house builder customers. It can also be used as a starting point for training resources, including for non-specialist stakeholders that need a basic understanding of the design process, including as a guide for procurement of services from appropriately qualified professionals.

4.4 Watch points

4.4.1 Design report

BS8485[4] advises that a design report should be prepared for gas protection measures. This is similar to a geotechnical design report and should identify the key assumptions made in the design, justification for the points assigned if using the points system, justification for choice of products including gas membrane specification (see Chapter 5), ventilation calculations (if relevant), and any other specific requirements during construction of all elements of the gas protection system. A diagram summarising gas protection design to BS8485[4] is provided in a recent CIRIA report[24] and is reproduced below Figure 4.2.

Key points to consider when following the guidance in BS8485 are:

1. Where points are allocated to any part of the protection system the designer should provide justification. This specifically applies to floor slabs or other structural barriers and many professionals do not realise that by allocating points to a floor slab to act as a structural barrier to gas migration they are taking responsibility for its design to be suitable for gas resistance;
2. The design of sub-floor ventilation requires site specific calculations to demonstrate the performance. The graphs provided in Appendix B of BS8485 are for information only and should not be used for detailed design.
3. The specification of the gas membrane requires consideration of more than just gas transmission rate. It requires consideration of durability, resistance to damage during construction, etc. BS8485 Clause 8 3.2 requires the designer to provide justification for the choice of gas membrane;
4. The gas protection design should be summarised in a design report and site specific design drawings should be provided.

Box 4.2 Designers and competence

A **Design Report** and **Construction Drawings** should be prepared detailing the site specific requirements for the gas protection system with respect to the development.

Gas protection design is more than just adding up points taken from tables in BS8485. If using the points approach, allocation of the points needs to be justified in the context of the risk, and specific details around each element of the gas protection system need to be included.

The gas protection design report should be seen as a working document and should be reviewed once all the development design details are fixed to make sure that other parts of the works have not changed and will not adversely affect the performance of the system or require additional protection elements (e.g. if foundations have changed to stone columns, or deep drainage attenuation tanks are proposed these could introduce preferential pathways for gas migration to the buildings, if the thickness or level of reinforcement of a structural slab has changed this may impact it's gas resistance etc.).

For low rise housing on CS2 and CS3 sites the design report does not have to be an extensive document. Site specific details for the gas membrane installation, and locations of vent bricks can be provided on architects' detail drawings that show the floor finishes, DPMs etc. Conversely a more detailed report and specific construction details are likely to be required for larger and complex multi storey developments.

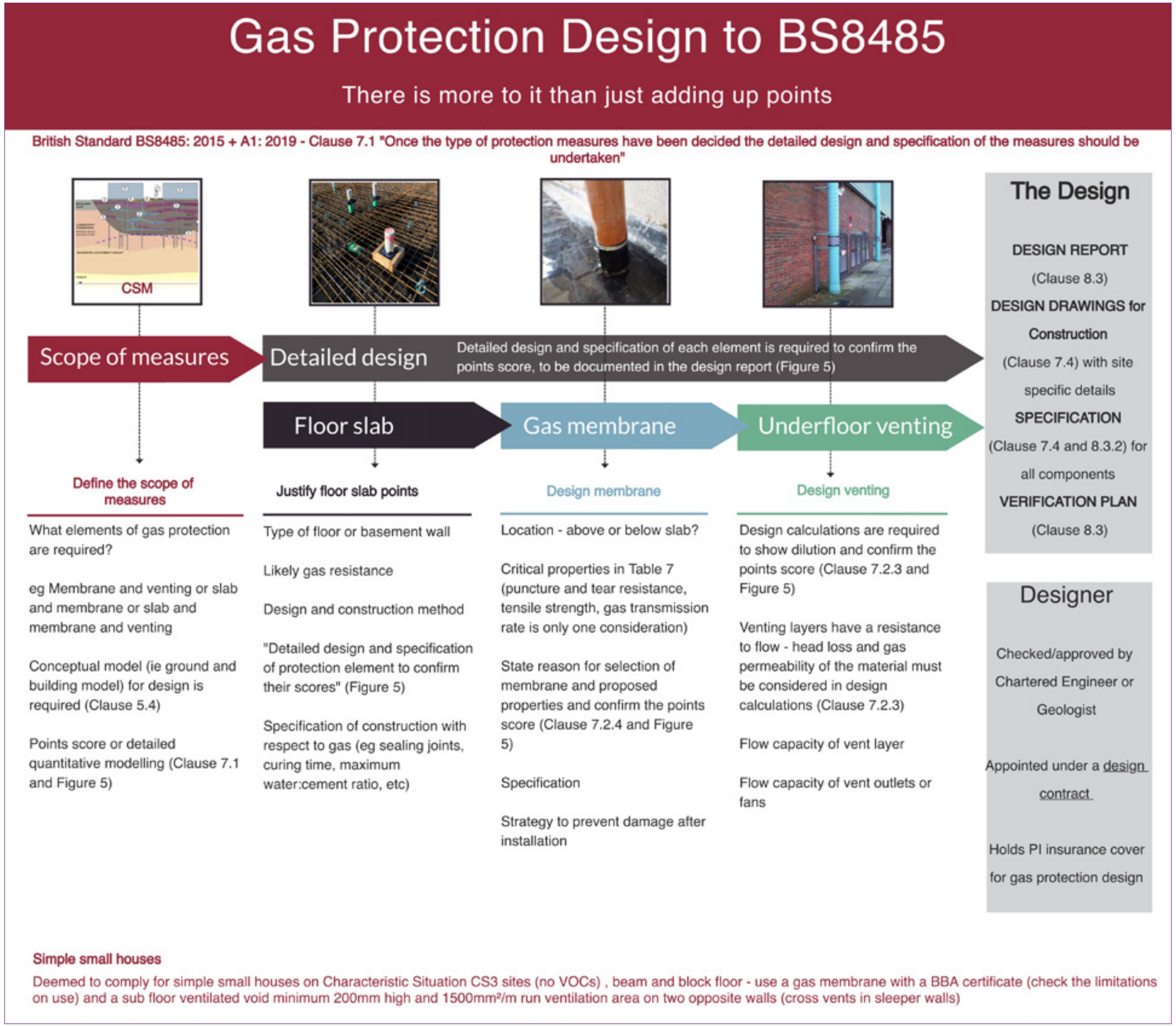


Figure 4.2 Summary of gas protection design

The design report should also include a Verification Plan for the gas protection system as specified in Clause 8.3.3 of BS8485. The designer is best placed to define the Verification Plan (i.e. the frequency and type of inspections and tests). The Verification Consultant will then prepare a detailed Verification Method Statement based on the designers' plan. Verification Consultants should not prepare the Verification Plan (unless they are also the designer and author of the Design Report). It is useful when writing the Verification Plan to define hold points beyond which construction should not continue until written confirmation is obtained from the Verification Consultant that the gas protection works are acceptable before elements are covered. This avoids missing verification and the extensive work that is often required to uncover gas membranes or show by other means that the installed systems are acceptable. Further consideration of the verification process is presented in Section 6.4.2.

4.4.2 Standard details

Some typical robust standard details for gas protection together with explanatory text are provided in Appendix C of this report for various types of building construction. Designers need to consider the accommodation of gas protection strategy requirements into modern building construction techniques. That should include both detailing and practical aspects of including membrane and venting provisions within typical wall and floor constructions, which must also meet requirements of the waterproofing (see section 4.4.7) and must not compromise building performance by indirect means (e.g. inadvertently forming a cold bridge, causing an interstitial condensation risk, blocking or partial blocking of vent positions). Schematic drawings of details adapted from those used on actual sites (including blockwork, timber frame, modular and precast construction) are provided in Appendix C. Modern construction methods are continuously evolving, and the gas protection designer should have sufficient knowledge, qualifications and experience to adapt gas protection designs to specific forms of construction without the need for explicit published guidance on incorporating gas protection into the specific form of construction. The designer should be able to justify the approach to gas protection taken in any form of construction.

Consideration also needs to be given to the inherent gas protection in the base construction that could be enhanced to provide the required gas protection without the need for the specific gas protection products (e.g. consolidation of damp proofing with gas protection measures into a coherent holistic solution). However, it may also make detailing simpler and construction easier if the gas protection is separate from the damp or waterproofing function. The most problematic areas are: detailing a gas membrane through walls, continuity at changes in floor level and around door thresholds as illustrated in Figure 4.3.

Areas that require careful consideration when detailing gas membrane

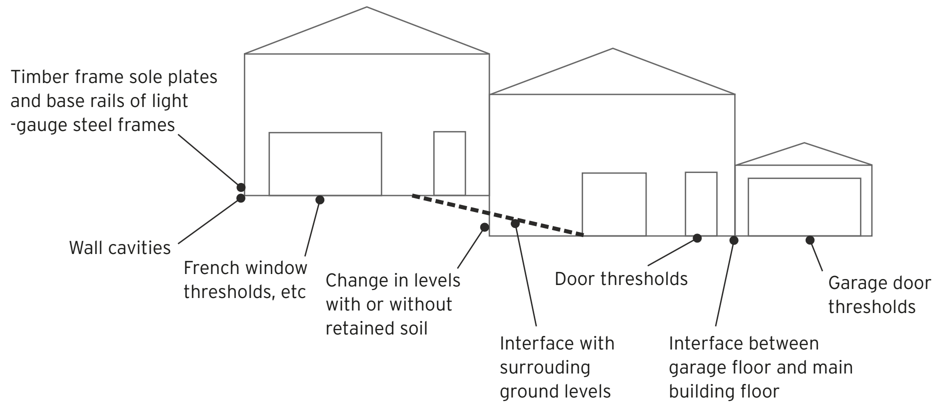


Figure 4.3 Issues when detailing gas membranes into low rise house construction

The key requirements for each element of the gas protection system should be identified and consideration given to whether these are "cast in stone" or can be adapted. For example, the position of the ventilation layer can be re-evaluated. It does not always need to be below the gas membrane and in some instances, it might be suitable to place it above the membrane, especially with modular construction. If this is the case it should be justified by the designer, based on the level of ground gas risk, size of building and air flow connections between the ventilated layer and the occupied space. Examples of typical construction details are included in Appendix C.

Some of the details avoid more common problems of installing gas membranes through cavity walls by placing the gas membrane lower in the construction where it is less susceptible to damage and easier to detail and install. The interface between timber frame and gas membranes is a common cause of damage which is avoided by placing the membrane lower in the construction.

Damp ingress can occur along horizontal gas membranes through cavity walls if the cavity tray is missing or not installed correctly. Cavity trays should be sealed to a horizontal gas membrane using an appropriate sealant. This is a key watch point during construction. Alternative solutions that have gas membranes stepping down across the cavity reduce the risk of damp ingress but lead to numerous penetrations through the membrane. Penetrations are the weak point in any gas membrane and should be minimised, therefore sealing a membrane around air bricks increases the potential for leaks and is not ideal.

4.4.3 Structural barrier – assessing gas resistance

BS8485 defines the structural barrier as the floor slab or substructure construction (including any waterproof concrete walls or floors in basements). In the GSV screening and points approach for defining the scope of gas protection points can be assigned to the structural barrier as part of the gas protection design. For low rise housing with beam and block floor construction this is not a concern because points are not assigned to that type of construction. It is more likely that points will be assigned to engineered floor slabs in high rise developments or to waterproof concrete basement walls (note the points for a structural barrier in BS8485 only apply to the waterproof concrete).

Determining the correct allocation of points to a structural barrier requires assessment of the inherent gas resistance of the floor slab and risk of significant gas migration through it. The gas protection designer should justify in the design report the points assigned to the floor construction. The gas protection designer may have to specify requirements for the floor design or construction and also appropriate sealing any joints in the floor slab (see section 5.4.2). Further advice is provided in Appendix A of BS8485.

Factors to be considered are:

- the maximum crack width(s) that have been assumed in the slab design. Structural designs should consider requirements to resist both flexural and shrinkage cracking
- the type of joints in the slab and how wide are they likely to be
- thickness of the concrete.

Note that in most cases the potential for significant gas migration on CS2 and CS3 sites through a significant thickness of concrete such as pile caps, thick foundations (>0.5m) below lift shafts and stair cores, etc is very low. These areas are difficult to install properly and are often damaged so avoiding membranes around such features is beneficial. It is often possible for the designer to avoid the need for gas membranes to wrap such areas. However, the risk assessor and gas protection designer should consider the structural design for each site/building and ensure that this is the case.

4.4.4 Membrane detailing principles and tips

Whilst the majority of a gas membrane is laid as a flat sheet, the edges require detailing through wall cavities and around complex 3D shapes. In high rise buildings with complex floor slabs, ground beams and foundations the detailing is complex, but even in low rise traditional construction there is a requirement for proper site specific detailing. Common points of difficulty include corners, door thresholds and changes in level between the main house and garages or between adjacent semi-detached or terraced units. These details are often the most prone to damage with different sub-contractors that interface with the membrane (e.g. bricklayers and timber frame installers) after it has been installed. In high rise buildings the difficult areas are interfaces at ground beams and piles, lift pits and stair cores as well as service entry ducts (further details on good construction practices are provided in section 6.4.1 and Appendix C). In all such instances it is important to ensure sufficient continuity across the membrane installation.

Box 4.3 **Designers and edge details**

The designer needs to consider and include details for how edges, joints and penetrations of the membrane are to be sealed. If possible complicated details should be "designed out" by specification to use proprietary systems for junctions and interfaces and simplified to ensure that it is practical to achieve a good seal on site.

When detailing gas protection, it is important to identify and resolve potential conflicts between the gas protection strategy and other relevant statutory documents and guidance that could influence the construction/detailing. In particular the gas protection design should not compromise compliance with Building Regulations and the following Approved Documents:

- Part C: Site preparation and resistance to contaminants and moisture: the location and detailing of the gas membrane should not cause damp or water ingress problems. Note that Part C offers limited advice that is current in relation to ground gases. It defers to other documents, namely CIRIA Report 149, BRE/Environment Agency Report BR 414 and BRE Report BR211 (for radon) when advising on remedial measures, but these have not kept pace with current construction methods and practices or changes to other Building Regulations, so do not necessarily offer solutions that are compliant.
- Part L: Conservation of fuel and power (and Section Six (energy) of the Scottish Standards) set the levels of thermal insulation required when carrying out building work. The gas protection should not compromise this for example by causing cold bridging. The use of active systems is not acceptable for other reasons (reliance on maintenance) but would also increase the use of power when compared to passive systems. From June 2022, Part L1 of the Building Regulations will require photographic evidence of the insulation that has been installed to be provided to sign off a dwelling. There is a requirement to have a photograph (for each plot) which shows the continuity and quality of insulation at an external door threshold. This is an important interface where each element should not compromise the other (and care will have to be taken to ensure photographs are taken before insulation is covered by gas membranes for example).
- Part M: Access to and use of buildings. It is important that where ground levels around buildings are raised to provide access that any sub floor vent points are maintained at an acceptable level and are not forced to be at or below ground level. Ground level or below ground level vents are not acceptable on low rise housing because of the risk of blockage (see Section 4.4.5).

There is a currently a lack of detailed site-specific design on projects and over reliance on just providing suppliers' standard details which may not be applicable. Site specific drawings and details are required for both the sub slab ventilation and the gas membrane installation. These are required so that the installer and verifier know what the design should be and what is required. Key issues in detailing gas membranes are:

- the thicker a gas membrane is the more robust it is (for the same material) but will be less flexible and harder to detail around corners, changes in level, etc. A balance has to be struck between the two requirements
- in any event all gas membranes will require protection from damage immediately after installation. There are two main forms of damage that occur: Deliberate damage caused by cutting the membrane to remove it where it is making brick laying or other works difficult. This type of damage has to be addressed by good site management and education (see CIRIA Report C801[24])
- accidental damage by people dropping sharp objects onto membranes or walking across the surface with grit in treads of their boots (the most common reinforced membranes are only 0.4mm thick between the reinforcement and can easily be punctured). The steel fibres in reinforced screeds can also easily puncture membranes. This type of damage is prevented by placing a protection layer above and possibly below the membrane (it is easier to puncture a membrane that is laid on a hard surface compared to one on a soft surface). The protection layer can be a specific item (e.g. protection geotextile or board) or it can be the insulation boards.

Box 4.4 Designers and edge details

Consideration of membrane properties (see Chapter 5) and detailing (this Chapter) goes hand-in-hand during the design process, as different membrane types might require slightly different detailing, due to flexibility and durability.

Constructability and the build sequence for gas membranes needs to be carefully considered, especially for basements and heavy floor slab construction for apartment blocks. On more complex or unusual building types it is useful to provide 3D isometric drawings showing the building sequence (examples are provided in Figure 4.4. This ensures that the gas membrane (or different parts of it) can be installed at the right time in the building programme.

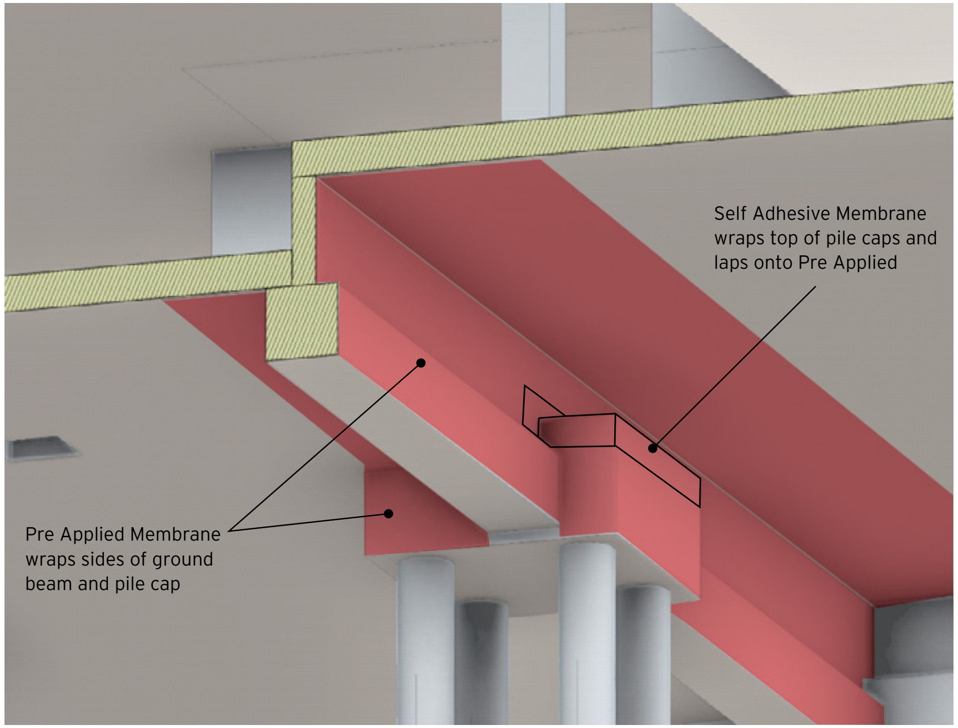


Figure 4.4 Example of 3D isometric drawing used to plan gas protection system

Gas membranes can be sealed using either adhesive tapes, heat sealing or welding. The designer should specify the type of jointing and sealing that is required. In terms of difficulty in forming the seam correctly the level of difficulty in order top down from most difficult is:

- Fully welded seams (twin wedge welding or extrusion welding) require trained and experienced operatives. The membrane needs to be carefully prepared and clean. The twin wedge seam can be air tested via the air channel between the two welds. QA for the welding should include test welds to determine the correct welding temperature and speed and testing of them.
- Taped seams are difficult and slow to form correctly. A roller and a hard firm stratum are required below the seam and the membrane should be completely clean and dry.
- Heat sealing is similar to welding but a full weld is not formed. The two sheets to be sealed are heated with a heat gun and a roller used to press them together. Again, a firm stratum is required below the membrane to allow sufficient pressure to be applied to form an effective seal.

Further information on sealing membranes is provided in Scheirs (2009)[25]. All sealing methods require skilled and trained operatives to form them effectively. The risk of poor installation is reduced by using specialist gas membrane installers, especially on larger or complex developments.

The most common method of sealing gas membranes to penetrations such as ducts or drainage pipes is to use self-adhesive gas membrane. This requires care and skilled and experienced staff. Preformed 'top hats' that are welded to the base membrane and sealed to the penetration with self-adhesive membrane and/or adhesive are also used. Further information is provided in Section 6.4.1 and Appendix C.

Where settlement or other movement of the membrane may occur relative to the structure the self-adhesive membrane should also be supported using a physical means such as jubilee clips around pipes or battens to concrete beams or surrounds to columns.

4.4.5 Ventilation design principles

BS8485[4] requires site specific design calculations to be provided for sub-slab venting systems. The graphs in Annex B of BS8485 are for information only and Clause 8.3.2 states " - - -the designer / specifier should provide ventilation calculations to show the ventilation capacity of the proposed system achieves the design specification. The calculations and the justification for the selected input parameters should be clearly reported." Note 3 of this Clause emphasises this by stating "Venting calculations are particularly important for large span footprints, complex constructions, and/ or where a combination of proprietary products is used. - - - "

The design process for a simple open sub slab void is summarised below with an example calculation provided in Appendix D.

1. Define level of performance. Venting systems are commonly designed to achieve an equilibrium methane or carbon dioxide concentration in the sub-slab system of 1%. For more sensitive situations the design may be based on an equilibrium concentration of 0.25% (e.g. if the void is above a gas membrane). Note that the design assumes steady state conditions which do not occur in practice and the ebb and flow of wind speed and direction means that in reality the gas concentration in the void can be higher than 1% for short periods.
2. Calculate gas flow from ground. The most common method is to use the "Pecksen Method" in which the hazardous gas flow rate is divided by 10 to give an emission rate in $l/h/m^2$ (e.g. for 10% methane and 1 l/h flow the emission rate from the ground will be $0.01l/h/m^2$). However more detailed assessment methods may analyse diffusion or advection flow from the ground using Darcy's or Fick's Law in the same way as analysis of VOC emissions into building from the ground is completed (See Wilson 2008[26] for further information). Often in ground gas assessments diffusion is the limiting flow mechanism from the ground (See Section 1.4.6). The designer of the gas protection system should check the data quality before using gas monitoring data for design of venting layers (See Section 3.4.1).
3. Determine amount of air flow required to dilute the gas. This is based on the gas flow from the ground and the equilibrium concentration required in the void. Fresh air flow required (total under whole building), Q is given by:

$$Q = q\{(100-C_e)/C_e\}$$

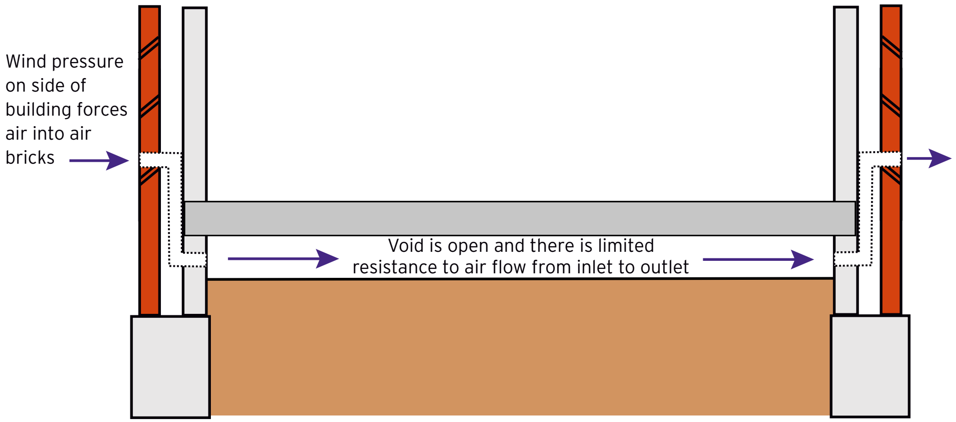
Where: q = surface emission rate of gas from the ground (total under whole building)

C_e = equilibrium gas concentration in the void

4. Analyse the system to make sure it provides sufficient ventilation. For an open void this follows the guidance provided in BS5925[27]. Using the fresh air flow required that is calculated in Step 3 above the required ventilation area along each of two parallel walls can be estimated.
5. Assess the time for gas to build up in no wind conditions. In the UK it is generally accepted that the maximum period when the wind speed is effectively zero (so there is no ventilation) is 10 hours. The gas should not exceed the critical value in the void over this period (typically 5% is used for both methane and carbon dioxide).

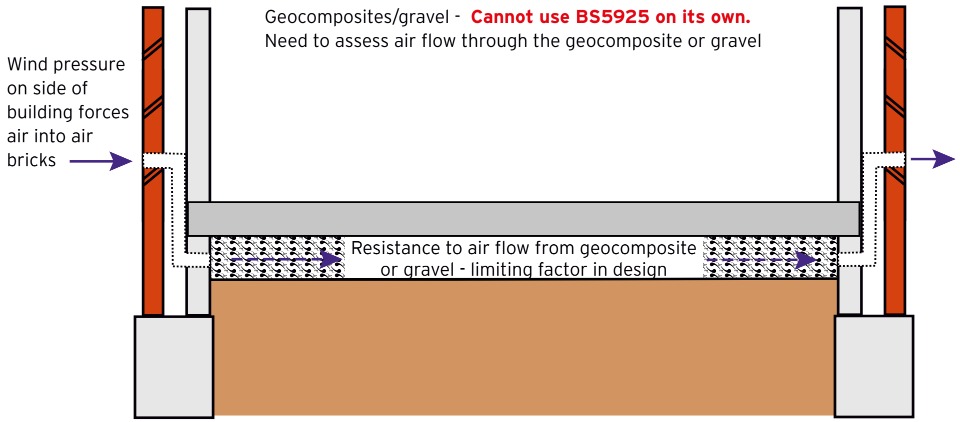
For low rise housing with a clear open sub slab void, ventilation provision of 1 air airbrick (6,000mm^2 vent area) every 2m along two opposite walls will be sufficient for houses up to 10m x 10m in area. Regardless of ground gas protection requirements, the NHBC advice for protection against moisture is that void ventilation should be provided to whichever gives the greater opening area of either (i) 1500mm^2 per metre run of external wall or (ii) 500mm^2 per m^2 of floor area. Therefore, minimum NHBC requirements are likely to be appropriately protective in terms of ground gases for low rise housing. A plan drawing showing the location of the air bricks should be provided and this should take account of compartments in the sub slab void and the locations of doors, access ramps, etc. Ground levels should be designed around buildings so that the bottom of the air brick is at least one brick course above ground level (150mm to top of air brick)[28]. Air bricks with the base of the openings at or below ground level are not acceptable for low rise housing because they become blocked. Ground level vents or gravel trenches are also not acceptable for low rise housing.

Where ventilation is provided using void formers (gravel, gravel with pipes, geocomposite, polystyrene or geocellular products) they do not behave the same as open voids. They have a resistance to air flow and this should be accounted for in the design calculations (see Figure 4.5). BS8485 Clause 7.2.3 states "Designs should use a gas permeability value which is representative of the media in its as-built condition, taking into account the continuity of the media beneath the floor slab, loss of volume due to compression, the pressure differences that apply across the media, and head losses in the terminals". Further information on the design approach for void formers (geocomposites) is provided in the Ground Gas Handbook[22].



Equation in BS5925 is to estimate air flow through a sharp edged orifice (hole) with free air movement on the inside

It calculates the vent area required to give the air flow through the air bricks (or other vent) for a given wind speed (pressure calculation is within the one equation)



Calculation in three parts

1. Calculate wind pressure on side of building
2. Estimate air flow in geocomposite to make sure air flow is sufficient for a given pressure (calculate from wind speed) - Darcy equation - need to know the intrinsic permeability of the geocomposite
3. Check vent area is sufficient to provide flow through geocomposite and is not the limiting factor

$$Q_w = C_d A_w U_r (\Delta C_p)^{1/2}$$

- A_w Equivalent area of an opening
- C_d Discharge coefficient for an opening
- C_p Surface pressure coefficient
- U_r Reference wind speed

Typical result for a house for flow through one air brick at either side of void - Q_w = 1.1l/s

Darcy's Law

The equation for Darcy's Law is given below:

Flow of gas being considered in ground,

$$Q_v = \left[\frac{Ki\gamma Ai}{\mu}\right] \text{ x gas or vapour concentration}$$

Where:

- Q_v = flow of gas being considered, in m^3/s through area A
- K_i = intrinsic permeability of material through which gas or vapour is flowing in m^2
- γ = unit weight of gas in N/m^3
- μ = viscosity of gas being considered in Ns/m^2
- A = area of migration perpendicular to migration direction in m^2
- i = pressure gradient along migration route (as a fluid gradient for the gas considered) = (gas pressure/unit weight)/length. The units for gas pressure in this equation are Pa.

Typical result for a house for flow through geocomposite connected to one air brick at either end - Q_w = 0.3l/s

Figure 4.5 Calculation approach for open void and void formers

Active sub-slab ventilation is not acceptable for any new build residential developments. A passively ventilated sub-floor system is required and is likely to be far more effective in the long term. Continuous gas monitoring in sub-slab voids has demonstrated that there is a high degree of redundancy in the systems, such that even if the majority of air bricks are blocked the venting is still effective. A clear open sub-slab void is the most effective form of venting and is the preferred form for all gases including radon.

Where pipes or void formers are laid in gravel at centres the systems should be designed so that air flow does not simply pass along the pipes or strips but flows through the gravel as well. If the pipes are connected to vents at both ends air will simply flow along them and will not flow through the gravel. Thus there will not be uniform dilution of gas in the gravel layer. In such cases there may be diffusion of fresh air into the gravel layer that can provide sufficient dilution if the pipe spacing is small and the emission rate of gas from the ground is very low. However in most cases such systems should only be considered as pressure relief. If ventilation is required the pipes or geocomposite strips should be interleaved and the calculations should take account of the resistance to gas flow from one pipe to another across the gravel layer (see Figure 4.6). Annex B.10 in BS8485[4] provides further information. The interleaving does reduce air flow significantly because the gravel is not a particularly efficient venting medium. Additional air flow can be achieved by providing high level vents using outlet stacks to roof height.

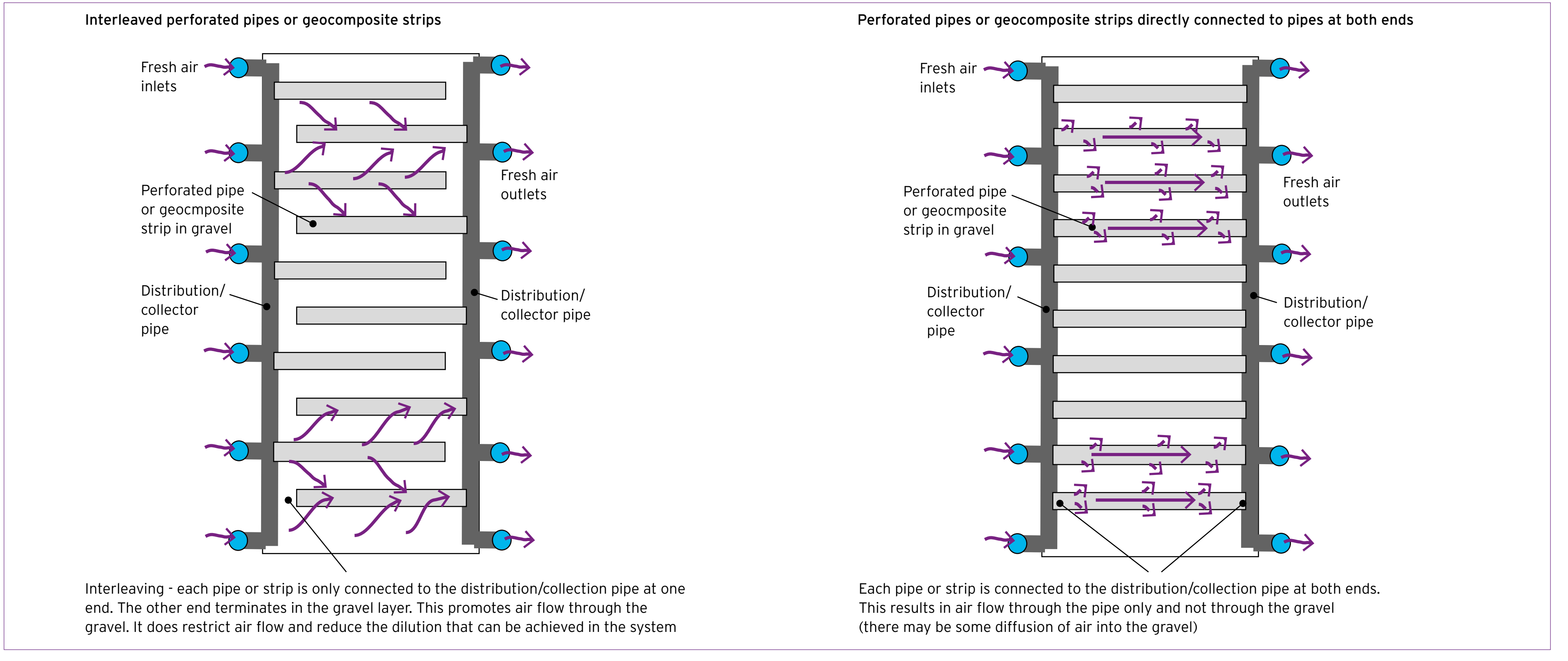


Figure 4.6 Interleaving of pipes or geocomposite strips

4.4.6 Design changes

Despite the improved management of sites and the requirement for verification of the installation of gas protection systems it is still unfortunately common for systems to be installed incorrectly or not at all. Common problems are gas membranes being omitted, being omitted across wall cavities, lack of independent verification or poor verification. Often the issue is not discovered until late in construction or even after completion of a dwelling. Retrofitting gas membranes is possible, but is difficult, often disruptive and expensive and there may be other more appropriate options (see CIRIA C795[23] for more detail on retrofitting options).

Where issues do occur the following should be considered:

1. Revisit the risk assessment to determine if it has followed the guidance in BS8485 correctly and has not resulted in overly conservative recommendations for gas protection. Currently it is often the case that gas protection is not required on many sites where it is specified. Follow the guidance provided in earlier sections of this report on risk assessment.
2. Consider whether there is inherent gas protection in the base construction (i) that is sufficient to provide adequate gas protection or (ii) could be enhanced to provide the required gas protection without the need for additional gas protection products. For example, does the combined presence of a block and beam floor, DPM, insulation and screed layer provide a sufficiently tortuous gas migration pathway to render the floor wide gas migration minimal compared to other open ingress routes?
3. The risk of gas ingress can be assessed by using tracer gas testing of the completed construction, if there is a suitable underfloor venting layer that can be used to introduce tracer gas.
4. Consider effectiveness of the ventilated void alone in minimising the risk from ground gas emissions (this can be backed up by data from void monitoring and by calculations). Void monitoring should preferably use continuous instruments following the guidance in CL:AIRE Technical Bulletin TB16[29]. Monitoring within the void and not close to air bricks is preferred because the concentrations close to air bricks will be diluted (See CIRIA C795 Section 5.4[23] for more information).

4.4.7 Basements, waterproofing and gas protection

There is often perceived to be a conflict between gas protection and basement waterproofing. There is no reason for there to be such a conflict. The main reason is the perceived need to provide sub slab ventilation which is usually not practical or effective around basements. In urban areas where the majority of basements are constructed the risk associated with ground gas migration into basements is normally very low and many waterproofing designs using waterproof concrete and a membrane will be sufficient to manage the gas risk as well. Most often waterproofing for residential development will include two or more types of protection (for example a combination of Type A (waterproof membrane) and Type B (reinforced concrete structure). On CS2 and CS3 sites the provision of waterproof concrete, possibly with a waterproof membrane that also has adequate gas resistance will provide sufficient resistance to ground gas ingress to a basement. However, to achieve good quality of the concrete wall and slab construction does require good supervision on site (as it does for it to be waterproof as well). Further information on basements and gas is provided by the Basement Information Centre[30] and in Ground Gas Information Sheet No 4[31]. If a basement is located permanently below the water table, the use of GSVs is not appropriate for ground gas risk assessment (Figure 4.7 overleaf) and analysis of dissolved methane (or other gas or VOCs) is required.

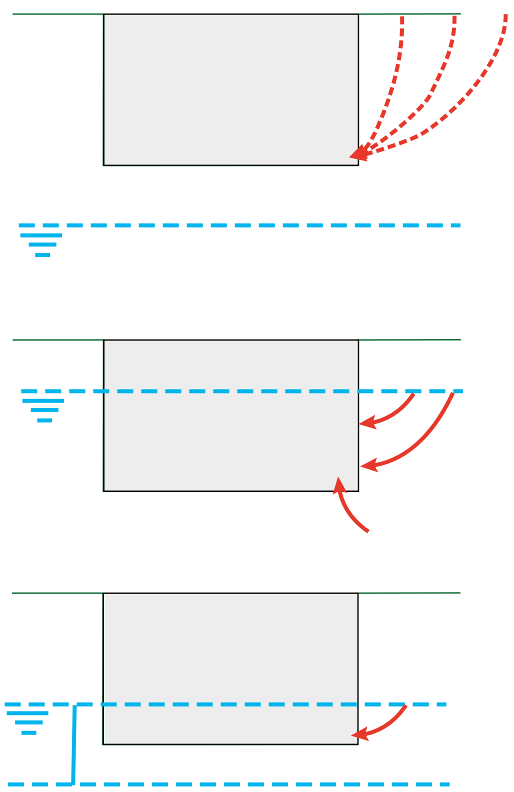
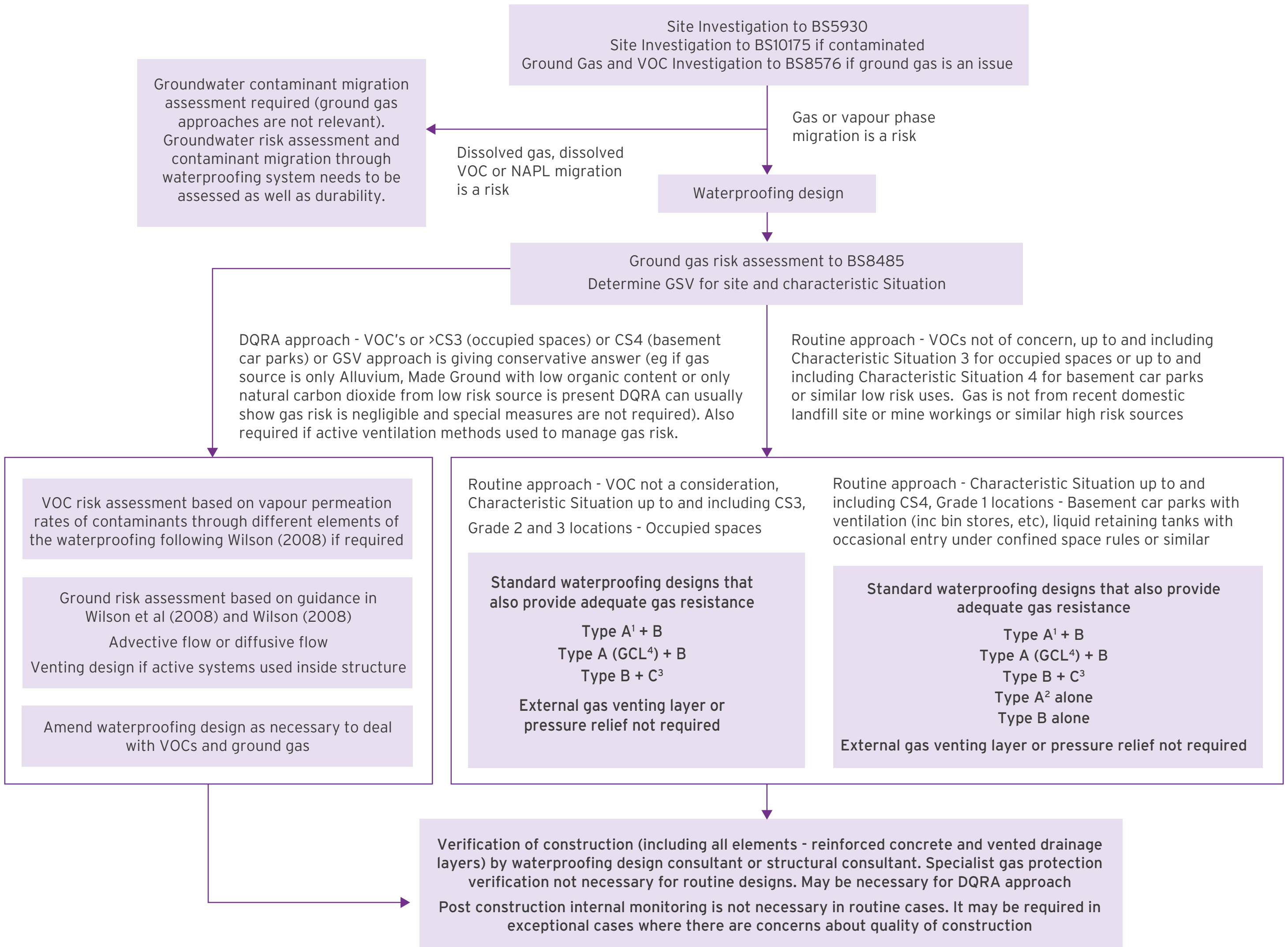


Figure 4.7 Water table scenarios in relation to ground gas risk for basements

As previously discussed in the text on investigation and monitoring (Section 2.4.2) investigation monitoring well response zones should be isolated into a single source or pathway. This is especially important if a source may be removed (e.g. Made Ground) as part of the basement construction. It is important that all potential (and credible) sources of gas and pathways for gas migration are investigated with gas monitoring wells installed in the unsaturated zone wherever possible. Gas monitoring data from flooded wells is not reliable and can give an unreliable indicator of elevated gas risk where none is actually present. If basements extend to depths below the groundwater level then dissolved gas concentrations should be measured along with groundwater concentrations of VOCs in order to enable appropriate assessment of gas risk. A flow chart summarising the integration of basement waterproofing and gas protection is presented overleaf (Figure 4.8). This is a screening level tool and the final basement gas and waterproofing strategy should be justified by appropriately qualified and experienced professionals.

BS 8102:2022[32] has introduced the possibility of using a combination of two different Type A solutions (ie Type A + Type A) where each one has different performance characteristics. From a waterproofing perspective this relates to using a Type A membrane on the outside of a concrete wall and a cementitious render on the inside. This would not be suitable for gas protection when using the simple points approach in BS8485 and is therefore not reflected in Figure 4.8.

Basement Waterproofing and Ground Gas Integration



Notes

1. Type A must be bonded, minimum 0.75mm thick excluding any bonding layer, GTR < 500ml/m^2/day/atm or minimum 0.5mm thick and GTR < 40ml/m^2/day/atm
2. Type A must be minimum 0.75mm thick (excluding any bonding layer), GTR< 40ml/m^2/day/atm
3. Drained cavities must have ventilation to maintain gas at 0.25% v/v and must be separated from occupied space by a gas resistant membrane that is protected from damage by occupants (block work or concrete wall minimum 150mm thick)
4. GCL must have GTR < 500ml/m^2/day/atm which may be achieved by an integral polymeric backing membrane
5. The key property for any membrane is tear and puncture resistance. The waterproofing membrane must have adequate values for these properties. For a GCL the polymeric backing must have adequate values.
6. BS 8102:2022 has introduced the possibility of using a combination of two different Type A solutions (ie Type A + Type A) where each one has different material characteristics. This would not be suitable for gas protection when using the simple points approach in BS8485. It would need DQRA to justify it on a site specific basis using gas permeability data for the products.

Figure 4.8 Flow chart for combined waterproofing and ground gas mitigation design for basements.

If a drained cavity is used as part of a gas protection system (by providing ventilation) it must be assumed that at some point methane at a concentration above 5% could be present in the cavity (unless proven otherwise). Cavity drains used in walls are often very thin (e.g. 8mm) and will provide a high resistance to air flow (i.e. they are not very efficient). They are therefore not particularly effective in diluting gas concentrations. Accordingly, the cavity must be isolated from the occupied space by a gas membrane. The gas membrane itself may be part of a cavity drain sheet, but it must be protected from damage (for example by drilling into walls for fixings) by at least 150mm of blockwork or concrete. The membrane must be sealed on all laps and penetrations and have a gas transmission rate less than 40ml/m^2/day/atm. The cavity drainage should be a standalone system and should not be connected to any internal drainage system that would allow gas into the occupied space. All sumps, channel drains, etc should be gas tight and vented externally to prevent gas building up.

The air flow in a cavity drain system and the dilution of gas in it should be analysed in the same way as for a geocomposite venting system below a floor slab (see Section 4.4.5). The analysis should take account of the air flow rate for the cavity drain material and head losses at changes in direction and in the pipework.

If there is groundwater with dissolved VOCs, dissolved methane or other gases in it (including radon in affected areas) the flow of groundwater into the cavity drain will require analysis along with analysis of the volatilisation into the cavity drain and migration into the occupied space. This should be done by a suitability qualified vapour intrusion specialist.

Routine solutions can be used in the following instances.

- Grade 2 and 3 waterproofing environments with gas Characteristic Situations up to and including CS3;
- Grade 1a and 1b waterproofing environment (basement car parks or similar) with gas Characteristic Situations up to and including CS4.

Detailed Quantitative Risk Assessment should only be required in the following instances and will be the exception rather than the rule:

- Basement is constructed in or close to recent (<40 years old) domestic landfill and gas migration to the basement is possible (the risk of gas migration should consider geology and topography and not just distance);
- Basement constructed in colliery spoil;
- Basement constructed over shallow mine workings or abandoned gas/oil wells;
- If the GSV approach is over conservative and the cost of a DQRA is less than the savings to be made in mitigation requirements; or
- VOCs are present.

4.4.8 Planned verification

As part of the design report the designer should specify the required verification for all elements of the gas protection system (including the floor slab or basement wall construction if that has been assigned points). Further information on verification is provided in Section 6.4.3 and an example verification plan is included in Appendix F.

4.5 Case study

4.5.1 Case study 1

A large multi storey housing development required gas protection measures comprising a gas membrane without a sub floor ventilation layer. The building was founded on stone columns above shallow mine workings. The scope of the gas protection was defined in the geo-environmental interpretive ground investigation report for the site. The architects drawings showed a gas membrane and venting layer but stated it was to "gas specialist's design". The contractor consulted a specialist installer and the price for the gas membrane installation was agreed based on suppliers generic standard details and including an allowance for some verification visits. Just prior to construction the verification consultant asked for the design drawings and design report.

The contractor was under the impression that the specialist designer was providing the design in conjunction with the supplier. Neither had professional indemnity insurance and were not qualified to provide design advice. A design consultant was appointed but the timescales for producing detailed site specific drawings and a design report led to delays on site. In addition, the consultant identified that a sub slab venting layer was required because the introduction of stone columns had increased the risk from mine gas ingress. This led to an increase in costs and further delay whilst the vent layer was procured and installed. Design consultant for the gas protection system should be appointed at an early stage to avoid delays during construction.

Stage 5 - Specification of materials

5.1 Process

The specification of the various elements of a gas protection system is the responsibility of a competent designer. It should not be left to the architect of structural engineer, nor to installers or material suppliers. The specification should be developed from the design and detailing determined in Stage 4 and should commence with a general check of the fitness for purpose of the various products capable of delivering the design. This would be followed by a check of particular materials against the design parameters with respect to ventilation and gas barrier materials. Depending upon the proposed gas protection measures, a check should be made of the specified materials against the planned verification to ensure appropriateness and adequacy.

The overall process and steps necessary for the specification of a gas protection system is illustrated in Figure 5.1 below. This is followed by comments on particular aspects related to specification, namely; competence (section 5.2), a summary of current issues arising from the industry consultation (Section 5.3), advice on a series of the watch points related to those issues (Section 5.4), followed by a couple of case studies (Section 5.4.4).

Stage 5

Gas Protection - Specification

Stage 5.1
Design report

Prepare report
To accord with BS8485

Define
Scope of measures

Design
Mitigate risks from all identified contaminant linkages

Specific to conceptual site model and design of new building(s)

Consider
Gas protection inherent to building design (e.g. floor slab)

Gas membrane

Ventilation

Potential conflict / adverse impacts between building and gas protection designs

Stage 5.2
Barrier design and specification

Identify and resolve
Conflicts between gas protection and other influences on construction

Review
Data sheets against specification

Gas transmission rates

Specification of concrete slabs / waterproof concrete

Provide
Detailing

Protection measures during construction

Check
Constructability and build sequence

Stage 5.3
Ventilation design

Define
Performance level

Calculate
Gas flow from ground

Determine
Required air flow

Consider
Ventilation of air bricks

Ventilation of void formers

Analyse system
Ensure sufficient ventilation

Consider no-wind conditions

Stage 5.4
Design changes

Re-visit
Risk assessment

Re-consider
Inherent building gas protection

Re-evaluate
Ventilation performance

Stage 5.5
Basements

Consider
Integration of waterproofing and gas protection

Stage 5.6
Verification Plan

Define
Scope of verification activities

Ensure
Compatibility of verification testing (if planned) with construction activities & programme

Define
Required competence

Figure 5.1 Material specification process

5.2 Competence, roles and responsibilities

The specification of the various elements of a gas protection system should be completed by a specialist engineer/ designer with relevant knowledge and experience (e.g. understanding of the material properties necessary to meet the design and mitigate the assessed risks in the context of the conceptual site model). In particular, the Architect / Structural Engineer should not be specifying the components of the gas mitigation measures. Installers or material suppliers should only be specifying the elements of a gas protection system (ventilation / barrier etc.) if they have competent people who have the skills and understanding of ground gas risk, material properties, and analysis of ventilation systems that is required.

The specification of gas protection systems requires a thorough understanding not only of the properties of gas membranes, ventilation layers, and air flow theory etc. but also factors in the ground that can affect ground gas risk, foundation and building construction methods. For clients it is important that there is clear responsibility for the specification of the gas protection system. The specifier is normally the designer and should be specifically appointed under a contract, and they should hold professional indemnity insurance that specifically covers them for the work.

5.3 Current state of the art

Based on the industry consultation survey responses the specification of materials stage was identified as having a lower frequency of problems encountered by practitioners compared to other stages. The modal response was that problems are "often" encountered and was stated by 34% of respondents.

The top causal factors for problems encountered in ground gas projects at the specification of materials stage were identified as "poorly defined responsibilities" (40) followed by "lack of competence" (39), "lack of training" (37) "lack of funds/ cost-cutting" (36) and "procurement process" (33). "Poor data quality" (9) was the least often identified factor for this stage of the process.

The key issues identified by survey respondents at the specification of materials stage were counted and grouped. The most frequently identified issues related to:

1. Inappropriate selection of gas membranes and/or no specification being provided.
2. Inconsistency in data around membrane performance and qualities, and lack of independence or bias in product specifications by suppliers.
3. Key membrane properties that were identified by respondents included: durability, gauge of membrane, whether a membrane is multi-folded for transport, potentially inappropriate use of aluminium foil membranes, taped joints, gas or vapour permeability for different compounds (methane, carbon dioxide and VOCs).

Survey responses generally focused on specification of gas membranes, however, specification of other materials used in the gas protection system also needs to be considered, This chapter seeks to address the key points identified above, but also provides details of the specification of ventilation elements and the structural barrier.

5.4 Watch points

5.4.1 Specification of gas membranes

5.4.1.1 Specification and BS8485

There is no "one size fits all" for gas membranes. The most suitable membrane will depend on the location within the building construction, how complex the detailing is and the gas that is of concern. Most designers will refer to the guidance in BS8485[4] when specifying a gas membrane. However, BS8485 is not a material specification and indeed it states this in the foreword: "As a code of practice, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading. Any user claiming compliance with this British Standard is expected to be able to justify any course of action that deviates from its recommendations."

Box 5.1 Specification and the Code of Practice

British Standard Specifications are highly prescriptive standards setting out detailed absolute requirements. They are commonly used for product safety purposes or for other applications where a high degree of certainty and assurance is required by the user community. There is no British Standard Specification for gas resistant membranes and BS8485 does not purport to be one. Therefore claims that a membrane "complies with BS8485" that are frequently made by suppliers are not true and are misleading. British Standard Codes of Practice, such as BS8485, recommend that sound good practice is undertaken by competent and conscientious practitioners. Such Standard Codes of Practice are drafted to incorporate a degree of flexibility in application, whilst offering reliable indicative benchmarks and are in common use in the construction and civil engineering industries.

It is the responsibility of the designer to specify an appropriate gas membrane for a site, taking account of site specific factors. The guidance in BS8485[4] indicates that the designer must assess any membrane by all the criteria stated in the standard for the specific circumstances of each site. It is not appropriate to claim compliance just because it meets one, or a few, selected criteria for membrane properties. A full assessment following the guidance requires the supplier to provide the designer with all the necessary information on the properties of the membrane deemed to be important on a site-specific basis (e.g. puncture and impact resistance values using an appropriate test method that represents site conditions/causes of damage). BS8485[4] requires a gas membrane to be specified that is:

- sufficiently impervious, both in the sheet material and in the sealing of sheets and sealing around sheet penetrations, to prevent any significant passage of methane and/or carbon dioxide through the membrane
- capable after installation of providing a complete barrier to the entry of the relevant gas
- sufficiently durable to remain serviceable for the anticipated life of the building and duration of gas emissions
- sufficiently strong to withstand in service stresses (e.g. due to ground settlement if placed below a floor slab)
- sufficiently strong to withstand the installation process and following construction activities until covered (e.g. penetration from steel fibres in fibre reinforced concrete, penetration of reinforcement ties, tearing due to working above it, and dropping tools)
- chemically resistant to degradation by other contaminants that might be present, and
- verified in accordance with CIRIA C735[33].

BS8485 goes on to state "There are many gas resistant membrane types available and membrane choice should be made according to the resistance of the material to the passage of the challenge gas and the resistance to site damage during and after installation in the designed position. The designer specifying the membrane should consider the combination of a particular membrane's properties to assess whether it is suitable in any given situation. The specified membrane and the reasons for its selection should be described in the design stage report".

Box 5.2 Factors to consider

Seven requirements for membranes are given in BS8485. This includes gas transmission rate but there are six other important factors.

The designer should justify the choice of membrane and protection requirements on a site specific basis. For example;

1. The minimum requirements stated in BS8485 for a gas membrane to be provided above a block and beam floor (mass per unit area >370g/ms and thickness not significantly less than 0.4mm between the reinforcement) is not suitable for use below cast insitu concrete floors or raft foundations and a more robust membrane will be required.
2. Aluminium foil membranes should not be placed in direct contact with concrete (floor slab or screed) as this can cause corrosion of the foil layer from even the smallest of tears in the thin plastic layer protecting the foil[34]. Figure 5.2 (left) below shows the aluminium foil in a self-adhesive strip that was in contact with concrete for just over a year. 50% of the foil has corroded and the gas transmission rate of the membrane will be higher than stated in the product data sheet. Figure 5.2 (right) shows pin pricks of corrosion that have occurred where very small nicks in the plastic have occurred (that were barely visible to the naked eye).

Figure 5.2 (left) corroded foil in a self adhesive membrane (right) corrosion pin pricks in a membrane

Box 5.3 Foil membranes

Foil membranes are unsuitable for cast in situ slabs unless sufficiently protected from wet concrete.

5.4.1.2 Gas transmission rates

The specification of the rate at which gas passes through a membrane is different depending on the gas being considered. Matters to consider in this respect are;

- Methane, carbon dioxide and other bulk gases that may be under pressure driven flow from the ground. The gas transmission rate is specified and is determined in accordance with BS EN 15105-1. Normally if the gas transmission rate is sufficiently low to be acceptable for methane it will also be suitable for carbon dioxide.
- VOCs or hydrocarbon vapours and trace gases that are not under pressure. The gas flow mechanism is limited by diffusion and the permeation coefficient (diffusion coefficient) is specified in m^2/s (tested in accordance with BS EN 15105-2). The thickness must also be specified by the designer (or the permeation rate through a particular product of a defined thickness).
- Radon. The gas flow mechanism is limited by diffusion and the diffusion coefficient is specified in m^2/s (ideally tested in accordance with Method C, ISO /TS 11665-13, which is also referred to as K124/02/95 on test certificates from Czech Technical University in Prague, although at the moment there is no one single standard that is used, this is the most common and also most appropriate). The thickness must also be specified by the designer because the permeation rate is governed by both the diffusion coefficient and thickness of the material. The higher the diffusion coefficient the thicker the membrane needs to be to achieve a given permeation rate.

The note to Clause 7.2.4 in BS8485 states that "a methane gas transmission rate of <40.0ml/day/m/atm (average) for sheet and joints (tested in accordance with the manometric method in BS ISO 15105-1:2007) is **usually** considered sufficient". There is a similar note to Table 7. Therefore, if a designer considers it is appropriate, given the conditions in which the membrane will be used, a greater gas transmission rate may be acceptable, particularly if the membrane has better durability and resistance to damage when compared to a thinner one with a lower gas transmission rate.

The maximum Gas Transmission Rate (GTR) that is appropriate depends on the reliance that is placed on the membrane to prevent gas ingress and the gas regime itself. BS8485 suggests a maximum value of $40ml/m^2/day/atm$. This applies where the membrane can be used in any Characteristic Situation and it is feasible that the membrane will be the only protection against gas ingress (when a low value of GTR is necessary).

Where membranes are used together with a reinforced concrete barrier, (e.g. membranes that are used in conjunction with a raft foundation or waterproof concrete construction), there is less reliance on the membrane. Concrete has a low gas permeability and flow only occurs in significant quantities at defects, joints or cracks in the concrete that pass through the whole depth of the concrete. The area for gas migration is very small and the allowable GTR for a membrane used in this situation may be increased.

For all gas membranes the GTR should be measured on the sheet material and also on a joint formed in the manner to be used on site (i.e. taped and/or welded). For VOC or hydrocarbon membranes permeation and durability test data should be provided following the guidance in CIRA Report C748[35]. This applies to any membrane being proposed for use to resist hydrocarbon vapour intrusion including those with aluminium foil layers. It is not correct that foil membranes are completely impervious to any gas as the foil will have holes in it, especially after installation, that allow some gas or vapour through.

Gas specific membrane parameter	Floor type	Test method	Limiting value	units
Radon diffusion coefficient	any	Method C of ISO/DIS 11665-10 [Note A]	No limiting value for radon diffusion coefficient. [Note B]	m^2/s
Methane Transmission Rate	block and beam	ISO15105-1	<40 [Note C]	$ml/m^2/day/atm$
Methane Transmission Rate	waterproof concrete	ISO15105-1	<700 [Note C]	$ml/m^2/day/atm$
Methane Transmission Rate	insitu reinforced concrete slab (or for use as Type C)	ISO15105-1	<400 [Note C]	$ml/m^2/day/atm$
VOC permeation rate	any	ISO15105-2	Specific to the contaminant being assessed. [Note D, Note E]	$ml/m^2/day/atm$

Note A – also referred to on many data sheets as Czech Technical University Test Method K124/02/95 which is simply an internal test reference and not a standard

Note B – Radon diffusion coefficient should be combined with the thickness of the product to give a radon transmission rate which should then be suitable for the likely radon concentrations that could be present in the ground at a particular site. Note radon barriers across Europe are at least 0.6mm thick.

Note C – Based on limiting values for biogas containment in Germany <10 $ml/m^2/day/atm$ = dense to gas, <400 $ml/m^2/day/atm$ = very good, 400 to <700 $ml/m^2/day/atm$ = good

Note D – VOC permeation rate test data is required for any VOC membrane including aluminium foil laminates. See CIRIA Report C748[35].

Note E – There is no limiting value for VOC permeation rates. The values for a particular membrane should be included in a revised vapour intrusion model with the VOC concentrations that could be present in the ground at a particular site. This will determine if the membrane is suitable.

Table 5.1 Gas transmission test parameters and limiting values for membranes

Gas transmission rate (GTR), gas permeability, and diffusion coefficient are three different properties of a gas or VOC membrane. Supplier's data sheets sometimes use incorrect terms which leads to confusion and misunderstanding. One issue is referring to GTR values as methane permeability and another is referring to the radon diffusion coefficient as radon permeability – both are incorrect.

The gas transmission rate (GTR) is defined as follows:

GTR = P/d ($ml/m^2/day/atm$)

P = coefficient of gas permeability ($ml.mm/(m^2.day.atm)$)
– also referred to as gas permeability in BS ISO 15105-1:2007).

d = thickness (mm)

The gas permeability is also known as the coefficient of gas permeability. The coefficient of gas permeability is an innate property of a material, but the actual GTR depends on how much of that material the gas has to pass through, i.e. how thick the membrane is. For membranes less than 1mm thick the GTR will be greater than the gas permeability. There are instances where suppliers have incorrectly transposed the lower value for gas permeability onto data sheets as the gas transmission rate. It is therefore always worthwhile asking for the laboratory tests sheets to confirm the actual values for use in design.

The diffusion coefficient is a measure of the mass of a substance that diffuses through a unit surface area in a unit time at a concentration gradient of 1. The diffusion coefficient on its own is not sufficient to assess the resistance to gas flow. To assess the rate of gas permeation through a membrane the thickness must also be known. This is important when assessing the likely rate of radon transmission through a membrane or other material. A thicker membrane with a higher radon diffusion coefficient may have a lower transmission rate than a thinner membrane with lower coefficient.

5.4.1.3 Membrane material properties

In order to assess a membrane against the guidance in BS8485 to determine if it is suitable for a particular application all of the factors listed in Table 7 of BS8485 must be assessed. Tensile strength, elongation, impact, puncture and tear resistance are of particular importance when assessing the ability of a membrane to withstand construction and there are no limiting values specified for these parameters. It is the responsibility of the designer to choose appropriate values for a particular application.

Box 5.4 Factors to consider

Specifiers must read and understand material data sheets – specifically the key performance indicators for the relevant gas / vapour.

Which properties of a gas membrane are critical to ensure adequate performance and what protection should be provided to the membrane after installation depends on where in the floor construction it is located. For example, in a membrane that is fully supported on top of a floor slab tensile strength is of little relevance. It will be a consideration for membranes placed below floor slabs where settlement of the underlying soil may occur. Puncture resistance is important for all applications. A problem in the industry is the belief that one size fits all when it comes to gas membranes. There are known issues of gas membranes being specified that are not suitable for the location. Issues include:

- Damage to unprotected membranes by steel fibre reinforced screeds or reinforcement cages. Any membrane below such construction should have a protection layer above and also have sufficient puncture resistance to small sharp objects (the standard puncture test uses a 50mm diameter plunger which is not representative of the things that damage these membranes on site).
- Corrosion and poor puncture resistance of thin aluminium foil membranes[34]. Such membranes (and self-adhesive tape) should not be used in locations where they will be in direct contact with wet concrete, nor in locations where they will be in contact with groundwater (e.g. around basements).
- If settlement below a floor slab is a concern, the membrane and joints should have sufficient tensile strength and strain properties to retain its gas resistance if the settlement occurs. For the case of composite aluminium foil membranes, under high tensile strain the foil ruptures well before the plastic outer membrane or reinforcement grid fails. The foil is the main reason the membranes have very low gas transmission or VOC permeation rates in lab tests and if it is ruptured the permeation rates can increase significantly. When assessing a membrane with a foil layer (or other composite) the designer should ensure that quoted tensile strength and strain values are representative of the integrity of the whole product and are consistent with the quoted gas resistance.

5.4.1.4 Specification of membrane types

In Norway radon membranes are certified by SINTEF[36] into different "user groups" with different limiting values for strength and durability properties that are then only suitable for use in specific settings. Each "user group" has requirements associated with how it must be used, i.e. the type of underlay and covering needed, where it is placed in the construction sequence. A similar system could be employed for the use of any gas or VOC membrane in the UK. This is also consistent with the guidance in CIRIA C748[35] that provides detailed advice on the various properties that should be specified for VOC membranes. CIRIA C748 is referenced in BS8485 therefore anyone specifying gas membranes should follow the advice in it regarding assessment of durability, ability to withstand damage, etc.

Three different locations in the construction have been defined as shown in Figure 5.3.

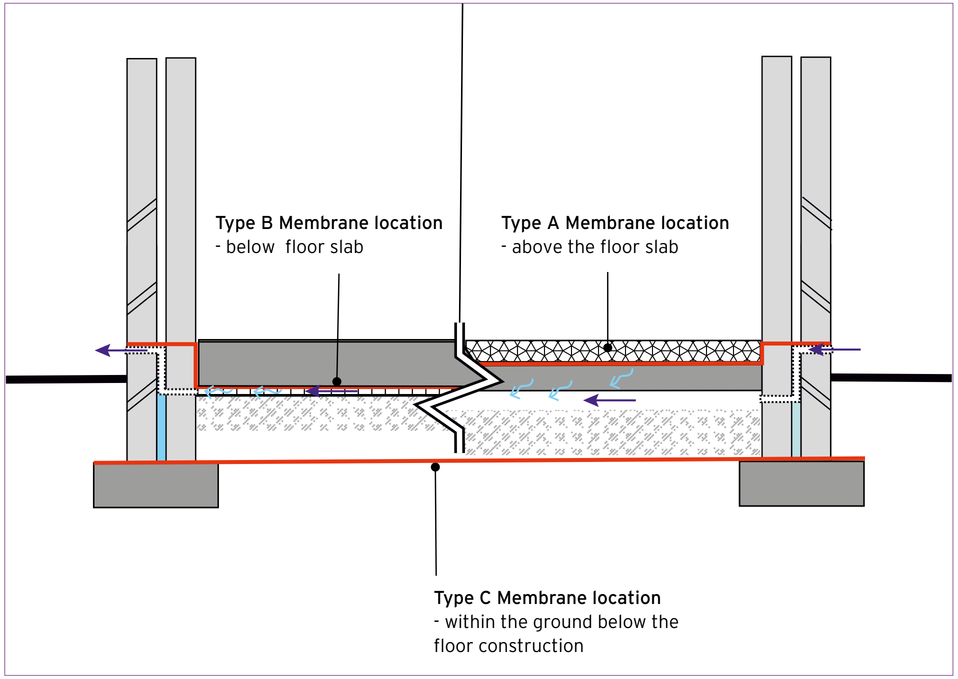


Figure 5.3 Membrane types and locations in a typical construction sequence

The properties in Table 5.2 should be declared by suppliers of gas membranes, depending on the location. This will allow designers and specifiers to make informed decisions on the most appropriate membrane in a particular location.

Parameter	Test method	TYPE A - Above Slab	TYPE B - below Slab	TYPE C - In ground	Unit
Weight	EN 1849	✓	✓	✓	g/m^2
Thickness	EN 1849	✓ ≥0.4	✓ ≥0.5	✓ ≥0.6	mm
Water vapour resistance (if also acting as DPM)	EN 1931	✓	✓	✓	$m^2/s/(pa/kg)$
Tensile strength	EN12311-1 or -2	x	✓	✓	N/50mm
Tensile elongation	EN12311-1 or -2	x	✓	✓	%
Shear strength of joints	EN12317-1 or -2	x	✓	✓	N/50mm
Impact resistance	EN 12691: 2018 (A)	✓	✓	x	mm height
	EN12691: 2001 (B)	✓	✓	✓	mm dia.
Resistance to static load	EN 12730: 2015 (A)	✓	✓	✓	kg
Resistance to tearing (nail shank)	EN12310-1	✓	✓	x	N
Seam jointing method	-	Taped or welded (welded only for VOC)	Welded	Welded	

Notes on taped joints:
Taped joints must be two stage - double sided internal joint, and single sided cover joint (on exposed face of membrane). For membranes where elongation is >200% taped joints must achieve the same tensile strength as the membrane. This can be omitted for welded joints, as welded joints are as strong as the membrane.

Table 5.2 Test data to be provided and assessed for gas membrane types

Type A	Membrane is supported on a prepared and level concrete floor or slab - protection is a consideration if cover does not occur within 1 day before any follow-on works occur.
Type B	Membrane is laid below a floor slab or platform below a modular building. Laid on level sub-base surface, or insulation, free of movement. Protection above the membrane required. Protection below a consideration of subgrade condition. Aluminium foil membranes not suitable unless isolated from concrete (e.g. by insulation).
Type C	Membrane is laid within the ground on level surface free of movement. Protection above and below the membrane required. Membrane should terminate outside of the perimeter wall. Aluminium foil membranes are not suitable in this location.

Table 5.3 Membrane types and protection requirements

5.4.1.5 Membrane protection

Protection boards and geotextiles should have specified performance properties. The overriding requirement for any protection layer should be that it provides adequate puncture resistance to protect the membrane from likely damage along with cushioning the membrane above and below. Geotextiles come in various thicknesses and manufacturing methods and if the material has less puncture resistant than the membrane it is protecting there is little point using it. Static puncture and dynamic perforation tests are useful indicators of performance.

A geotextile used for protection of gas membranes should at the very least meet the requirements for the Protection function (P) in one of the harmonised Technical Specifications for geotextiles or geotextile related products (known as application standards, for example BS EN 13257: 2016 for the Characteristics required for use in solid waste disposal). BS EN 13719: 2016 gives an indication of long term protection efficiency for landfill liners but may also be useful in other applications (for example the loads used in the test are similar to loads that might be applied to some protection layers during construction, e.g., wheel loads from construction vehicles that may run over a protection layer).

Another suitable standard for protection geotextiles providing the protection function is BS EN 13256[37]. The geotextile will provide two functions: resistance to puncture, but also cushioning to increase the puncture or impact resistance of the gas membrane. Experience has shown that in order to provide sufficient cushioning the geotextile should have a unit weight of at least 300g/m^2 (BS EN 9864[38]) and a minimum thickness at 2kPa of 1mm (BS EN 9863-1[39]). To provide increased puncture resistance the static puncture resistance of the protection geotextile should be at least 3500N (BS EN ISO 12236[40]). Protection geotextiles are normally non woven needle punched products and should have electronic and manual inspection during manufacture to ensure there are no needles left in the product.

> **Box 5.5** **Understanding construction proposals**
>
> The specifier needs to understand the construction proposals for the building (e.g. the use of steel fibre-reinforced concrete or screed which can damage membranes) in order to incorporate suitable protection

Protection boards are normally twin walled fluted polypropylene and are also used to protect final finishes such as flooring and carpets. There are no British or European Standards that apply to the protection boards. The most common ones used to protect gas membranes are 3mm thick and have a unit weight of 350g/m^2. This is suitable where there will be medium to high foot traffic. There are no British Standards or standard test methods for protection boards. However, the long term compression performance of such boards once covered should be considered if they are to be left in place carrying load under the slab or floor finishes.

5.4.2 Specification of concrete slabs and/or waterproof concrete

Where points are being allocated to the floor slab construction following the guidance in BS8485[4] then the gas protection designer may have to specify certain requirements for the floor slab or basement construction. Examples include:

1. Specifying suitable sealing to free movement/armoured or construction joints and isolation joints.
2. Specifying suitable water bars for gas or VOC resistance in waterproof concrete construction.
3. Specifying design requirements to limit concrete cracking, e.g. shrinkage in the concrete floor slab will be controlled in accordance with the design to British Standards. Design of reinforcement to control shrinkage in general reinforced concrete is covered by BS EN 1992-1-1, and for water-resisting concrete reference should be made to BS EN 1992-3. Limiting crack widths for water resisting concrete are also provided in Section 5.4 of NHBC Standards.
4. Specifying general requirements for the concrete construction to minimise the risk of cracking or poor quality concrete with increased gas permeability. NHBC Standards Section 5.4 also has requirements for achieving quality construction of waterproof concrete that should be followed. Some of these requirements can also be applied to standard concrete flooring where appropriate to achieve the required level of gas resistance.

Box 5.6 **Examples for specification of concrete slab design to meet gas resistance requirements**

An example of how the gas protection designer has specified requirements of the slab design to meet gas resistance requirements is provided below.

The floor slab is to be cast in situ reinforced concrete construction with all joints sealed. Day/construction joints to be scabbled prior to following pour. Shrinkage in the concrete floor slab will be controlled in accordance with the design to the relevant British Standard but not to any elevated standard beyond that required for a suspended in-situ concrete slab. The concrete will be constructed in accordance with Section 8 of the National Structural Concrete Specification for Building Construction[41]. Specifically, it shall be adequately cured and compacted. Water shall not be added on site to ready mixed concrete to improve its workability.

If a floor slab (or screed) is steel fibre reinforced a gas membrane below it will require a protection layer to prevent the steel fibres puncturing it. If reinforcement mesh is used in any areas to control cracking it should be supported on spacers that will not penetrate the gas membrane (e.g. "concrete square bar spacers known as "mars bars").

An example of the slab sealing specified by the gas protection designer is provided below.

Column isolation joints should be sealed at the top with 20mm of two part polysulphide pouring grade sealant (after a period to allow for 75% of shrinkage movement to have occurred). Any armoured construction/contraction joints should be sealed at the top with 20mm of one part high modulus modified polymer sealant which cures on exposure to moisture vapour. Sealants installed following manufacturer's guidance for cleaning and preparing surfaces.

5.4.3 Specification of ventilation elements

The key elements that will affect the performance of the sub-slab ventilation system should be specified.

5.4.3.1 Telescopic vent connectors

Telescopic vent connectors are used to connect the sub slab void or other vent layer to the air brick in the face of the building wall. If the vent connections are located below the gas membrane, they do not need to be gas tight. Where vents are located above (or penetrate) the gas membrane any joints should have a gas tight seal. There is a trend for wider cavities to be provided because of increasing thicknesses of insulation. Any sliders to allow for the increased width as well as the telescope joints above will need gas tight seals if above or penetrate the gas membrane. Vent connectors should have the same or greater air flow area as the outlet covers or airbrick covers.

5.4.3.2 Ventilation of air brick covers.

The ventilation area provided by air bricks is the actual free area that air can flow through and not the total area of the air brick. Suppliers should state this area on the data sheets. For example, the air brick in Figure 5.4 has an overall area of 14,835mm^2 but a ventilation area of 6,170mm^2.

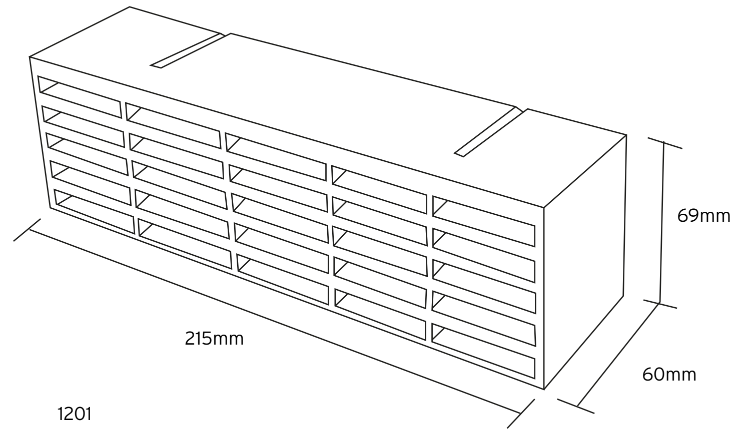


Figure 5.4 Air brick ventilation area

5.4.3.3. Void formers

Gas permeability of void formers should be specified by the designer to ensure that the product that is supplied is consistent with the assumptions made in the design venting calculations (see section 4.4.5). The most commonly used void formers (25mm geocomposite layer and polystyrene systems) have been analysed to determine the intrinsic permeability of the materials using CFD modelling. An alternative it is to test the void former to determine its in plane water flow capacity[42]. The gas transmission rate can be determined following the approach described by Thiel and Narejo[43]. It is important to note that the in plane water flow tests should be carried out at a sufficiently low hydraulic gradient so as to be comparable to the likely gas pressure gradient (or allowance made in the assessment for any difference). Where void formers are carrying structural loads the long term creep strength at 60 years should be specified (based on the structural design assessment). This requires creep rupture testing with various failure times (see CIRIA Report C737[44]).

Box 5.7 Air flow check

Check the air flow through all parts of the ventilation system to ensure that it is all compatible with the assumptions in the gas risk assessment and mitigation design. Small openings and tortuous routes for gas/air flow can limit the performance of ventilation systems. Air flows through air bricks and geocomposite void formers should be checked to determine their suitability to achieve the desired performance.

5.4.4 Product Certification

Many products used in gas protection will have appropriate certification from an independent technical approvals authority accepted by NHBC, such as the like of BBA Agrément Certificates or similar. The certificates provide assurance to designers and contractors that products have the properties claimed and they are produced under a suitable quality assurance system. Regular auditing is typically undertaken by Certifiers and these also ensure that what has been certified is what is delivered to sites.

The certificates do not absolve the designer of the responsibility to ensure that the product is suitable for a particular application. BBA certificates and other certification schemes are only intended to help designers and regulators understand the potential performance of a product[45]. The certificate should be read carefully, especially with regard to aspects such as design life, limitations on the applications covered by the certificate, installation requirements, whether a membrane requires protection after laying and the degree of traffic it can stand (can it withstand vehicular traffic?).

Products also have to comply with the Construction Products Regulations (CPR). There are some situations where products without a BBA (or similarly recognised) certificate are more suitable than one with a certificate (assuming the product is manufactured under an audited QA system and complies with the Construction Product Regulations (CPR)). In this case the designer should provide justification for the product suitability in a particular application. For example, if a membrane is required to resist tensile forces caused by ground settlement, then the tensile strength and elongation may be important properties that need to be specified and analysis completed to justify that a membrane is suitable.

It is often erroneously believed that certification of products by an independent technical approvals authority (such as the BBA) is required to comply with Building Regulations or to gain building control approval. This is not the case (DECC, 2012[45]). If there are doubts about any quoted values, for example, the gas transmission rate of any particular product, then the actual test reports should be requested by the risk assessor or designer to ensure that an appropriate product is being used in a particular application.

5.5 Case studies

5.5.1 Case study 1 – Specification of gas membrane and concrete raft to meet gas resistance requirements

A site was being developed for housing over an old open cast coal mine that had been backfilled with overburden. There was still a residual risk from mine gas emissions from old workings present beyond the site boundary that outcropped in the pit walls. The site was assessed as being at high risk from mine gas emissions and thus the use of the points system in BS8485 was not appropriate to be used for the gas protection design.

Site specific analysis of gas flow through the raft foundation and gas membrane was completed. This demonstrated that there was sufficient redundancy in the raft/membrane system such that a sub slab ventilation layer was not required. Further analysis showed that the risk of gas becoming pressurised below the raft was minimal and a pressure relief layer was not required either. This removed the need for venting to pass through the raft foundation and gas membrane.

Because the gas membrane was to be placed below the raft foundation it was recognised that a high puncture resistance was required from sharp objects that would not be achieved by a membrane meeting the minimum requirements in BS8485 (0.4mm thick in between the reinforcing scrim). A 0.6mm thick HDPE membrane was specified, based on the assessment of puncture resistance and gas permeation, despite it having a gas transmission rate in excess of 40ml/m^2/day/atm.

The raft foundation was specified to have no walls penetrating through it and have stiffening beams at the edges and below internal load bearing walls. The only penetrations through them are for water pipes and foul drainage. The main part of the raft was specified to be 150mm thick and there were to be no open contraction/free movement or isolation joints. The raft foundation therefore was therefore inherently resistant to gas migration through it.

In addition it was specified that the raft was to be reinforced concrete and designed by structural engineer, the faces between pours to be adequately cleaned and scabbled and the concrete to be placed in accordance with the specification (adequately vibrated, cured, etc).

5.5.2 Case Study 2 – Example specification of VOC membrane based on modelling and permeation data

A site investigation identified unacceptable VOC concentrations in the ground below a housing development site, sufficient to pose a risk via the indoor vapour inhalation pathway. The geoenvironmental report specified that the development was to be provided with a membrane capable of reducing VOC ingress to acceptable rates (noting that membranes do not completely stop the ingress of VOCs). The detailed design of the VOC protection measures was completed by a SoBRA accredited risk assessor for vapour intrusion. It required site specific vapour intrusion modelling of permeation through the reinforced concrete raft foundation and the proposed VOC membrane. This used permeation data for specific VOCs present on site through the membrane and published data to assess permeation rates through concrete (including cracks). The analysis followed the guidance in Wilson[26] and in CIRIA Report C748[35].

The results indicated that methane, carbon dioxide and VOC concentrations would not exceed the acceptable concentrations defined below:

- Methane 0.01% (100ppm) and carbon dioxide 0.1% (1000ppm) - the limiting values for Class 4 suggested in CIRIA Report C795[23].
- VOCs – appropriate reference concentrations for each VOC (based on published UK guidance for VOC risk assessment (e.g. reference concentrations used to derive the LQM/CIEH Suitable 4 Use Levels[46]).

The analysis allowed appropriate gas and VOC membranes to be specified, with specific limiting permeation rates for the VOCs being a critical element.

Stage 6 - Construction and verification

6.1 Process

The construction and verification of a gas protection system in a project depends upon the professional implementation of the measures designed in Stages 4 and 5. Those planned works must be well defined and well communicated to all of the workforce who may be involved in, or interact with, those gas protection measures. This awareness is critical if the specified protection is to be installed and survive intact the construction process. It is also critical that once completed, all relevant parties are confident that the gas protection measures have been installed and will perform as designed and specified. Such confidence can only be gained by an appropriately rigorous programme of verification and publication of a report presenting robust lines of evidence.

The overall process and steps necessary for completing a programme of construction and verification is illustrated in Figure 6.1 overleaf. This is followed by comments on particular aspects related to the construction and verification stage, namely; competence (section 6.2), a summary of current issues arising from the industry consultation (section 6.3), advice on a series of the watch points related to those issues (section 6.4), followed by a couple of case studies (section 6.5).

Stage 6

Construction, Installation and Verification

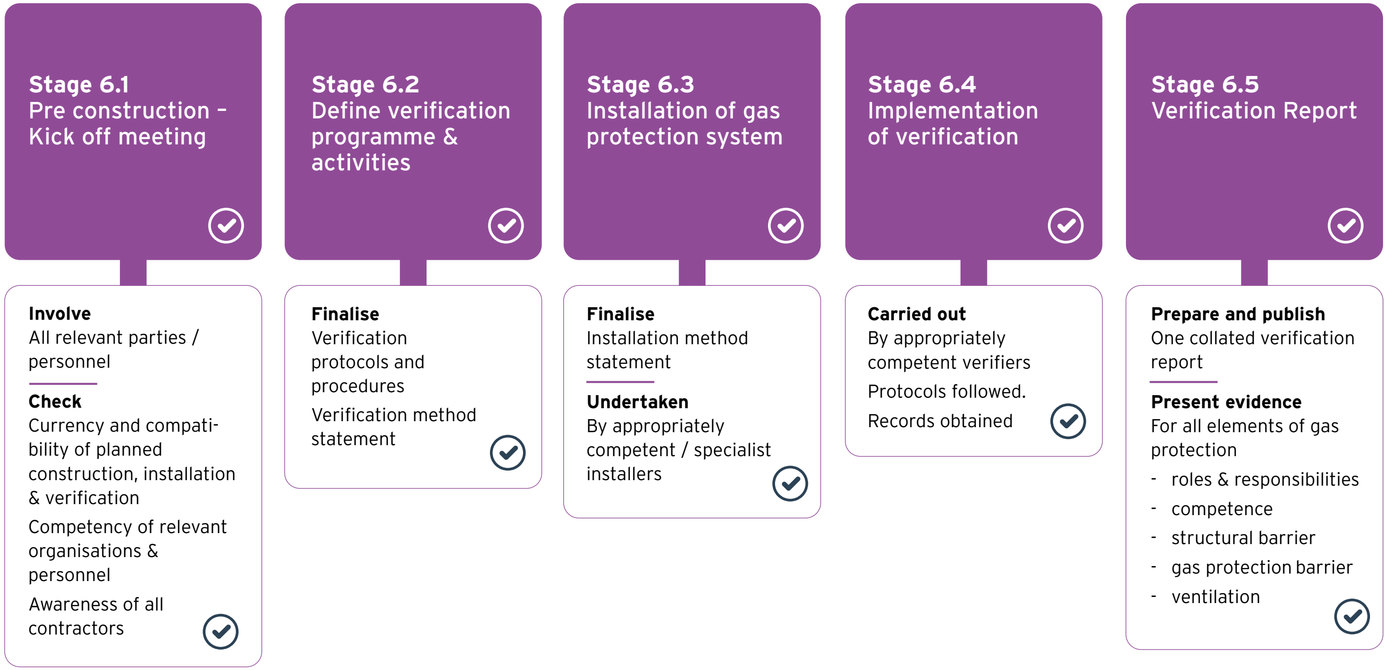


Figure 6.1 Construction, installation and verification procedure

6.2 Competence, roles and responsibilities

6.2.1 The use of specialists

Installation of any gas membrane (for methane, carbon dioxide, VOCs, radon, or any other gas) should be carried out by competent and well trained staff. A specialist gas membrane installation company (specialist installer) will ensure that each installation team has at least 50% of staff holding an NVQ level 2 (gas membrane installation) and/or TWI/CSWIP plastic welding accreditation and that the remaining staff are working towards one of those qualifications. They will have also undertaken additional product application training for welded jointing and sealing of specialist ground gas and waterproofing systems. A specialist installer should hold the relevant contractors groundwork insurances which include clauses for installation of critical barrier materials, such as ground gas and/or waterproofing systems.

A specialist installer should have an understanding of the risks associated with their activities, and an understanding of the materials used in gas protection systems, their storage, handling, preparation and application/installation, and have been provided with all relevant product technical data sheets, installation guidance documentation, and material safety data sheets for products it proposes to install. It is expected that all on site personnel for a specialist installer would be competent at completing a basic toolbox talk to site managers as to the risk of damaging a gas protection system installation during follow on trade work, post install and sign off/verification.

The installation should also be verified by a suitably qualified independent verifier for all gases and vapours – described in more detail in Section 3.2.2 of CIRIA C735[33] and in CIRIA C801[24].

The key points are:

- The use of specialist installers and verification consultants reduces the potential for poor installation (and reduces the risk of needing costly remedial works)
- The use of groundworkers or general contractors for gas membrane installation requires an increased level of verification and increases the risk of defects being present and costly remedial works being required (see CIRIA C735[33])
- The use of specialist installers and verifiers can increase the costs compared to groundworker or general contractor installation. However, any such increase is minor in comparison to the cost of correcting inadequate installation or verification, especially if it is not discovered until much later in the build programme.

Not every project will warrant the use of specialists, especially very small or very simple projects. In such cases the general contractor doing the install should receive adequate training from the suppliers of materials and independent verification is still required (an increased level of verification will be required, and this may be by a geoenvironmental consultant, building surveyor or other professional with relevant experience and qualifications in gas protection verification). Larger or more complex projects (e.g. apartments with complex foundation details) will benefit from using specialist installers and verifiers. The designer of the gas protection system should specify the requirement for specialist installers and verification consultants as well as the scope of the verification (in a verification plan).

The designer of the gas protection system should establish a clear remit of roles and responsibilities within the verification plan, recognising that often the groundworker or builder will need to collect some information to satisfy the overall verification strategy for the site (for example confirmation that the sub -slab ventilation has been installed as per the design).

The developer's or main contractor's site managers should be fully aware of the installation and construction issues associated with gas protection installation (including the venting layers and not just gas membranes). Any site manager working on a site where gas protection measures are required should be familiar with the advice and guidance provided in CIRIA Report C801[24].

6.2.2 Qualifications and accreditation

The qualifications and accreditations relevant to installers and verifiers are briefly outlined below.

Installers. For installers the relevant qualification is the NVQ Level 2 Diploma in Substructure Work Occupations (Installation of Gas Membranes-Construction). At least one member of the installer's staff working on any site should hold this qualification. On more complex projects the designer may specify that all staff hold the qualification. The TWI/CSWIP plastic welding accreditation is also an acceptable qualification providing the installers can also show experience and understanding of the specific issues relating to gas membrane installation.

Verifiers. CL:AIRE administers the Gas Protection Verification Accreditation Scheme which has been devised for personnel engaged in the verification of gas protection systems. There are two levels of accreditation: Technician (TGVP) and Specialist (SGVP). The Technician level is for those who are involved in site based inspections and preparing site visit or inspection sheets. The Specialist has additional competences that cover preparing overall verification reports. There is also a NVQ Level 4 Diploma in Verification of Ground Gas Protection Systems.

CL:AIRE also administers the Gas Protection Verification Declaration Scheme, under which a CLAIRE accredited SGVP can apply a quality mark to their verification reports. Each certificate has a unique reference number. The unique reference number is publicly available for viewing on the register of SGVPs as each unique number is assigned against the person's name. The SGVP is required to create an account on CL:AIRE's website to allow tracking of the "declaration of compliance" and to assist with auditing.

Reports prepared by Specialist in Gas Protection Verification provide all stakeholders involved in land contamination management with confidence that risks associated with ground gases have been adequately managed. In particular it also helps demonstrate to a Suitably Qualified Person (SQP) under the National Quality Mark Scheme (NQMS) for land contamination management, that the gas protection verification work has been undertaken by competent personnel.

6.3 Current state of the art

Based on the industry consultation survey responses the construction and verification stages were identified as having the highest frequency of problems encountered by practitioners compared to other stages. The modal response for both stages was that problems are "often" encountered and was stated by 44% of respondents on average.

A broad spread of causal factors was identified for problems at this stage of the process, with many factors being selected frequently. The top causal factors for problems encountered in ground gas projects at the construction and verification stages were identified as "lack of training" (65 and 50) followed by "lack of competence" (57 and 49), "clashes with other site constraints/trades" (58 and 42), "poorly defined responsibilities" (44 and 47) and "poor quality assurance" (44 and 43). "Lack of guidance or standards" (7) was the least often identified factor for both stages of the process.

The key issues identified by survey respondents at the construction and verification stages were counted and grouped. The most frequently identified issues related to:

Construction

1. Damage to membranes
2. Poor workmanship by gas membrane installers or groundworkers, and installation of protection measures being completed by non-specialists, or those not adequately trained
3. Awareness or understanding by clients or other trades on site
4. Sealing of penetrations to gas membranes
5. Dealing with inclement site weather conditions during installation.

Verification

1. Lack of skilled, competent or well trained people carrying out verification, or poorly defined scope and responsibilities.
2. Lack of verification plan (also mentioned at design stage, but included here).
3. Poor, or incomplete sources of evidence. Sometimes no specification/design to check against. Integrity testing missed.
4. Some elements of the gas protection design often missed and not verified, i.e. ventilation.
5. Design changes not documented. Membrane repairs not supervised or verified.

6.4 Watch Points

6.4.1 Construction - membrane installation

It is vital that the site operatives installing the gas protection system know what is required from the design drawings and make sure they are followed. Before starting work on any part of a protection system the operatives and supervisor should consult the design drawings. Specific areas that need to be understood for low rise housing are:

- location of air brick vents and type of air brick cover;
- specification of gas membrane to ensure correct product is used;
- jointing method to be used (welding, taped or heat sealed (for example taped joints are not suitable for VOC membranes);
- sealing details (e.g. for a VOC protection system pre-fabricated membrane top hats or VOC self-adhesive membrane are likely to be required to seal penetrations and not general self-adhesive membrane).

Guidance for site staff on how to minimise the risk of poor installation occurring and damage to gas membranes after installation is provided in CIRIA C801[24]. Irrespective of whether gas protection system is being installed by a specialist installer, by a groundworker or by a general builder/contractor, the staff undertaking the work should have been provided with adequate training to ensure that the system is installed correctly, in accordance with good practice, the design drawings, specification and manufacturers guidance.

Advice on seam sealing is provided in Section 6.4.1.1. All seams, including taped seams and self-adhesive membrane requires adequate pressure to be applied to it using a roller (see Figure 6.2). This can be achieved suing a hand held roller or a specific machine that applies the pressure automatically as it welds. Welded seams are preferred, and it is actually quicker to install a welded seam than a correctly formed taped seam complete with over tape. On walls the seams should run from top to bottom and not horizontally across the wall.

Figure 6.2 Correct installation of a seams by applying pressure (left) taped seam, (middle) heat sealed seam, (right) welded seam with twin wedge machine

When welding or heat sealing the machine should be warmed up and a test seam should be completed to ensure the correct temperature is being used. The seam can be pick tested and a peel test carried out to show the weld has been effective. The correct pressure on a welding machine also need set be set before the test weld. This should be recorded on the QA sheets for the installation.

6.4.1.1 Penetrations

The weakest point in any gas membrane installation is the sealing at joints, for penetrations (drainage pipes, columns, etc.), and at corners. The designer should liaise with the architect and, where appropriate on larger buildings, the building service engineer to minimise the number of penetrations that occur through the membrane.

For VOC membranes or where the membrane will be subject to settlement the penetrations should wherever possible be sealed using the right size top hat or cloak that are welded to the base membrane and sealed to the penetration using an appropriate adhesive or VOC resistant self-adhesive membrane (applied with heat and seam roller). Top hats around pipes or ducts should be a snug fit and should also be physically attached using jubilee clips around the pipe/duct. Sometimes the collars, sockets or other details mean that top hats cannot be fitted easily. The services should be designed to minimise these types of detail where the membrane has to be sealed to them.

For methane and carbon dioxide membranes where settlement is not an issue the penetrations can be sealed using gas resistant self-adhesive membrane (GRSAM). This should be carefully applied to ensure a robust and gas tight seal as summarised below and illustrated in Appendix E.1.

1. Prepare the surface of the pipe or other penetration by making sure it is clean and free of debris, oil, etc;
2. The base membrane should be carefully cut tight to fit around the pipe penetration
3. If necessary, prime the pipe, duct or column, etc as recommended by the supplier of the gas resistant self-adhesive membrane (on surfaces such as metals, concrete - not necessary for plastic pipes)
4. For a 150mm pipe cut a 300mm by 300mm square piece of GRSAM with a 150mm dia hole at the centre. This should also be a snug fit to the pipe
5. Cut 100mm wide strips of GRSAM, 150mm long (75mm adheres to the pipe and 75mm adheres to the base membrane). Preheat the GRSAM to activate the bitumen adhesive in the membrane. Apply the first strip to the penetration and then fold it down to the base membrane and seal it, ensuring there is no void below it at the base. Sealing should be completed using the heat gun and roller.
6. Apply subsequent strips overlapping the previous one by 25mm, until the seal is complete all around the penetration.
7. Take the 300mm square with the hole cut in it and locate it over the penetration and strips of GRSAM and seal to base membrane with heat and roller. Apply pressure to the GRSAM while continually applying heat to make sure it adheres to the base membrane and the penetration.

6.4.1.2 Corners

Corners can be formed using heat sealed joints and appropriate cutting of the membrane. The corner is then finished using self-adhesive membrane. The process is summarised below and illustrated in Appendix E.2.

1. The base membrane is carefully and neatly cut to allow it to be folded tight into the corner with no voids below it – especially at the bottom. There must be enough membrane to pass across the cavity and external leaf of bricks.
2. The membrane overlap is sealed using heat gun and pressure applied from the roller.
3. The corner is reinforced using a preformed corner unit or by using self-adhesive gas membrane. The preformed corners can be heat sealed or can be made from self-adhesive gas membrane. The example in the photo in Appendix E.2 (for Step 3) is sealing using sheet self-adhesive membrane. A 150mm by 150mm square is inserted into the corner after preheating and is sealed using heat and a roller.
4. A self-adhesive upstand is applied over the corner and cut so that it fits neatly over the base membrane. It is again sealed using heat and a roller to apply pressure.
5. A top cover section of self-adhesive is applied using heat and pressure from the roller.
6. A bottom cover section is applied using heat and pressure from the roller.

6.4.1.3 Weather

The installation of gas membranes should take account of weather conditions. Effective seals cannot be formed if the membrane is wet, dirty or if it is too cold. If the membrane is wet it must be dried prior to seaming or sealing. Taping or welding should not be carried out when the air temperature is less than 5oC unless measure are taken to preheat the materials prior to the seals being formed. Pre- heated conditions should be maintained until materials have cured / fully sealed in accordance with supplier / manufacturer's guidance.

6.4.1.4 Protection

Even where membranes are installed to a good standard they are far too often damaged after installation. Typical issues with low rise housing are damage by brick laying, light gauge steel or timber frame and door installation when membranes are cut or drilled through. In high rise development with thick reinforced concrete foundations damage during reinforcement installation is common. Suitable reinforcement chairs should be provided that do not penetrate the membrane and hot cutting and welding should not be allowed over the membrane (unless it is adequately protected).

Everyone working on site after the membrane is installed should be made aware of the importance of the gas membrane and to avoid damaging it. This requires good site management and communication (See CIRIA C801[24]). Bricklayers, light steel and/ or timber frame installers and door installers should all receive a tool box talk explaining that they are not to cut or drill into gas membranes. Gas membranes should be covered with a protection layer as soon as possible after installation to minimise the risk of damage.

Box 6.1 The workforce and gas protection measures

The workforce must be made aware of and appreciate the gas protection measures so as to treat them with appropriate care. It can be very costly to deal with damage it is not discovered until later in the build.

6.4.2 Construction - installation of ventilation

Where the sub floor ventilation is required as part of the gas protection scheme it should have the same level of diligence and care applied to it as a gas membrane. It should be installed as required on the design drawings and measures taken to prevent damage to it after construction. Common issues are:

- telescopic air vents not sealed at sliding joints (where required)
- telescopic air vents not connected into vent layer or void
- void or vents blocked by debris or not of sufficient height
- where void former layers are used they are not connected to the outlet pipework
- outlet pipework is blocked or not connected to outlets
- venting through internal walls in the void is omitted when it is required.

6.4.3 Verification

6.4.3.1 Standards

The purpose of verification is to provide confidence that the gas protection measures have been installed in accordance with the design to an acceptable standard. It is important that verifiers understand that the installation work does not have to be flawless but it must be carried out to a reasonable standard that would be expected of a reasonably competent installer and will therefore achieve its design purpose. It is vital that everyone involved in the membrane installation and verification process understands what information they need to provide for the verification report. For example, the groundworker may need to provide location referenced photographs of the air bricks or of the clear void.

6.4.3.2 Plan

To reduce the potential for verification activities being missed the verification plan should be prepared by the designer and be included in the gas protection design report. This is shown in Table 8 and Clause 8.3.3 of BS8485[4] where the recommended verification approach (i.e. the verification plan) is part of the design phase. The verification plan (what is required) is then developed into a verification method statement (i.e., how it is to be done) by the verifier.

Box 6.2 **The Verification Plan**

A Verification Plan needs to be provided at the design stage. This should outline the required evidence for verification, and the responsibilities of named parties in completing the verification works. The Verification Plan will be referred to during the construction works and is crucial to demonstrate the effective installation of a gas protection system.

The verification plan should state who the parties are where this is known and what the responsibilities of each party are (e.g. designer, installer, verifier, main contractor)[33]. Any requirements from the Local Authority, NHBC or other regulators or insurers should be noted. The verification plan should include all the elements that are considered to be part of the gas protection system (including the floor slab or waterproof concrete construction if this has been assigned points under BS8485[4]). The Plan should also identify "Hold Points" beyond which construction should not progress without written confirmation from the verifier that the gas protection measures up to that point have been inspected and verified as being in accordance with the design. An example verification plan is provided In Appendix F.

6.4.3.3 Pre construction / installation

Prior to starting work on any element of the gas protection system a site meeting should be held to make sure all parties are aware of their roles and responsibilities (noting that these include the ground worker).

6.4.3.4 Verification reporting

Verification reports need to clearly state precisely which elements of the gas protection system have (and have not) been subject to inspection / verification. For example, if a strip of gas membrane has been laid through the walls and this was not verified, but the main membrane installation is subsequently verified, the verifier should make it absolutely clear in their report that the perimeter strip has not been verified. Similarly, the report should make it absolutely clear if verification is based on photos or other information supplied by a third party or where remote inspection methods have been employed but no actual site inspection visits were made.

Regardless of the risk based approach to verification[33], if a verification report is required for every housing plot rather than the development as a whole, then the independent verification consultant will need to verify every plot. If the verification is required for the site as a whole, then the verifier may (or may not) choose to rely on photos provided by the installer or developer for some or all of the individual plots. In any event every plot needs photos of both the membrane installation and vented void or foundation solution in situ either as part of the independent verification, from the gas protection installer or the developer.

6.4.3.5 Design changes

Any changes to the design during construction or installation should be documented by the verifier, along with confirmation that the changes have been approved by the designer. It is not the responsibility of the verifier to approve design changes and any such changes should always be referred back to the designer.

6.4.3.6 Internal and sub-floor void monitoring

Internal or sub-floor void gas or vapour monitoring is not recommended as a routine verification procedure for any gas (including in basements), where the use is solely residential (and it is not classified as a workplace). It is not necessary to verify basement gas protection using internal monitoring apart from exceptional circumstances (e.g. where the construction is in doubt). There are practical and commercial difficulties with internal monitoring. For example, to be of any use the monitoring must be completed when the basement is fully heated and vented to replicate in service conditions. This may cause delays in handover to allow the monitoring to take place. Furthermore, the monitoring requires instruments or sampling and analysis methods with low limits of detection (1ppm for methane) and in a new building there are numerous sources of VOCs and other flammable gases (including methane) that can give a false indication of gas ingress from the ground. If internal monitoring is carried out it needs to cover the whole building footprint and continuous monitoring at a few fixed points is of little use in verifying the performance of gas protection, unless those points have been shown to be the only points of gas ingress by other monitoring/testing methods.

Ideally sub slab void monitoring should follow the guidance in CL:AIRE TB16[29]. Monitoring via air bricks is not acceptable except for simple unobstructed void spaces with no sleeper walls (for the reasons explained in this CL:AIRE bulletin and in CIRIA Report C795[23], Section 5.4) and even then, the effects of dilution at the air brick should be taken into account when interpreting the results.

6.5 Case studies

6.5.1 Case Study 6.1 Verification of gas protection system

A new prestigious office development was deigned to incorporate gas protection measures appropriate to meet the typical requirements of Characteristic Situation 2 to address the hazardous ground gases recorded on site and the migration potential from a nearby off-site landfill. A specialist gas protection installation company were subcontracted by the earthworks and foundation contractor and carried out the installation of the gas protection system. Third party verification was provided by the building owner’s consultant.

The gas protection system comprised a combination of gas resistant membrane and ventilation. The ventilation was provided by a void former placed over a rolled granular sub-base. The void former was overlain by a proprietary gas membrane with all sheet joints hot welded in accordance with the specialist installer’s Method Statement. The membrane was sealed to all service entries and penetrations using ‘top hats’ and proprietary gas resistant bituthene tape. Perimeter ventilation was provided by a series of vent pipes that penetrated the ground beams and connected the sub floor ventilation with a gravel filled perimeter trench.

A third party Verifier visited site periodically during the earthworks and the installation of the gas protection system. The inspection and verification was carried out in general accordance with CIRIA C735 and comprised a series of visits over a three month period. A record of all site inspection visits with supporting photographs was published as supporting evidence in the final Verification Report.

During construction some issues were identified with the installed gas protection system by the Verifier's site inspections. These issues were recorded on the site visit, immediately brought to the attention of the contractors on site and then confirmed in writing (e-mail). Subsequent visits then paid particular attention to the issues raised to confirm satisfactory resolution (also recorded on the site visit records). Those issues (and their resolution) are briefly described below;

i) The visual inspection identified that initially in some locations vent pipes were set too low in the ground beams and therefore did not intersect the void former. The wrongly located pipes were blocked off / abandoned and new pipes constructed at the correct elevation to intersect the void former.

ii) Initially some vent pipes were found by the verifier to have been cut flush to the internal vertical wall of the ground beam and then sealed by the membrane which was turned down and laid against that vertical surface. This fault was discovered by the verifier lying in the vent trench excavation, inspecting the vent pipe by torchlight and seeing at the far end, the membrane and not the void former. Accordingly, the offending section of the membrane was cut and removed and secondary pipework inserted to ensure a positive connection (a procedure devised by the installer and approved by the verifier).

iii) Initially some service entries were buried without any evidence of them having been sealed correctly. These service entries were excavated, sealed, subject to satisfactory reinspection and then filling was allowed to take place.

iv) Initially some damage to the membrane was observed mainly on vertical surfaces where earthworks were undertaken with inappropriate materials and lack of care. The damaged sections of the membrane were repaired and reinspected. Inappropriate materials were excluded from the fill and the need for care re-emphasised.

All the issues initially identified during construction (and the consequent potential loss of integrity of the gas protection system) were appropriately resolved. On the final site inspection (following remedial action to re connect the vent pipes to the void former) the verifier was able to confirm that the gas protection system and its various elements were acceptable and complied with the specification. The Verification Report was prepared presenting all of the evidence summarised above. The report was accepted by the local planning authority and the relevant planning condition discharged.

The key lesson from this case study is that the verifier must be prepared to critically examine all elements of the gas protection system. In this case, the large proportion of the membrane was installed well by the professional and skilled staff of the specialist installer. However, the integrity / continuity of the ventilation measures required a level of communication / co-ordination between the earthworks contractor and the specialist installer which, in some instances, failed to materialise. Assurances to the verifier from the earthworks contractor that "all was well" were not accepted and the insistence that valid supporting evidence must be obtained resulted in the discovery of flaws in the gas protection system, which could then be rectified, safeguarding the development to the satisfaction of the regulator and the building owner.

6.5.2 Case study 6.2 Good practice approach to installation and management of follow-on trades

A vapour intrusion risk assessment identified the need for a VOC membrane to the houses in a development on a former aircraft factory site. The key contaminants of concern were tetrachloroethene PCE, trichloroethylene (TCE) and vinyl chloride. A site specific design had considered the permeation rates of the VOCs through the membrane and a suitable product was specified based in its permeation data. However, because of the high levels of VCOs remaining in the ground the robustness and good installation was an important consideration, more so than on lower risk sites.

The design was for a full line out installation of the membrane with it passing through the cavity walls as one sheet.

A pre-start meeting was held on site with the developer, groundworker, specialist installer, verification consultant and designer of the VOC mitigation. The high risk nature of the site and contaminants was made clear to all and it was explained that delivering this site was going to be a team effort – the purpose of the meeting was to clearly define the roles and responsibilities of all parties. A Responsibility Matrix was agreed by all parties. The key items of the design were explained along with the verification requirements. The ventilated void depth, air brick installations and membrane installation all required verification by a specialist consultant on every plot.

Prior to the specialist verification consultant visiting site all the relevant information from the specialist installer and developer was provided for each plot to be verified (sub-floor venting check, sleeper wall verification check and sub-grade acceptance check were uploaded to a shared Dropbox file). On this site there was no capacity for these elements to be 'missed' so it was important to make sure all the information was in place.

It was also made clear that a protection strategy post installation of the VOC membrane was critical. This was agreed and including a maximum exposure time before covering the membrane with a screed or brick/block work and the need for re verification if the time was exceeded. The importance of the VOC membrane was explained to all personnel working after the install via toolbox talks. A 'clean boots' policy was adopted where any access onto the membrane construction was required prior to covering with the screed.

Good communication was maintained between all parties during construction to deal with design changes and any other issues.

This approach allowed the membranes to be installed successfully with minimal issues during construction. At the end of construction the Local Authority Contaminated Land Officer (CLO) and NHBC had the confidence in the installations to sign off relevant Conditions.

References

7.1 Guidance matrix for gas protection Stages

Stage 1
Desk Study and Preliminary Risk Assessment

Stage 2
Ground Investigation

Stage 3
Risk Assessment

Stage 4 and 5
Design, Detailing and Specification

Stage 6
Installation and Verification

BS EN ISO CD 21365: Soil quality - Conceptual site model for potentially contaminated sites

BS8576: Guidance on investigations for ground gas - permanent gases and volatile organic compounds (VOCs)

BS8485: Code of Practice for the design of protective measures for methane and carbon dioxide ground gases in new buildings (*including general guidance on design, but not specific detailing*)

BS10175: Investigation of potentially contaminated site - Code of Practice

CIRIA C801: Hazardous ground gas - a site management guide

CIRIA C665: Assessing risks posed by hazardous ground gases to buildings
(This guide has been superseded by BS8485, but still contains useful information)

CIRIA C735: Good practice on the testing and verification of protection systems for buildings against hazardous ground gases

AGS Guidance the description of anthropogenic soils

CIRIA C795: retrofitting hazardous ground gas protection measures in existing or refurbished buildings (*including useful information on VOCs*)

CL:AIRE RB13: The utility of continuous monitoring in the detection and prediction of worst case gas concentration

CL:AIRE TB16: Complete continuous monitoring in underfloor voids

CL:AIRE TB17: Ground gas monitoring and "worst-case" conditions

CL:AIRE Verification of Gas Protection Measures Videos https://claire.co.uk/information-centre/video-and-podcast-library/category/8-verification-of-gas-protection-measures

CL:AIRE TB17: A pragmatic approach to ground gas risk assessment

CL:AIRE TB18: Continuous ground gas monitoring and the line of evidence approach to risk assessment

Reliability and risk in gas protection design: 20 years on, Part 1 Wilson S. Card G. and Lucas J. Ground Engineering August 2019

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CIRIA C682: The VOCs handbook investigating, assessing and managing risk from inhalation of VOCs at land affected by contamination

CIRIA C748: Guidance on the use of plastic membranes and VOC vapour barriers

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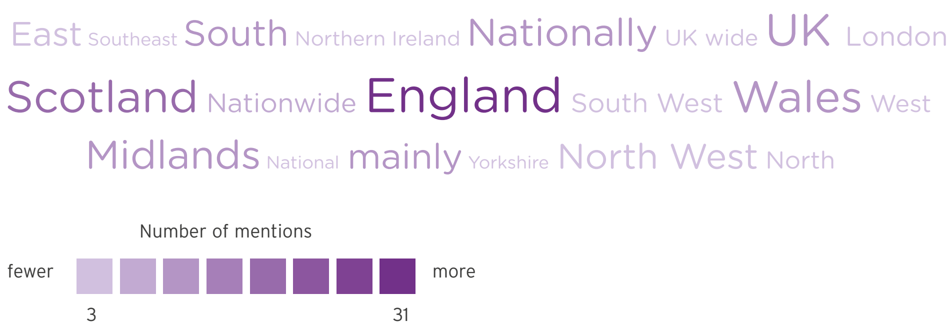
Appendix A - Responses to Questionnaire

A.1 Respondents

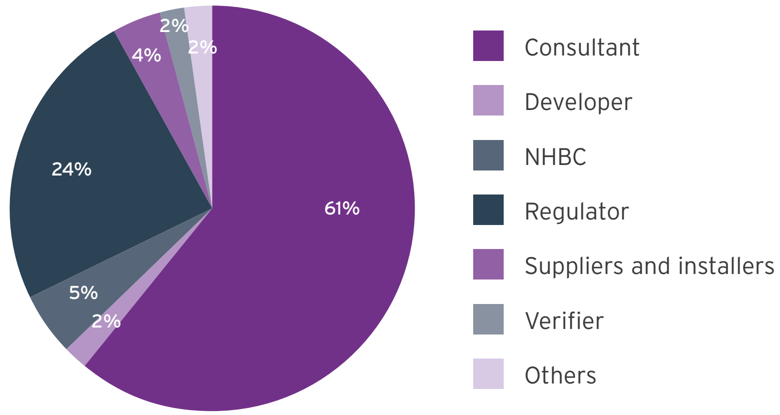
There were 119 fully completed responses to the survey.
A further 24 incomplete responses.

Q2. In which part(s) of the UK do you work?



Q3. Describe your role in relation to ground gas investigation, assessment and mitigation in residential developments

Role of respondent



The majority of respondents were consultants, although there was very good representation from regulators and NHBC LQE team.

Within the "consultant" category were people holding various levels of responsibility from technical directors, those involved with reviewing others work, and those managing and completing site works and generic gas risk assessments. A number of consultants also mentioned that they were involved in verification.

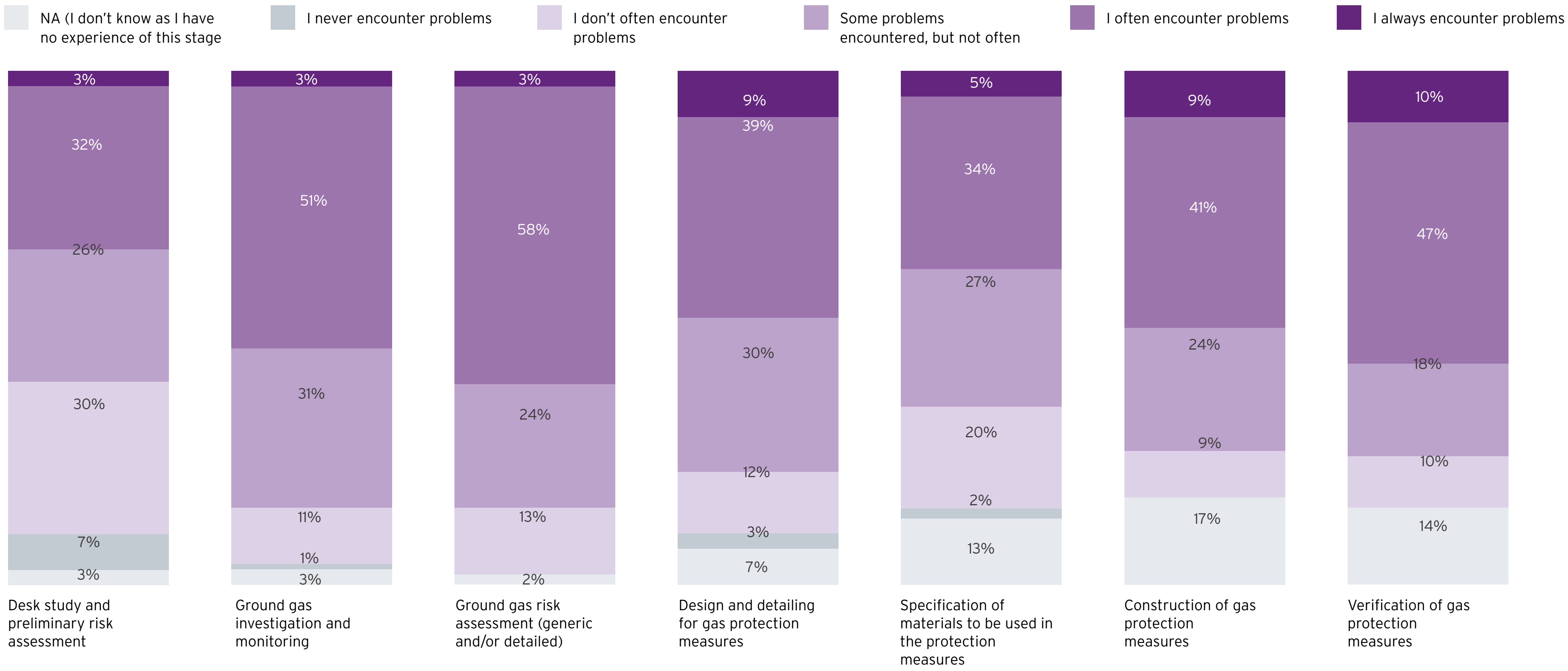
Eight respondents (7%) were installers, suppliers or verifiers. Only two respondents (<2%) were developers.

The category "other" includes two respondents, one monitoring contractor and one person describing themselves as a "designer".

A.2 Overview of the problems and causal factors

Q4. In your experience in which parts of the ground gas protection process for residential development do you think the most problems occur?

When do most problems occur?

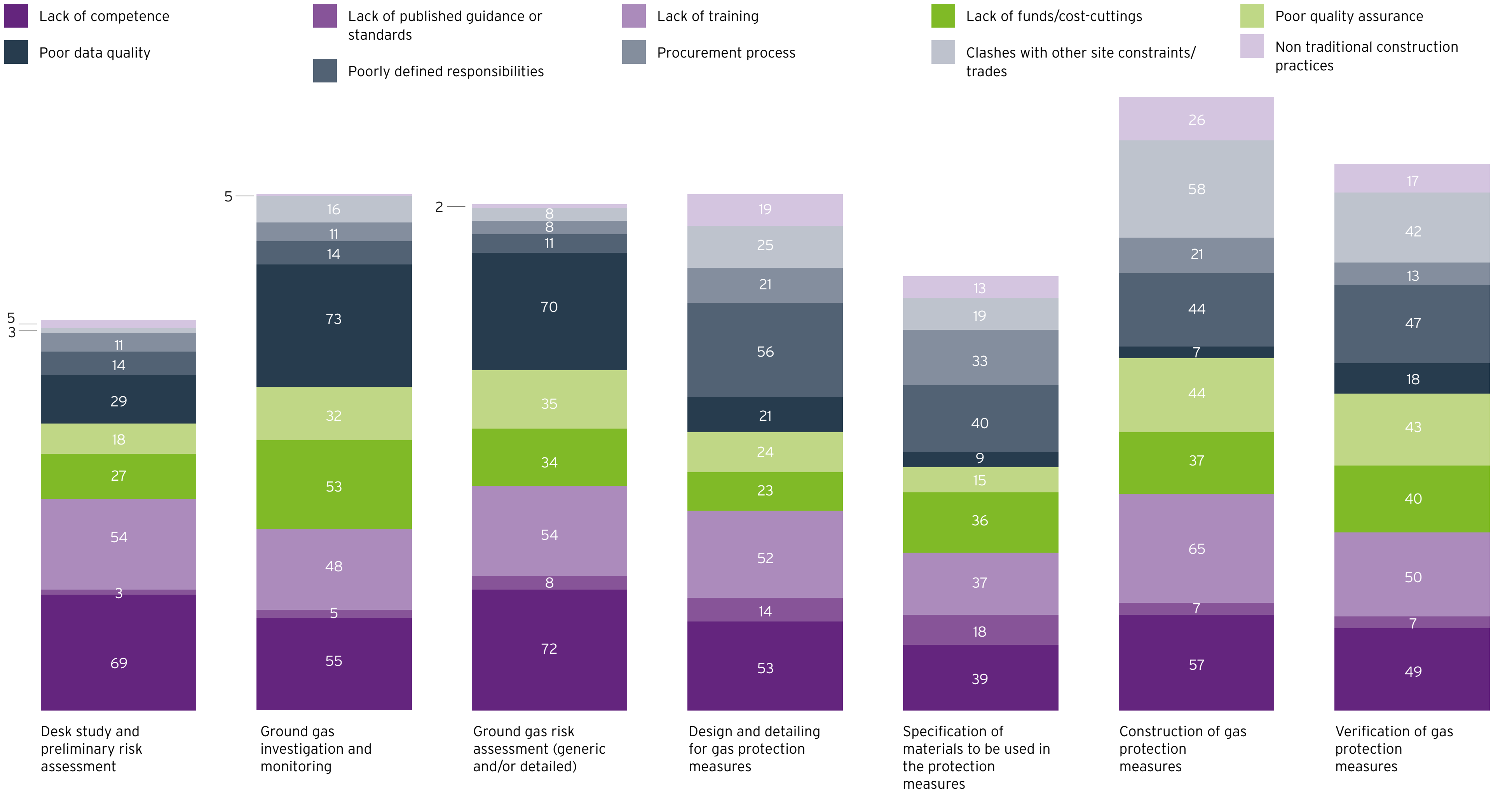


"I often encounter problems" was the modal response for every stage of the process. There wasn't a huge difference between stages, with problems generally encountered at every stage.

Statistical analysis of the responses (responses given weightings and averaged) shows that the stages of construction and verification were where the most problems were encountered on average. Investigation, risk assessment and design were the next most problematic followed by specification of materials and finally the desk study stage had the least problems. Although the most problems were perceived at the construction and verification stages these were also the ones which the most respondents had no experience.

Q5. Thinking about the problems that you have seen at each stage of the ground gas protection process, what are the factors causing these?

Casual factors



Lack of competence and **lack of training** were identified in all stages of the process as important causal factors for problems.

Lack of funds / cost-cutting was identified fairly often across the board, but was not the highest frequency causal factor identified for any stage.

Excluding competence, training and funding as they occur across all stages similarly, the top three causal factors (only if mentioned over 25 times) for each category are in the table below:

Stage	1st	2nd	3rd
Desk study and preliminary risk assessment	Poor data quality	none over 25	none over 25
Ground gas investigation and monitoring	Poor data quality	Poor quality assurance	none over 25
Ground gas risk assessment (generic and/or detailed)	Poor data quality	Poor quality assurance	none over 25
Design and detailing for gas protection measures	Poorly defined responsibilities	Clashes with other site constraints / trades	none over 25
Specification of materials to be used in the protection measures	Poorly defined responsibilities	Procurement process	none over 25
Construction of gas protection measures	Clashes with other site constraints / trades	Poorly defined responsibilities	Poor quality assurance
Verification of gas protection measures	Poorly defined responsibilities	Poor quality assurance	Clashes with other site constraints / trades

Poor data quality was identified by many as relevant to the investigation and risk assessment stages.

Poor quality assurance was also identified across all stages, did not dominate any, but most relevant for ground investigation, risk assessment, construction and verification.

Poorly defined responsibilities was observed to be most relevant at the later stages of the process from the design stage onwards through specification, construction and verification.

Procurement process was only identified at a frequency of over 25 for the specification of materials phase but was identified at all other stages at moderate frequency (8 to 21).

Clashes with other site constraints / trades was identified as important for design, construction, and verification stages.

Lack of guidance or standards was not identified by many respondents as a causal factor, although where it was, it was most often associated with the design and specification stages.

Non traditional construction practices was not a very frequently identified causal factor, but did have a frequency of 26 for the construction phase and was mentioned by 13 or more people for design, specification and verification too.

A.3 Key areas for inclusion in the guidance document

Desk study stage

Conceptual Site Model and plausible pathways for gas migration. Including changes in site conditions due to proposed development.

Low risk sources that can be discounted at desk study stage or can be de-risked with minimal ground investigation (no monitoring).

Information sources: highlight sources of information that should be used (over just an environmental search report) including LPA records and walkover.

Generation potential for gas sources. Including age, distance from buildings, depth of Made Ground, Alluvium or other natural organic soils.

Unconventional sources. Including vapours and coal mining.

Ground investigation stage

Investigation objectives and fit to the CSM.

Well design for ground gas monitoring. Depth, unsaturated, targeted to source stratum.

Well construction with tips for protection of monitoring points on active construction sites.

Sufficient data gathering. Lines of evidence (alternative data sources to just monitoring), temporal, special, continuous monitoring advantages. Check list – Have I got enough data?

Intelligent monitoring. Data quality, QAQC procedures, training of operatives, accurate recording of data. Advantages of data logging, rather than manual readings. Feedback loops and alerts.

Risk assessment

Multiple lines of evidence approach. More than just monitoring data. Cannot be a gas risk assessment if you don't put data into context.

Relevance to CSM. Gas risk assessment must be relevant to the pollutant linkage being assessed. There must be a source, a pathway and a receptor.

Low risk sites, analysis of the evidence burden needed to conclude the risk is low. Could include decision flow chart or case studies. How to reduce uncertainty so that you can be more pragmatic and less conservative with confidence.

Data quality check. Agreement or conflict in lines of evidence.

Design

Responsibility for design. Specialists with correct skills need to do this.

Design report. Summary of what it is and what it needs to include.

Membrane detailing tips and standard details. Edge detailing, thresholds, membrane protection, service penetrations, foundations.

Ventilation design principles. Calculations and venting pipe and mat layouts.

Design changes. How to track and manage these.

Constructability. Build sequence and practicalities of installation.

Specification of materials

Membrane properties. How to interpret data sheets and test data.

Competence and bias. Are those specifying the materials competent to do so?

Introduce concept of: in ground, below slab, and above ground as three broad categories for suitability.

Construction

Damage to membranes. How to prevent this from occurring, using a durable membrane, good housekeeping, protection fleeces to protect membranes, substrate preparation. Programme works so that they are not damaged after verification.

Poor workmanship by installers. Non-specialists completing this, or lack of quality checks. Joints, bonding on seals, impediment to ventilation.

Awareness and understanding by client or other trades. Requirement for communication, toolbox talks on site and training for site managers and developers. To prevent damage, and to ensure design is met.

Sealing penetrations. Sealing in or around underground utilities passing through membrane.

Weather conditions.

Verification

Verification recommended for all gas mitigation as this is part of the remediation system.

Verification plan. Requirement to include one with the design, and what it should cover.

Sources of evidence. Check-list for what should be included as evidence for each type of element: membrane, ventilation, competence of installers, independent verifier site visits.

Document design changes. (Need a design to check against.)

Integrity and lance testing.

Membrane repairs.

Appendix B - Bibliography

B.1 Hazardous ground gas - existing key guidance summary

Document reference	Summary description
BRE Report 414 Protective measures for housing on gas-contaminated land. BRE 2001[47]	Provides advice on the design and construction issues associated with housing development on sites where there is ground gas.
Guidance on evaluation and development proposals on sites where methane and carbon dioxide are present. NHBC 2007[1].	Guidance for low rise housing developments and incorporated a "traffic light" system.
Assessing risks posed by hazardous ground gases to buildings. CIRIA 2007[3].	Consolidated good practice in investigation, the collection of relevant data and monitoring programmes in a risk-based approach. The mitigation and management of potentially unacceptable risk is described.
Local authority guide to ground gas. CIEH 2008[22] (also published by Whittles as Ground Gas Handbook).	Written to be useful for local authority regulators in their assessment of proposals for gas protection systems.
RB13 The utility of continuous monitoring in the detection and prediction of worst case ground gas concentrations. CL:AIRE 2011[18].	Describes the potential for use of continuous monitoring equipment.
RB17 A pragmatic approach to ground gas risk assessment. CL:AIRE 2012[13].	Details circumstances when gas monitoring may not provide best indications of hazard to development on low risk sites. Recommends alternative approach (conceptual site model, based on comprehensive desk study, investigation and laboratory data.-
BS5876 Guidance on investigations for ground gas, permanent gases and VOCs. BSI 2013[14].	Provides advice for defining the generation risk potential of a gas source and for determining the appropriate level of gas assessment and the monitoring requirements.
Reliability and risk in gas protection design, 20 years on. Ground Engineering 2019[5].	Provides information on low risk sources of gas (fill materials, natural carbon dioxide and alluvial soils).
C735 Good practice and verification of protection systems for buildings against hazardous ground gases. CIRIA 2014[33].	Details the advantages and disadvantages of commonly available techniques, emphasises limitations of various methods and sets out how the verification should be reported to demonstrate that risks have been appropriately managed.
BS8485 Code of practice for the design of protective measures for methane and carbon dioxide ground gases for new buildings. BSI 2019[4].	Overarching and most up to date guidance for screening level assessment. Intended for designers and regulators. Recognises sensitivity factors requiring consideration and the range of risk mitigation solutions. Allows professional judgement regarding; acceptability of risk, potential for more rigorous site assessment, or adoption of conservative design.

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Complete continuous monitoring in underfloor voids. TB16 CL:AIRE 2018.

Ground gas monitoring and “worst-case” conditions. TB17, CL:AIRE, 2018.

Continuous ground-gas monitoring and the lines of evidence approach to risk assessment. TB18, CL:AIRE, 2019.

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B.4 Building Research Establishment (BRE)

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Soil quality – Conceptual site models for potentially contaminated sites. BS EN ISO CD 21365. BSI, 2019.

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B.8 Basement information centre

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- Ground Gas information Sheet No 3. Screening approach for landfill gas migration around landfill sites.
- Ground Gas information Sheet No 4. Basement waterproofing and ground gas.
- Ground Gas information Sheet No 5. Gas membranes and "compliance" with BS8485.
- Ground Gas information Sheet No 6. Using purge and recovery tests in ground gas risk assessment.

B.10 NHBC

Guidance on Evaluation of Development Proposals on Sites Where Methane and Carbon Dioxide are Present. 10627-R01(04). NHBC and RSK Group. NHBC, 2007.

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B.14 Land Contamination & Reclamation

Modular approach to analysing vapour migration into buildings in the UK. Wilson S. July 2008 Land Contamination & Reclamation 16(3).

Quantifying risks due to ground gas on brownfield sites. J.A. Sladen, A. Parker and G.L. Dorrell. Land Contamination & Reclamation 9(2).

Appendix C - Standard Details

C.1 Introduction

The design and detailing of gas protection systems should aim to make installation as simple as possible and where possible to place the gas membrane out of harms way from follow on trades. It is important to avoid complex details as far as possible. There is also a requirement to ensure that the gas membrane details do not promote damp or water ingress to the building. Issues to be taken into account by the gas protection designer includes:

- level of gas risk;
- the materials and components used in the gas protection system;
- interface with the foundations, floor slab and structure;
- joints, abutments, steel columns/wind posts and service penetrations; and
- steps and level changes.

Further detail on specific aspects is provided below.

C.1.1 Venting or pressure relief is not required below robust concrete slab/pile caps, etc for small footprint buildings or basements with waterproof concrete

When considering the need for venting or pressure below a building designers should take account of the following factors.

Evidence from internal monitoring shows that methane and carbon dioxide gas, as well as radon, does not migrate through intact well constructed reinforced concrete at a significant rate (it does occur but very slowly). This is also stated by BRE in its radon guidance (BRE 211, 2015). This may not be the case for some chlorinated hydrocarbons that can migrate fast enough through intact concrete to cause hazardous concentrations inside a building (CIRIA C795).

Gas does not migrate through narrow cracks at a fast rate either, unless there is a significant gas pressure in the ground (only likely in landfill sites). The cracks are tortuous and have rough walls which limits the rate of gas migration through cracks that are 0.3mm wide or less. Cracks also have to pass through the complete depth of concrete to allow significant passage of gas.

The main ingress points in most buildings are open ducts, pipes and wide armoured construction joints or isolation joints. In residential housing with ground bearing slabs the perimeter crack can allow gas migration through it.

Raft foundations that are designed by structural engineers and do not have walls penetrating through them provide a robust barrier to gas migration. When combined with a robust gas resistant membrane venting or pressure relief below them is not necessary for CS2 and CS3 sites. The same would apply for VOC intrusion and radon if a suitably robust membrane is provided (that has permeation test data in accordance with CIRIA C748 for VOC sites).

Another conclusion that can be drawn is that there is generally no need to wrap pile caps, lift pits and other thick concrete construction with gas membrane in high rise construction where the site is classified as CS2 or CS3. Note that wrapping may be necessary to achieve waterproofing requirements in some cases.

Gas pressure is not likely to build up below a floor slab where the building has small dimensions and/or where the gas flow from the ground is dominated by diffusion (Alluvium, Made Ground with low organic content, etc).

C.1.2 Allow venting to be above or below the membrane

There is no reason why the ventilation layer cannot be located above the gas membrane in some situations for small footprint buildings (typically low rise residential). If this is done it should be justified by the designer of the gas protection system. This will simplify the detailing of modular and precast insulated flooring systems. The only reason venting is normally placed below the membrane is because of convention. Providing venting below the membrane on modular buildings often results in ground level vents being required. These are less effective than airbricks and in low rise housing should not be used because they easily become blocked or covered. Therefore, the venting above the membrane is a more robust solution in these situations as it can be vented via air bricks.

C.1.3 Gas membrane detailing and damp proofing

It may be better to separate out the gas protection from the damp proofing. In practice the damp proofing may be detailed to be combined with the gas membrane, but that is a choice to be made by the designer. A lot of issues in detailing gas membranes occur because one product is trying to do two things, to the detriment of both objectives. Removing the combined function can allow the gas membrane to be located in other locations where it will not act as damp proofing but is easier to install and detail, thus providing a more robust gas protection detail.

However, the gas protection designer must ensure that the gas membrane details do not promote damp or water ingress or problems. This is particularly important with timber and metal frame construction and at level changes (see below

C.1.4 Simplify the installation as far as possible to minimise sealing around air bricks, corners, door thresholds, etc

The more sealing details there are, using cloaks or self adhesive membrane, the more points of weakness in the gas membrane, which are the highest risk areas where gas ingress usually occurs. The design of the building and the location of the membrane should minimise penetration through the membrane of any sort (pipes, columns, air brick ventilators, etc).

C.1.5 The location of the membrane in the construction will determine what properties are critical to ensure adequate performance and what protection should be provided to the membrane after installation.

The properties of a gas membrane that are critical to ensure adequate performance and also what protection should be provided to the membrane after installation depends on where in the floor construction it is located. A problem in the industry is the belief that one size fits all when it comes to gas membranes. There are known issues of gas membranes being specified that are not suitable for the location. Issues include:

- Damage to unprotected membranes by fibre reinforced screeds or reinforcement cages. Any membrane below such construction should have a protection layer above and also have sufficient puncture resistance to small sharp objects (the standard puncture test uses a 50mm diameter plunger which is not representative of the things that damage these membranes on site).
- Corrosion and poor puncture resistance of thin aluminium foil membranes (See Lucas and Wilson, Geosynthetics International (2020) Corrosion and puncture resistance of aluminium foil gas membranes beneath concrete slabs). Such membranes (and self adhesive aluminium tape) should not be used in locations where they will be in direct contact with wet concrete, nor in locations where they will be in contact with groundwater (eg around basements).
- If settlement below a floor slab (or other tensile strain on a membrane) is a concern the membrane should have sufficient tensile strength and strain properties to retain its gas resistance if the settlement occurs. It is known that if excessive tensile strain occurs in aluminium foil membranes the foil ruptures well before the membrane fails. The foil is the main reason the membranes have very low gas transmission or VOC permeation rates in lab tests and if it is ruptured the permeation rates can increase significantly. The tensile strength values that are normally quoted on data sheets occur at strains that are too high to maintain the quoted gas resistance (the foil ruptures at much lower strains) and design has to take account of the failure strain of the membrane and the foil layer. The suitability of taped seals at columns, etc should also be assessed to make sure that they are not likely to pull away if settlement or other movement occurs.

Radon guidance in Norway (SINTEF) adopts an approach that grades radon membranes and provides limiting values for strength and durability properties. This can be adapted for use for any gas or VOC membrane in the UK. This is also consistent with the guidance in CIRIA C748 that provides detailed advice on the various properties that should be specified for VOC membranes. CIRIA C748 is referenced in BS8485 therefore anyone specifying gas membranes should follow the advice in it regarding assessment of durability, ability to withstand damage, etc. Recommended tests and, where appropriate, limiting values are provided in Section 5 of this report.

There is very little recognition that membranes placed below concrete slabs and around basements need to be stronger and more resistant to damage than those placed above floor slabs which are supported. There tends to be a focus only on gas transmission rate with no consideration of the other gas membrane properties. This is because BS8485 does not give guidance on values or test methods for other properties (but it does refer to CIRIA C748 which gives more detailed guidance).

C.2 3D site specific details

There are some locations where detailing a gas membrane to provide gas resistance in a manner that does not comprise damp is complex. The gas protection designer should identify any such locations for each site or building and provide site/building specific 3D drawings for the gas membrane installation. Standard details are not acceptable. Some common locations are shown below.

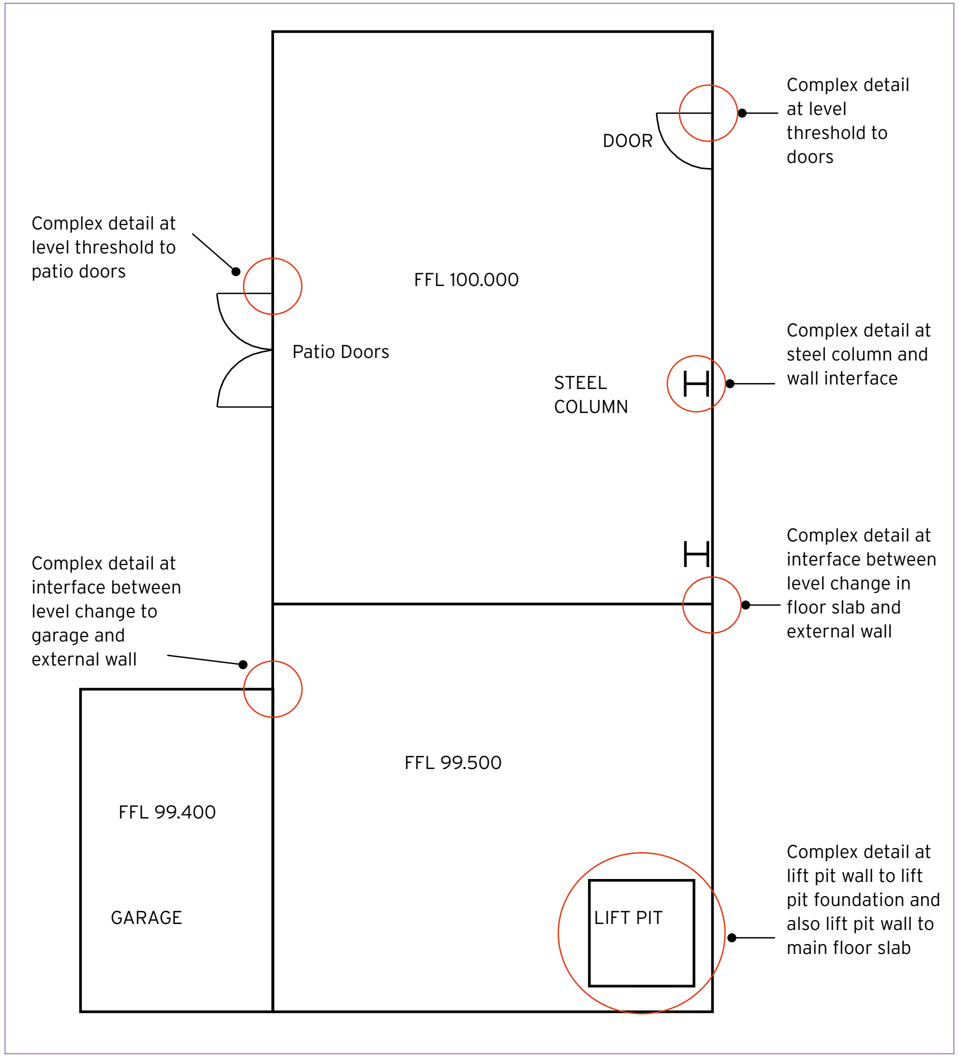


Figure C1 Common locations where 3D details are necessary and careful co-ordination of installation is required

All these situations are common in building construction and it is important that at these locations the designer ensures that the gas protection (and damp proofing) is effective. Issues to take into account include:

- the nature of the substructure and superstructure construction and their resistance or susceptibility to water or water vapour ingress. For example consider the need to fix timber or light gauge steel frames through the membrane and whether this can be avoided and the control of moisture next to these. Requirements for drained and/or ventilated cavities and the ability for timber sole plates to breathe. Also consider the inclusion of insulation which will require discussions with the Architect;
- height difference between floors and whether waterproof concrete and an external bonded membrane would be a more suitable solution;
- height of soil retention and presence of voids;
- ground conditions and gas risk;
- continuity at the interface between the change of level and external walls (3D details required);
- relationship between internal and external levels:
- considering continuity and effectiveness of underfloor venting; and
- continuity at returns, steel columns or wind posts and changes of wall construction (eg concrete to cavity wall).

This list is not exhaustive and the gas protection designer should consider each building construction and identify potential problem areas that will require 3D details.

The areas where 3D details are required are also often the areas where it will not be possible to install the gas membrane in a single operation. The gas protection designer needs to consider the buildability of the system and particularly the gas membrane. The gas protection designer must consider how the building will be constructed and how the membrane will be incorporated into it and at what stage(s).

C.3 Standard Details

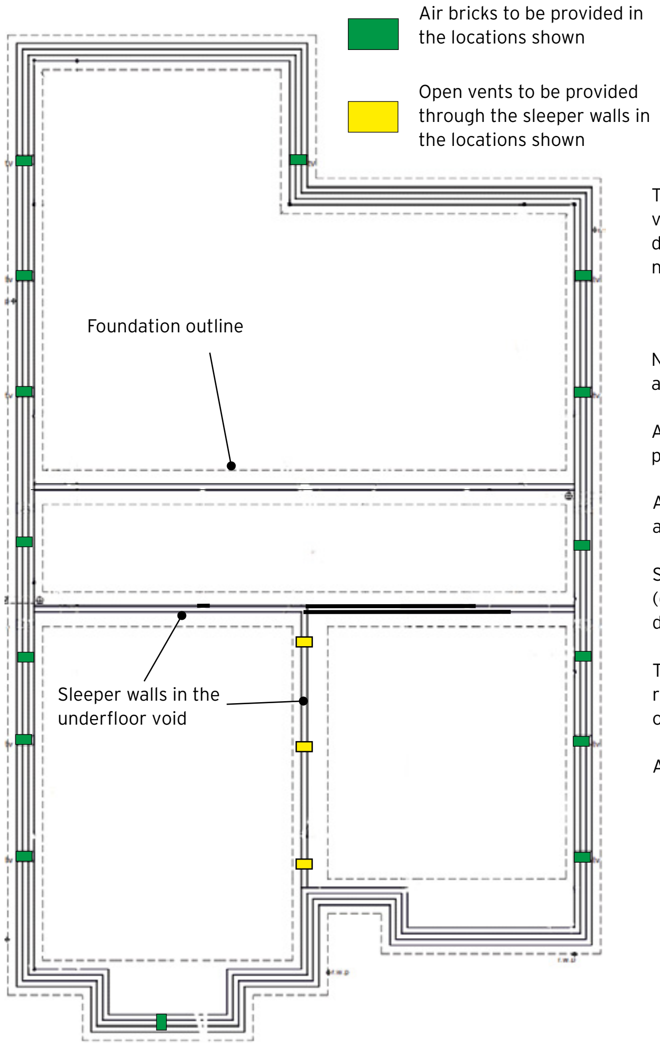
The standard details apply only to sites that are classified as Characteristic Situation CS2 or CS3. Most sites that are currently classified as CS4 are incorrectly assessed using poor data (eg from flooded monitoring wells in Alluvium). Sites correctly classified as CS4 will be rare (more recent domestic landfill sites or severely impacted by mine gas emissions). In such cases the provision of simple gas protection measures is not appropriate. Indeed, it is often the case that traditional low rise housing will not be suitable without significant works to external areas being required along with additional in ground protection to the buildings (eg 3m+ deep capping layers over the gas source or even complete removal and processing of the waste to manufacture materials to form development platforms). Therefore, site specific risk assessment and design is required for sites classified as CS4 and above sites and the standard details for gas protection provided in this section should not be applied on their own to higher risk sites. The details may be appropriate for VOC or radon but this should be assessed by the designer for each site.

C.3.1 Standard Details - Air bricks and sub slab ventilation

Air bricks are often omitted or do not vent all the spaces below a ground floor slab. This is because construction drawings showing the location of air bricks are rare and, even when available on site, are not followed. The result is that bricklayers end up deciding on the location of the air bricks. This is not acceptable where the airbricks are part of the gas protection system. The locations of air bricks need to be designed to ensure no conflicts with doors, ground levels, etc. Air brick positions should be shown on plans (example in Figure C2). Ground levels around buildings and floor levels should be designed to ensure air bricks are 150mm above surrounding ground levels. Ground level and below ground level vents (air bricks or vent boxes flush with the ground) should not be allowed as part of sub-slab venting systems for low rise residential housing. Ground level vent boxes may be considered for use as part of pressure relief (if it is required) but the designer should consider the impact of complete blockage.

Where telescopic air bricks penetrate above any gas membrane the upper part of the cranked ventilator must be sealed so that it is gas tight and cannot allow gas to migrate into the wall cavity.

Typical sub floor design drawings (below beam and block floor) showing location of airbricks and cross wall ventilation



The gas protection design to be submitted to the NHBC should include a plan of the sub-floor void showing the air brick locations (or other vent outlets) and cross wall ventilation. This drawing should be followed on site and the operatives should be aware of the required number and location of air bricks (or other vent points).

Note air brick positions to be cross checked with doors, french window, downpipes, etc to avoid clashes.

Adjustments must not be made on site without reference back to the designer of the gas protection system.

Air bricks nominally at 2m centres - but install at positions shown. Provide same number of air bricks on two opposite walls.

State ventilation area required for the air bricks (normally > 6,000mm²/m) and cross vents (6,000mm²/m the simplest approach is to use short sections of 100mm diameter PVC drainage pipe through the sleeper wall or construct it with gaps in the blockwork).

This gives 3,000mm² vent area/m of wall in this example. This is above the minimum requirement of 1500mm²/m but is required to provide even coverage and prevent dead spots on this building.

Air bricks properly ducted in accordance with Chapter 6.1 ‘External masonry walls’.

Additional air brick on this face to avoid dead spot in bay area

Figure C2 Example drawing showing air brick locations

C.3.2 Standard Details - Gas membranes

Note that these details only apply to CS2 and CS3 sites. Where a membrane is to provide a combined gas resistance and damp proofing the following should be noted:

1. The damp proof course through the external walls must be at least 150mm above external ground levels.
2. Where a gas membrane is horizontal through the cavity it must be sealed to a cavity tray above using tape or sealant. The cavity tray should ideally be a preformed system (including preformed corners, change of level links and threshold barriers) or be welded at joints and the installation should be verified.
3. The sole plate of timber framed construction must not be exposed to damp/condensation by the gas membrane detail.
4. Close co-ordination is required between bricklayers and membrane installers to ensure a good quality installation across cavity walls.
5. For timber frame construction the use of an appropriate airtight wall breather membrane on the internal face of the cavity along with ventilation of the cavity may remove the need for the gas membrane to span the cavity.
6. The top of air bricks must be at least 150mm above external ground level.

The ideal installation is to install the membrane in a "full line out" approach where the gas membrane is installed continuous across the floor and cavity wall (Figure C3 and Figure C4) below. The advantages of this are:

1. Membrane can be installed in one visit by a specialist installer (NVQ Level 2 and BBA licensed installer scheme) using welded seams.
2. Membrane can be verified in one visit by an independent verification consultant (CL:AIRE GPVS).
3. Main membrane over floor area can be protected after installation to minimise risk of damage by follow on trades using insulation (for concrete B&B floors).

Figure C3 Full line out installation (continuous gas membrane - membrane installation

Figure C4 Full line out installation (continuous gas membrane - slab concreted

A perimeter cavity installation is where the gas membrane is installed across the cavity as a perimeter (illustrated in Figure C5 and Figure C6). The main membrane is then installed later in the construction when the walls and roof are completed. The perimeter membrane has to be well protected from damage and often it is damaged to an extent that the main membrane cannot be sealed to it. It also significantly increases the joint length in the membrane installation, which is a weak point. The verification of the perimeter requires increased visits and is often missed, leading to problems obtaining approval from regulators. It is therefore not the preferred approach if it can be avoided. The cavity tray installation requires verification to ensure it is installed correctly and will not cause damp problems.

Figure C5 Perimeter cavity membrane with main infill membrane - perimeter cavity gas resistant membrane / DPC

Figure C6 Perimeter cavity membrane with main infill membrane - with infill membrane completed

C.3.3 Standard Details - Beam and block floor

Detail 1 – Membrane above B&B floor and over air bricks (Figure C7)

- Detailing is easier
- Avoids complex and difficult sealing around air bricks and ventilators
- Risk of damp ingress - Requires good attention to detail and coordination between trades during construction of cavity trays and keeping cavity free of debris, especially behind the cavity tray.
- Key Point: The cavity tray should ideally be a preformed system (including preformed corners, change of level links and threshold barriers) or be welded at joints. It should extend beyond the edge of the gas membrane and out to the face of the external leaf of bricks. The cavity tray should be sealed to the underlying gas membrane with a suitable sealant or by using materials that compress together to form a seal under the weight of brickwork. The cavity tray installation requires verifying to ensure it is installed correctly and will not cause damp problems.
- Close co-ordination is required between the bricklayers and membrane installers to ensure the membrane across the cavity is not damaged when the external brick is constructed, and the cavity tray installed.
- Note if fibre reinforced screed used and there is no insulation above the membrane it will require a protection layer
- Ensure any insulation that is required in cavity is placed before membrane is installed

Typical beam and block floor and gas membrane detail for CS2 and CS3 sites

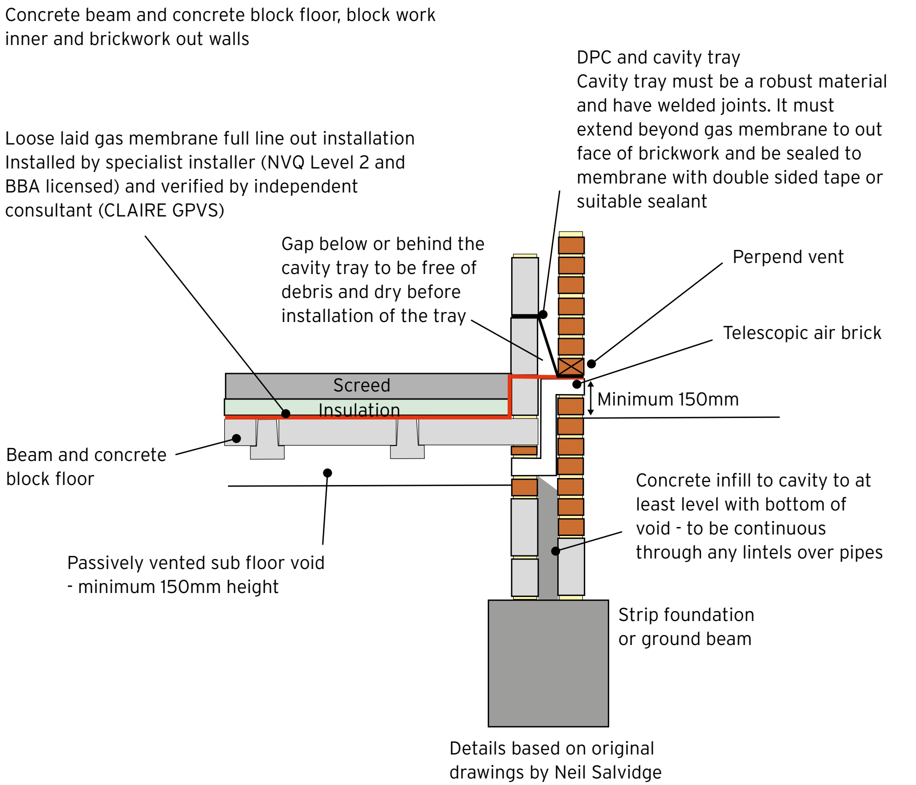


Figure C7 Membrane installed above B&B floor and over air bricks

Detail 2 – Membrane above B&B floor but drops down across cavity (Figure C8)

- Reduces risk of damp ingress
- Creates numerous seals around air bricks which will require good attention to detail to avoid increased risk of gas ingress
- These are extremely difficult to install successfully, even for a specialist installer. Unlikely to be installed correctly by a groundworker
- Self-adhesive membrane may de-bond over time as it is not supported around the telescopic vent in in the cavity
- Fixes the vent location prior to outer wall being built and it may not align with brickwork, which will lead to bricklayers damaging the seals as they try and adjust the position of vent.
- Requires 100% verification and likely to require increased number of visits by specialist installer and verification consultant after brickwork is brought up to top of air brick level
- Note if fibre reinforced screed used if there is no insulation above the membrane it will require a protection layer
- Ensure any insulation that is required in cavity is placed before membrane is installed.

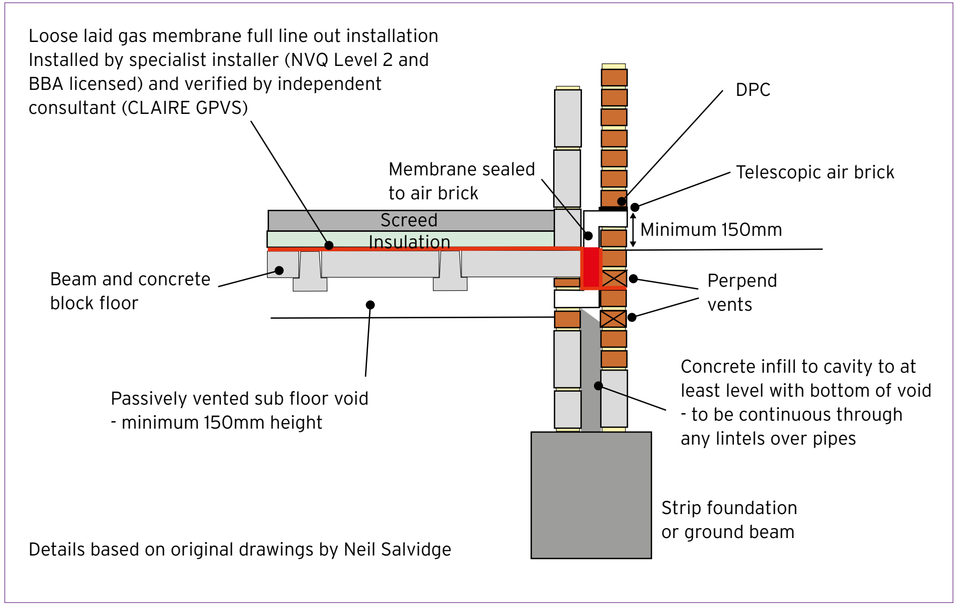


Figure C8 Membrane installed above B&B floor but dropped down across cavity

Detail 3 – Membrane below the void (Figure C9).

- Simplifies detailing and installation
- Reduces risk of damage to membrane by follow on trades (requires concreting over prior to any brickwork)
- Not to be used where there is shallow groundwater (minimum of 0.5m between continuous ground water and underside of membrane).
- For low rise housing with a small plan area on CS2 and CS3 sites gas pressure will not build up below the membrane and pressure relief is not necessary.

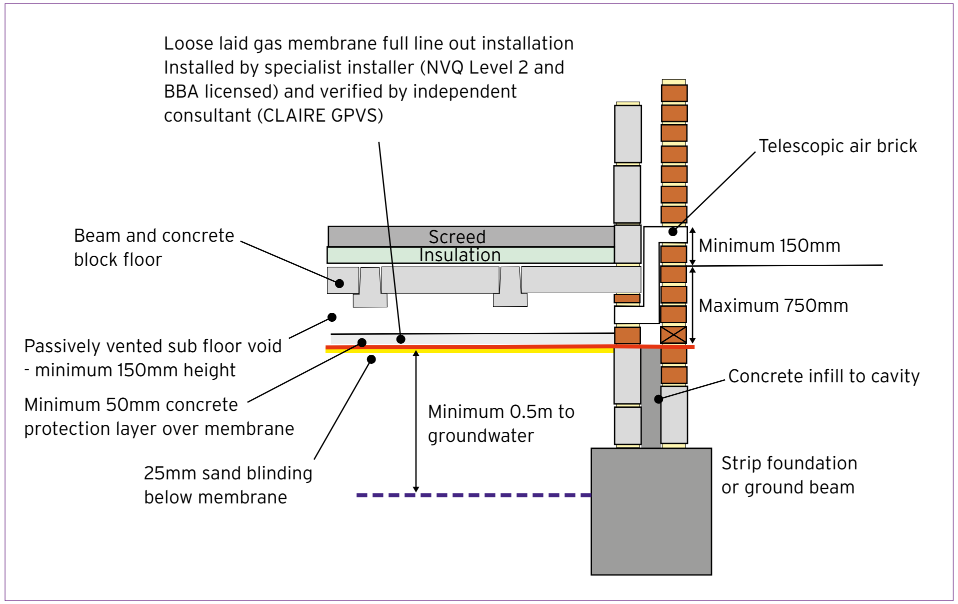


Figure C9 Membrane installed below the void

C.3.4 Standard Details - Cast insitu suspended floor

Detail 4 – External vents instead of air bricks (Figure C10)

- Detailing is easier
- Avoids complex and difficult sealing around air bricks and ventilators
- Ground level vents are not suitable around low rise housing due to the risk of complete blockage, filling in or covering over. Small vent stack risers are required.
- Note if there is no insulation above the membrane it will require a protection layer
- Ensure any insulation or infill that is required in cavity is placed before membrane is installed.

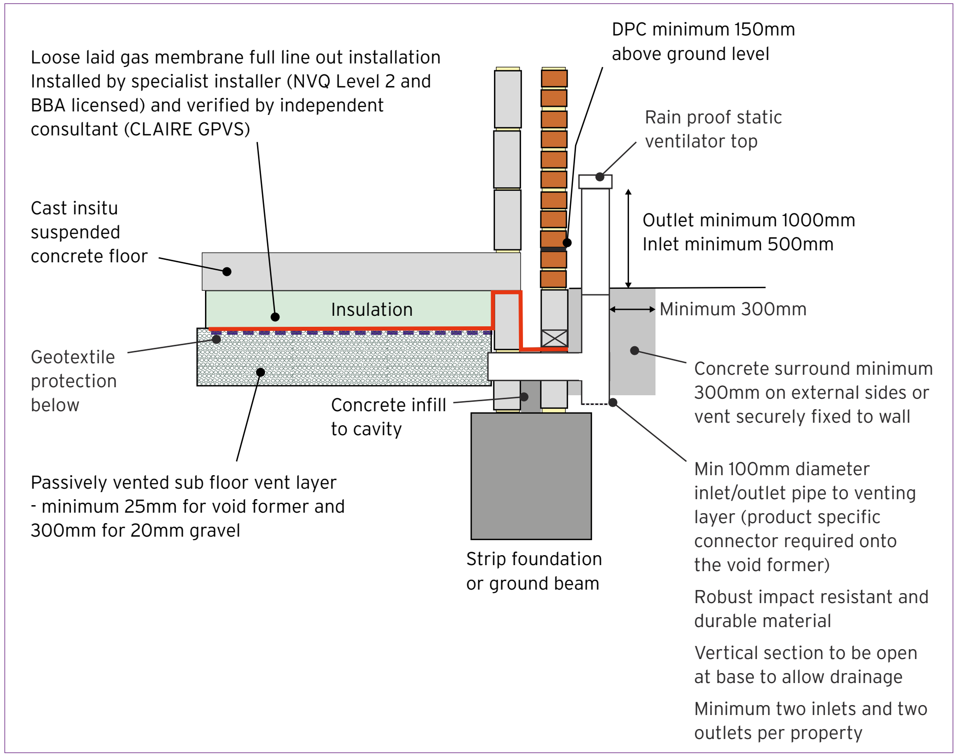


Figure C10 Membrane installation with external vents

Detail 5 - With air bricks (Figure C11).

- To avoid a step down in the membrane that is in an inwards direction the membrane has to be sealed around the telescopic air bricks.
- Creates numerous seals around air bricks which will require good attention to detail to avoid increased risk of gas ingress
- These are extremely difficult to install successfully, even for a specialist installer. Unlikely to be installed correctly by a groundworker
- Self-adhesive membrane may de-bond over time as it is not supported around the telescopic vent in in the cavity
- Fixes the vent location prior to outer wall being built and it may not align with brickwork, which will lead to bricklayers damaging the seals as they try and adjust the position of vent.
- Requires 100% verification and likely to require increased number of visits by specialist installer and verification consultant after brickwork is brought up to top of air brick level.
- Key Point – The cavity tray should ideally be a preformed system (including preformed corners, change of level links and threshold barriers) or be welded at joints. The cavity tray should extend out to the face of the external leaf of bricks.
- Note if there is no insulation above the membrane it will require a protection layer
- Ensure any insulation or infill that is required in cavity is placed before membrane is installed.

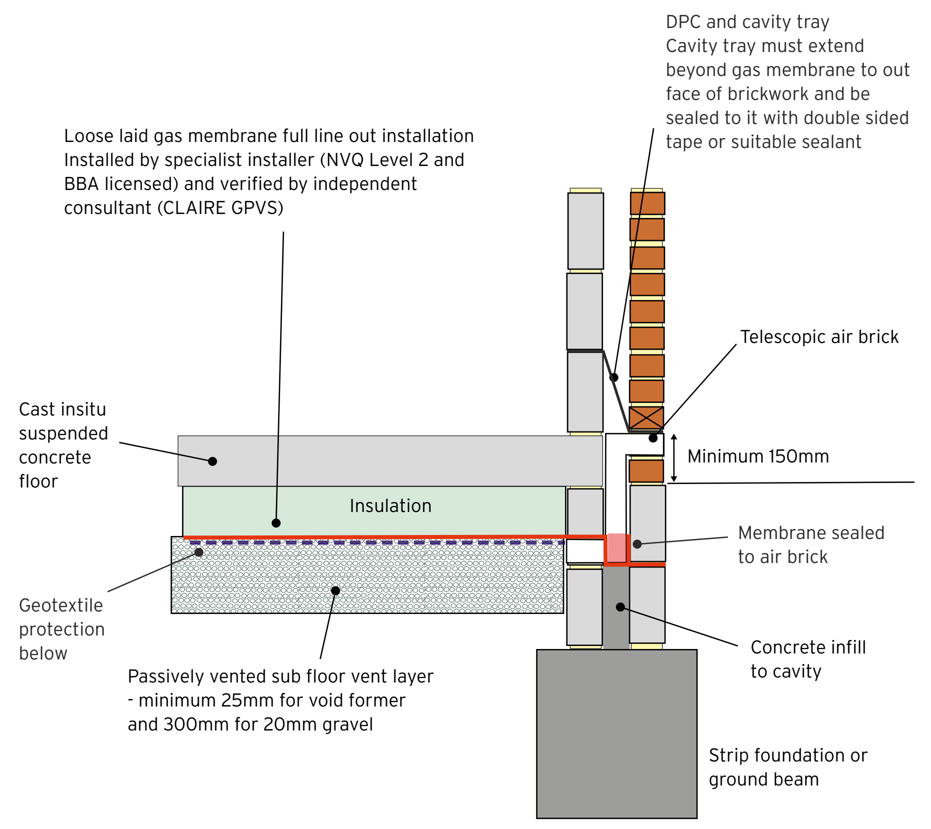


Figure C11 Membrane installation with air bricks

Detail 6 – Membrane below the venting layer (Figure C12)

- This simplifies the gas membrane installation and avoids having to seal around the air bricks
- It also avoids detailing around thresholds and reduces the risk of damage to the membrane
- It will also minimise visits by specialist installers and verification consultants
- Not to be used where there is shallow groundwater (minimum of 0.5m between continuous ground water and underside of membrane).
- For low rise housing with a small plan area on CS2 and CS3 sites gas pressure will not build up below the membrane and pressure relief is not necessary.

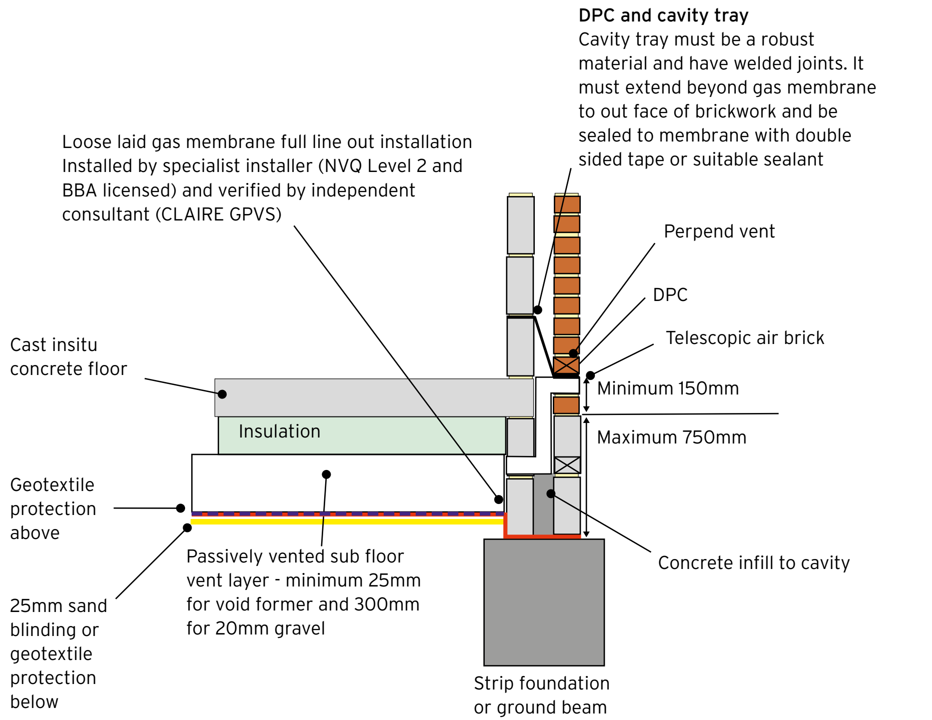


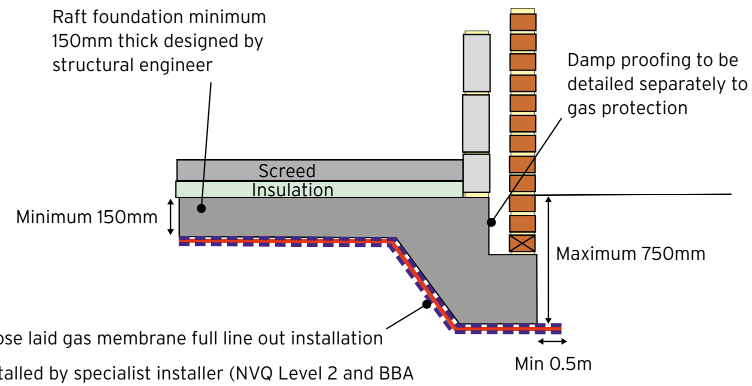
Figure C12 Membrane installed beneath the venting layer

C.3.5 Standard Details - Raft foundations

Detail 7 – immediately below raft (Figure C13)

- Remove the need for venting below raft foundations
- The gas membrane is placed immediately below the concrete construction
- Avoids installation and detailing through cavity wall, which is often a cause of problems
- It is exposed to potential damage during steel fixing and will require protection layers above and below
- Seams need to be aligned so they run parallel to slopes in the formation
- It is not exposed to damage once raft is cast.

Sub raft ventilation layer is not required if the raft is designed by a structural engineer and the membrane is verified by a competent person and has a declaration on the CL:AIRE GPVS



Loose laid gas membrane full line out installation

Installed by specialist installer (NVQ Level 2 and BBA licensed) and verified by independent consultant (CLAIRE GPVS)

Protection geotextile above

Sand blinding 25mm or protection geotextile below the membrane

Figure C13 Membrane installed immediately beneath the raft

Detail 8 – below sub-base (Figure C14)

- Remove the need for venting below raft foundations
- This detail simplifies placement of the membrane
- Rafts sometimes have flat undersides which makes this more appropriate
- Avoids installation and detailing through cavity wall, which is often a cause of problems
- Minimises risk of damage during steel fixing
- Requires protection against damage during sub-base placement – but this is less likely than with steel reinforcement if membrane is protected.

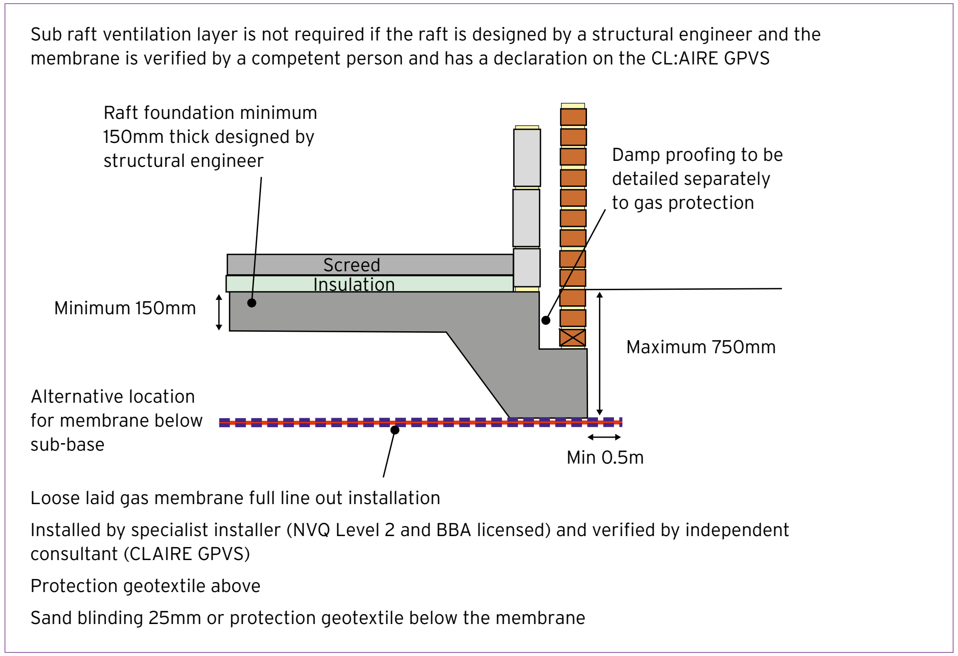


Figure C14 Membrane installed beneath sub-base

Detail 9 – On top of the structural raft (Figure C15)

- If the gas membrane is placed on top of the structural raft it will require protecting by a concrete screed over it.
- The use of timber or other flooring above it is not acceptable
- Minimises risk of damage during steel fixing for the raft reinforcement
- Note if there is no insulation above the membrane it will require a protection layer.

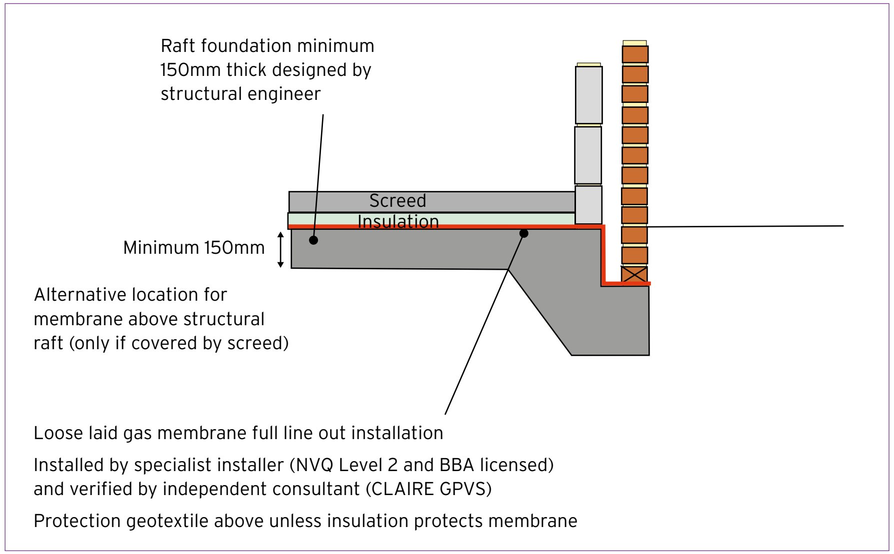


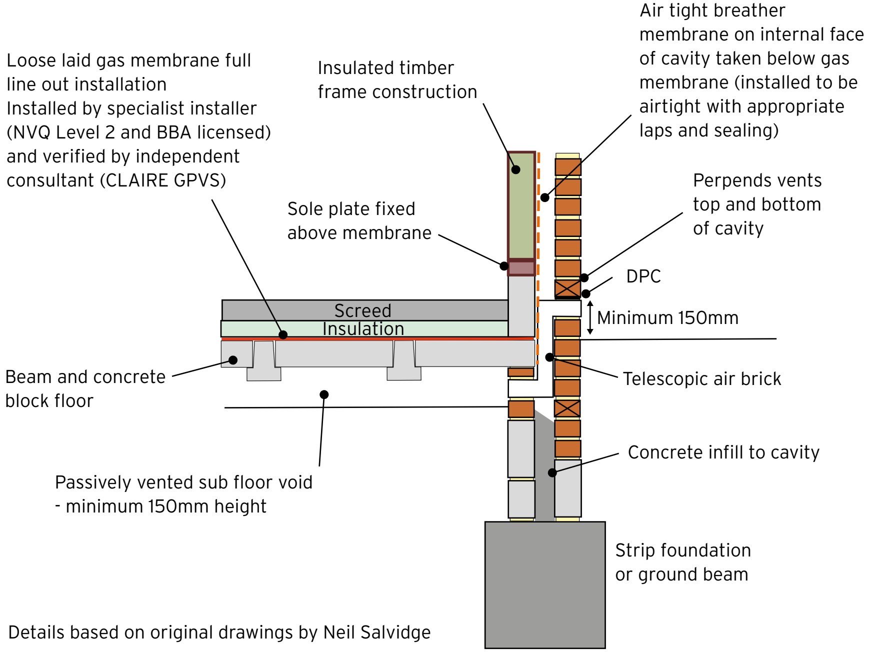
Figure C15 Membrane on top of structural raft

C.3.6 Standard Details - Timber frame

Detail 10 and 11 – Block and beam floor (Figure C16 and Figure C17).

- The issue with timber frame is ensuring that the sole plate does not compromise the gas membrane installation and the gas membrane installation does not expose the timber frame to water or damp.
- All structural timber should be located at least 150mm above finished external ground level, except for localised ramping (incorporating satisfactory drainage and ventilation detailing) for level threshold requirements
- Wherever possible the fixings for the timber frame sole plate should not pass through the membrane.
- Where this is not possible the fixings should be gas tight. Sealing can be most effectively achieved by placing a layer of self adhesive membrane below the sole plate and shot firing fixings through it
- Where an appropriate air tight breather membrane is installed to be air tight on in the internal face of the cavity and there is also venting of the cavity at the top and bottom, the gas membrane does not need to pass across the cavity for methane and carbon dioxide CS2 and CS3 sites (this may also be the case for VOCs and radon based on a site specific risk assessment)
- Breather membrane to have an air permeability <1m³/m³/h@50Pa tested in accordance with BS EN 12114
- Cavity ventilated top and bottom using perpend vents. Lower row below the lowest timber level. Maximum spacing 1200mm horizontally. Minimum vent area of 500mm²/m of wall and maximum of 1500mm²/m of wall (slightly ventilated in accordance with British Standard BS EN ISO 6946).

Concrete beam and concrete block floor, timber frame construction



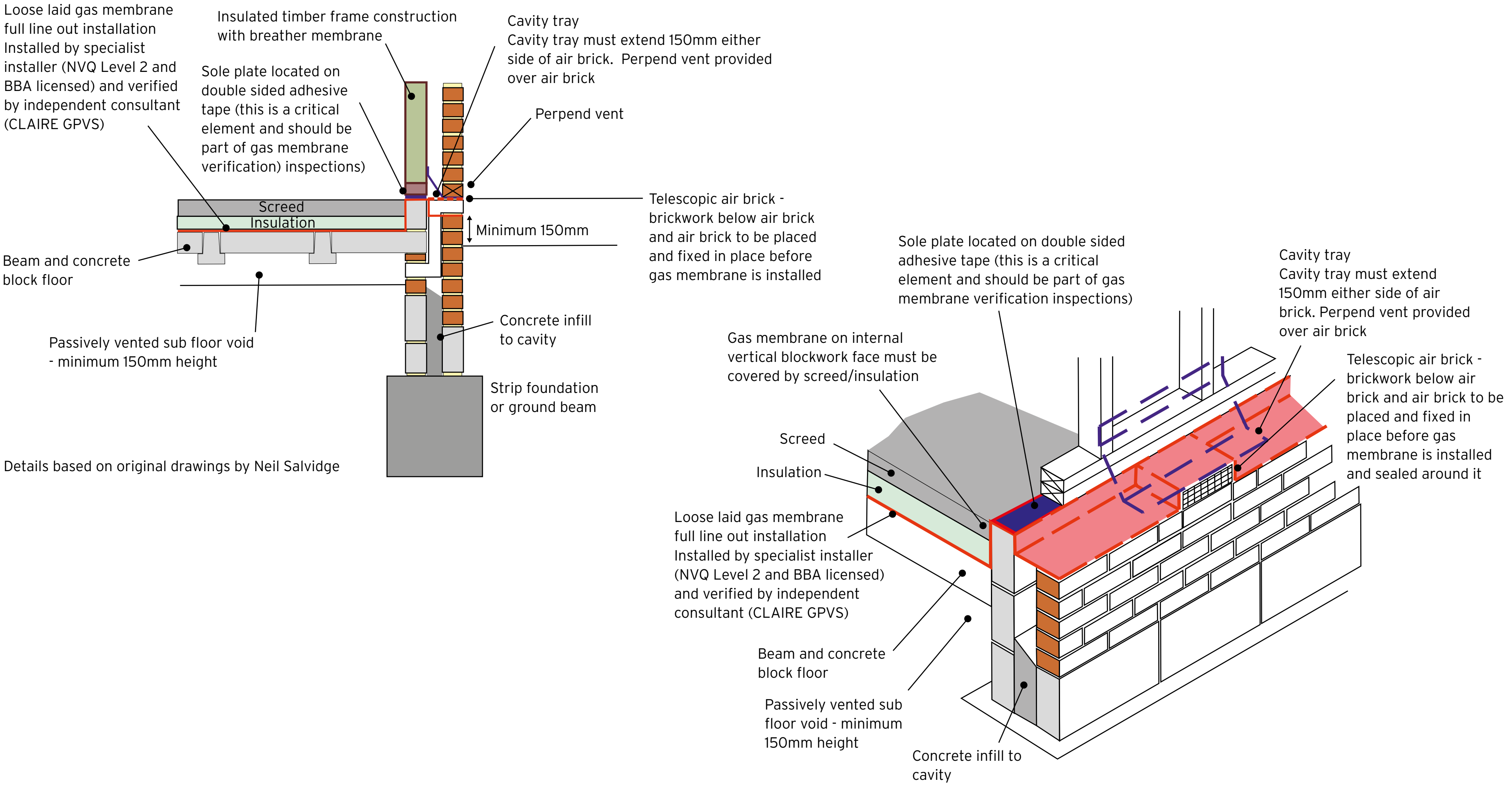
Timber frame should ideally be fixed to block work above gas membrane to avoid fixing through it.

Timber frame sole plate is not to be trimmed after installation over the gas membrane.

Figure C16 Timber frame - block & beam floor

Timber frame sole plate fixed through gas membrane. Sole plate located on strip of double sided self adhesive tape. Note the use of double sided tape and acceptable fixing thorough it should be included as an item in the verification plan. Verification is required.

Timber frame sole plate is not to be trimmed after installation over the gas membrane



Details based on original drawings by Neil Salvidge

Figure C17 Timber frame - Block & beam floor

Detail 12 – Timber frame – cast in situ suspended floor (Figure C18)

- All structural timber should be located at least 150mm above finished external ground level, except for localised ramping (incorporating satisfactory drainage and ventilation detailing) for level threshold requirements
- Wherever possible the fixings for the timber frame sole plate should not pass through the membrane.
- Where this is not possible the fixings should be gas tight. Sealing can be most effectively achieved by placing a layer of self adhesive membrane below the sole plate and shot firing fixings through it
- Where an appropriate air tight breather membrane is installed to be air tight on in the internal face of the cavity and there is also venting of the cavity at the top and bottom, the gas membrane does not need to pass across the cavity for methane and carbon dioxide CS2 and CS3 sites (this may also be the case for VOCs and radon based on a site specific risk assessment)
- Breather membrane to have an air permeability <1m^3/m^3/h@50Pa tested in accordance with BS EN 12114
- Cavity ventilated top and bottom using perpend vents. Lower row below the lowest timber level. Maximum spacing 1200mm horizontally. Minimum vent area of 500mm^2/m of wall and maximum of 1500mm^2/m of wall (slightly ventilated in accordance with British Standard BS EN ISO 6946)

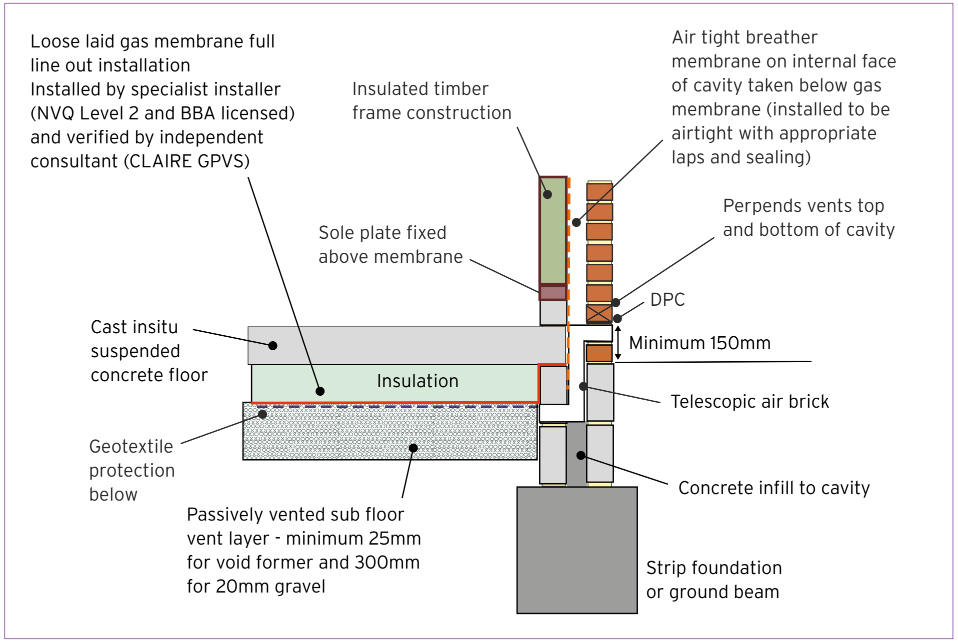
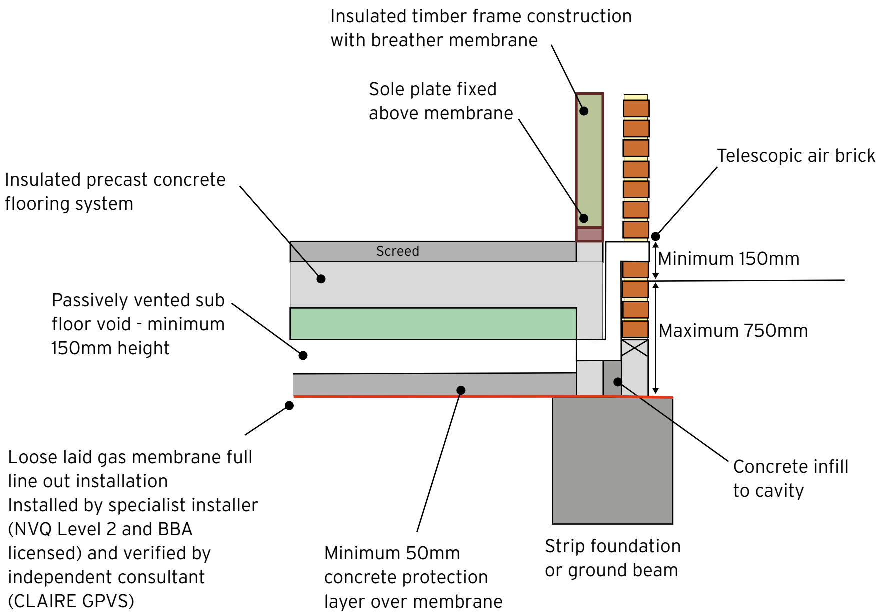


Figure C18 Timber frame - cast in situ suspended floor

Detail 13 – Timber frame and Insulated pre-cast concrete flooring system (IPCFS) (Figure C19).

- The best position for the membrane is below the ventilated void
- This avoids having to detail the membrane through the cavity and possibly sealing around air bricks
- It also removes the membrane from a position above the slab where it can be damaged by the timber frame installers

IPCFS with timber frame construction



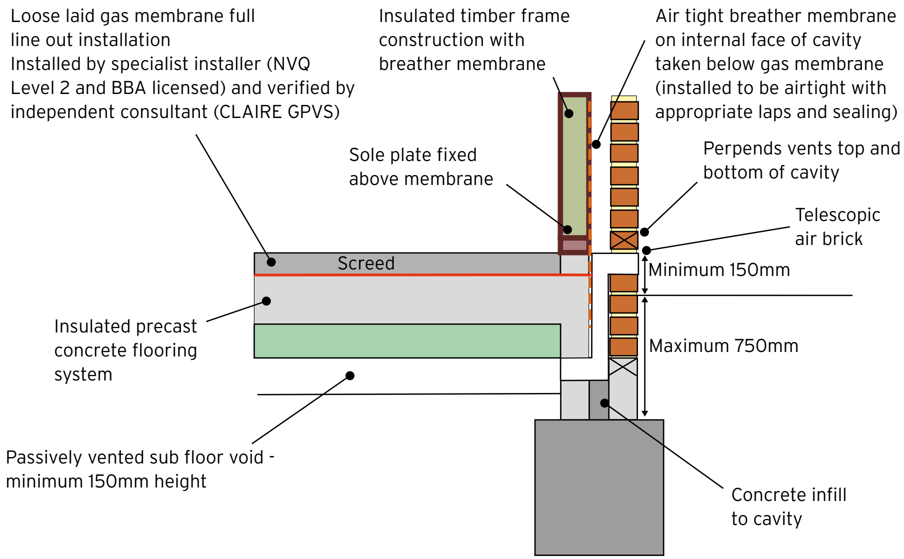
Timber frame is fixed to the floor above gas membrane to avoid fixing through it.

Figure C19 Timber frame and Insulated pre-cast concrete flooring system (IPCFS)

Detail 14 – IPCFS with timber frame construction and airtight breather membrane (Figure C20).

- Alternatively the membrane can be placed over the top of the floor without spanning the cavity where an appropriate air tight breather membrane is installed to be air tight on in the internal face of the cavity and there is also venting of the cavity at the top and bottom. This applies for methane and carbon dioxide CS2 and CS3 sites (this may also be the case for VOCs and radon based on a site specific risk assessment)
- Breather membrane to have an air permeability <$1m^3/m^3/h$@50Pa tested in accordance with BS EN 12114
- Cavity ventilated top and bottom using perpend vents. Lower row below the lowest timber level. Maximum spacing 1200mm horizontally. Minimum vent area of $500mm^2/m$ of wall and maximum of $1500mm^2/m$ of wall (slightly ventilated in accordance with British Standard BS EN ISO 6946).

IPCFS with timber frame construction and air tight breather membrane



Timber frame is fixed to the floor above gas membrane to avoid fixing through it.

Figure C20 IPCFS with timber frame construction and airtight breather membrane

C.3.7 Standard details – Particular situations.

Detail 15 – Lift pits (Figure C21).

- Lift pits to multi story residential apartments are normally sat on a thick foundation slab that will be gas resistant. Thick pile cap concrete >500mm depth is also gas resistant.
- Simplified details avoid unnecessary complex detailing by avoiding sealing below pile caps and other thick concrete structures.
- The precise method of sealing to the sides of the pit and pile caps or foundation will depend on the construction sequence and shuttering used. A minimum of 300mm seal onto the top/side of the foundation will be required where a precast lift pit is being sealed.
- Self adhesive membrane should not be left unsupported for extended periods or it will peel. If it has to be left unsupported provide physical support (eg battens)
- Note that waterproofing requirements may dictate additional elements to be provided over and above those required for gas resistance

Typical lift pit detail for CS2 and CS3 sites

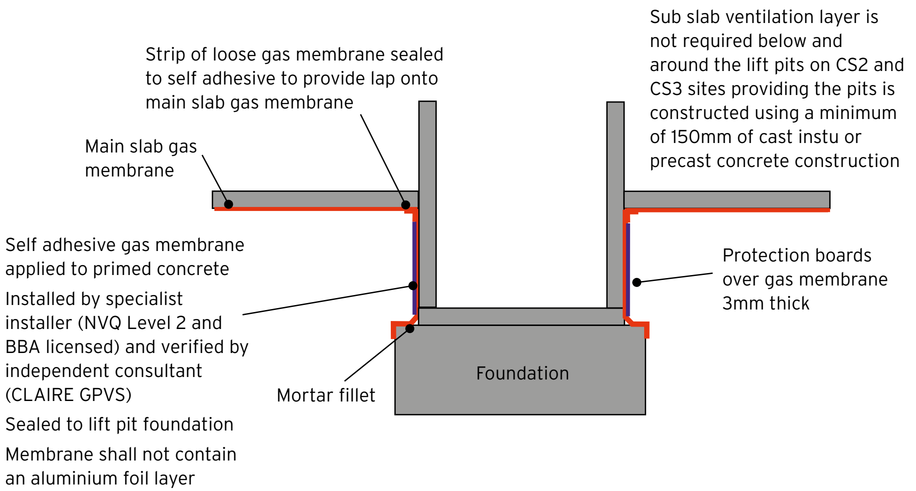


Figure C21 Lift pit detail

Detail 16 – Floor slab / pile cap (Figure C22).

- Pile caps >500mm thick to multi story residential apartments are normally thick reinforced concrete that will be sufficiently gas resistant for CS2 and CS3 sites.
- Simplified details avoid unnecessary complex detailing by avoiding sealing below pile caps and other thick concrete structures.
- The precise method of sealing to the sides or top of the pile caps will depend on the slab/pile cap interface design and the construction sequence and shuttering used. Normally a minimum 500mm seal of the membrane down the side of a pile cap is provided.
- Note that waterproofing requirements may dictate additional elements to be provided over and above those required for gas resistance

Floor Slab/Pile Cap Detail

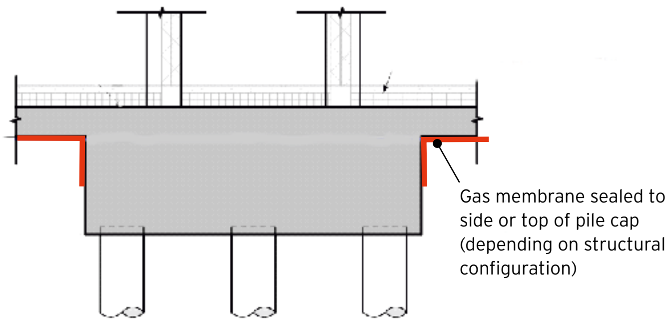


Figure C22 Floor slab / pile cap detail

Detail 17 – Pipe and other penetration sealing (Figure C23).

- Seal using self-adhesive membrane. This is the most common form of sealing where there is no risk of movement of the gas membrane (e.g. settlement)
- The service penetrations must be adequately spaced from each other and from walls to allow the gas membrane to be installed (100mm clear space around the pipe)
- Where settlement is an issue use top hats and physical fixing in addition to sealant or self-adhesive (e.g. jubilee bands).

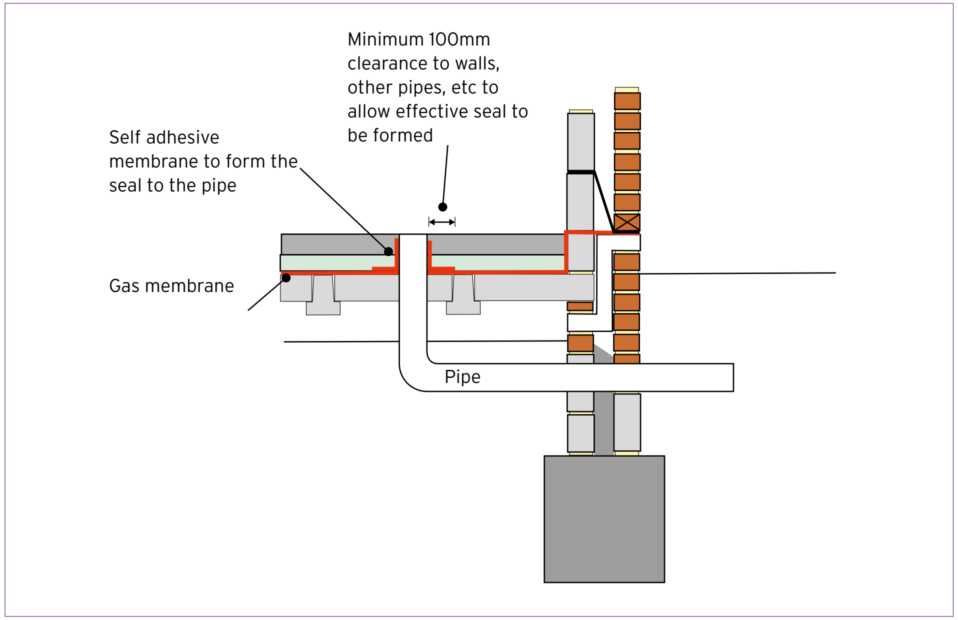


Figure C23 Pipe (and other penetrations) detail

Detail 18 – Service duct internal sealing (Figure C24).

- Seal using expanding foam and liquid applied gas membrane (Electric cables and water pipes in some areas)
- Note in some areas water companies believe that expanding polyurethane foam will degrade water pipes (this is not the case) and will not permit its use.

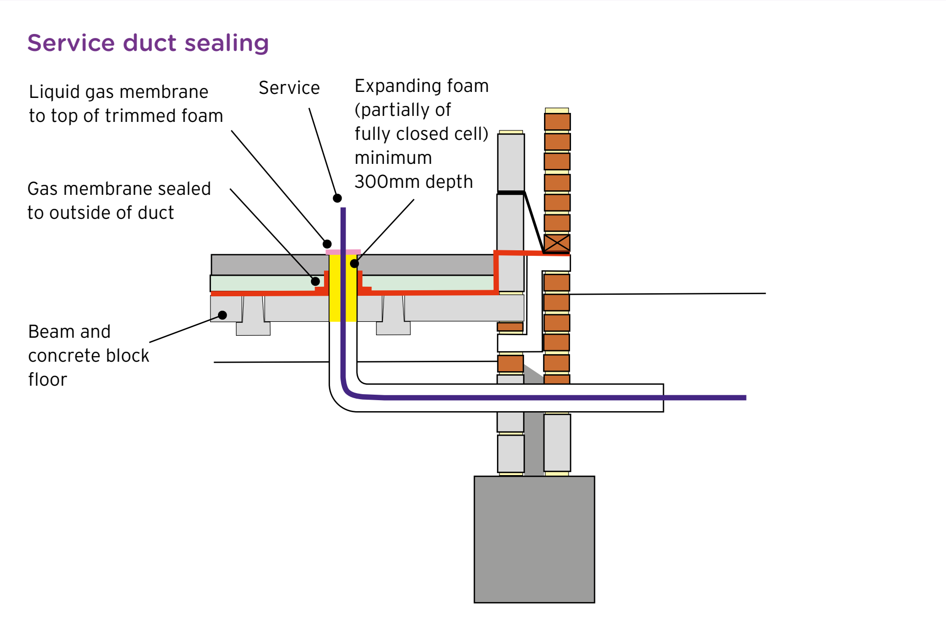


Figure C24 Service duct – internal sealing detail

Detail 19 – Service duct internal sealing – alternative for water pipes (Figure C25).

- Alternative seal using a system approved by water and sewerage companies for use around water pipes

Service duct sealing - alternative for water pipes

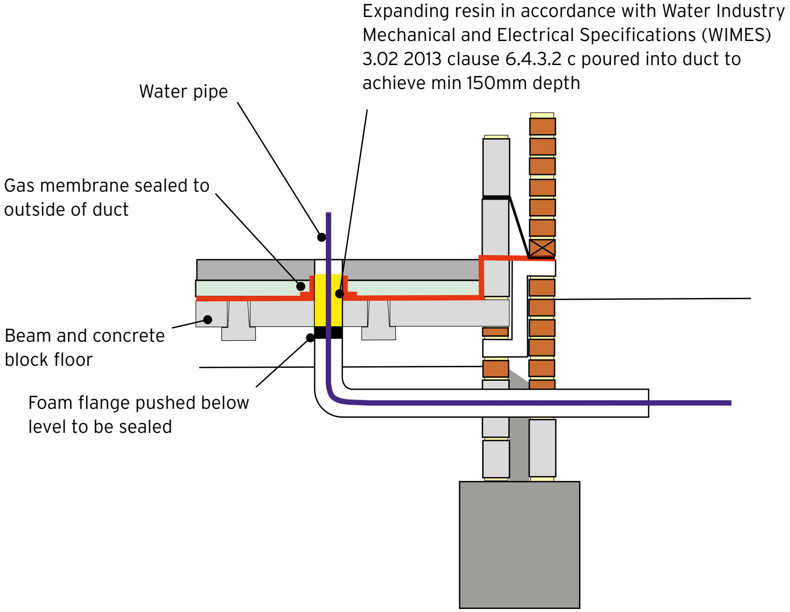


Figure C25 Service duct sealing - alternative detail for water pipes

Detail 20 - Wall between house and garage (Figure C26)

- Ensure that both vertical and horizontal continuity in the membrane is achieved at the change of level (see 3D detail for change of level below)
- Ensure continuity of cavity tray

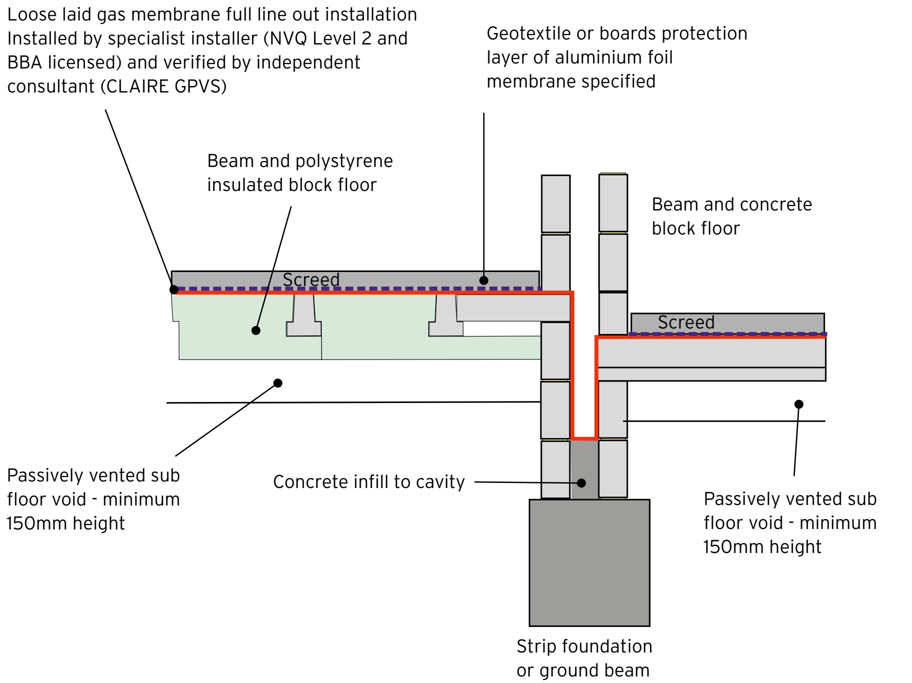


Figure C26 Wall between house and garage detail

Detail 21 – Level threshold (Figure C27)

- Ensure that both vertical and horizontal continuity in the membrane is achieved at the threshold
- Ensure continuity of cavity tray at the edges both vertically and horizontally

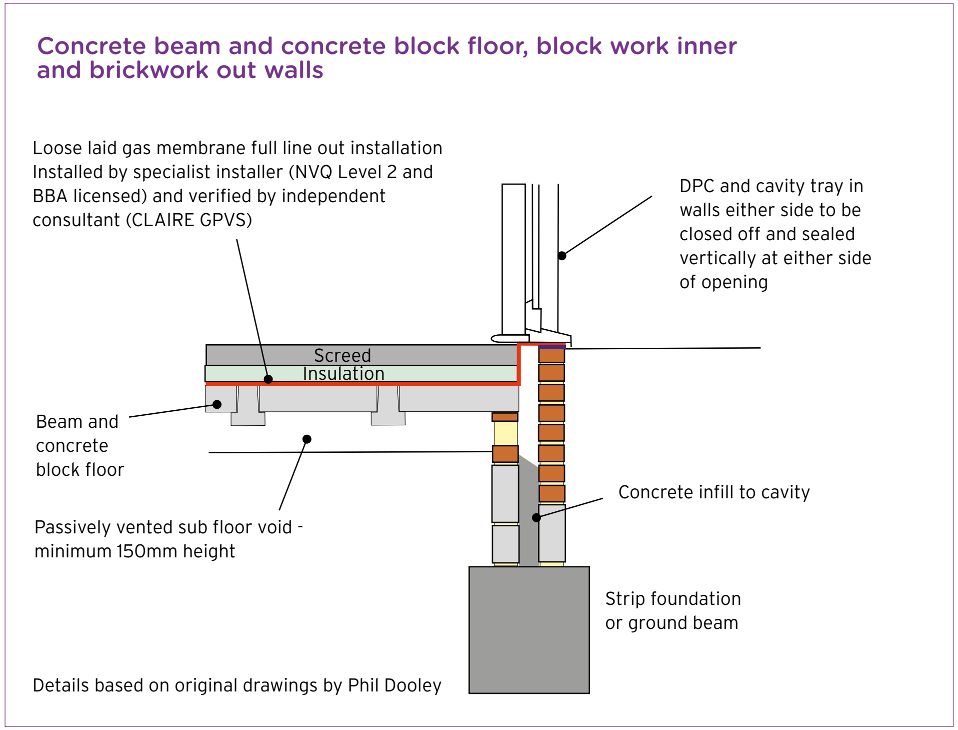


Figure C27 Level threshold detail

Detail 22 – Change of level (Figure C28 and Figure C29)

- Changes of level details are complex at the external wall junction. It is essential that at such junctions a site/building specific 3D drawing of the proposed gas membrane installation is provided by the gas protection designer.
- Ensure that both vertical and horizontal continuity in the membrane is achieved at the change of level (ie gas cannot track horizontally along the cavity from the high level to the low level above the low level cavity membrane).
- Ensure continuity of cavity tray both vertically and horizontally
- Provide suitable drainage perpends and also ensure damp protection of timber frame construction (for timber frames consider whether waterproof concrete wall construction and an external membrane behind the retaining wall would be a better solution).

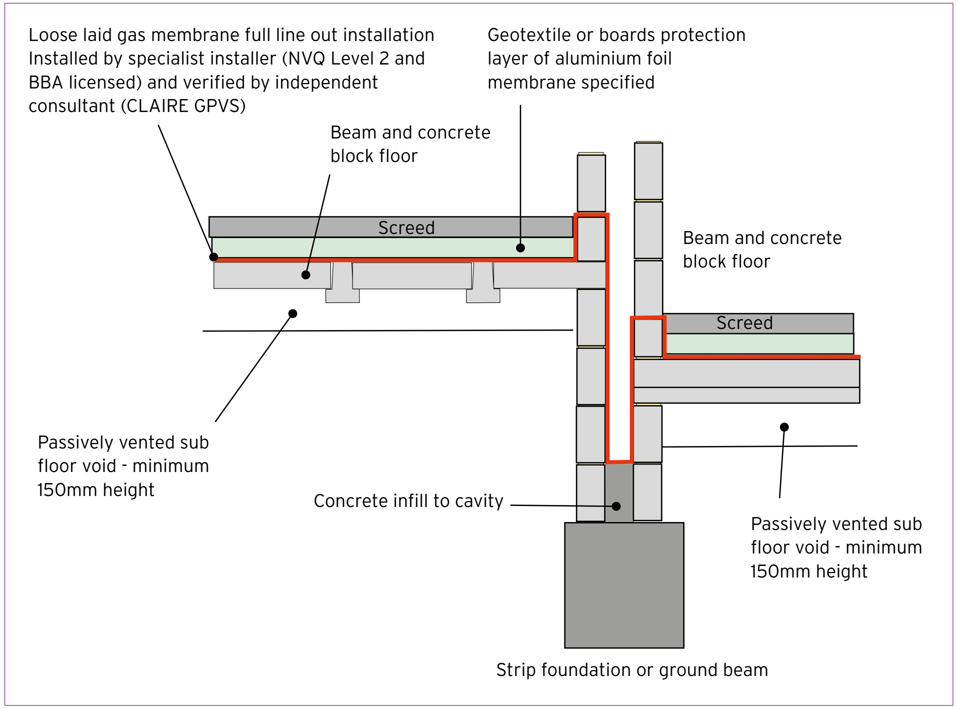


Figure C28 Change of level detail

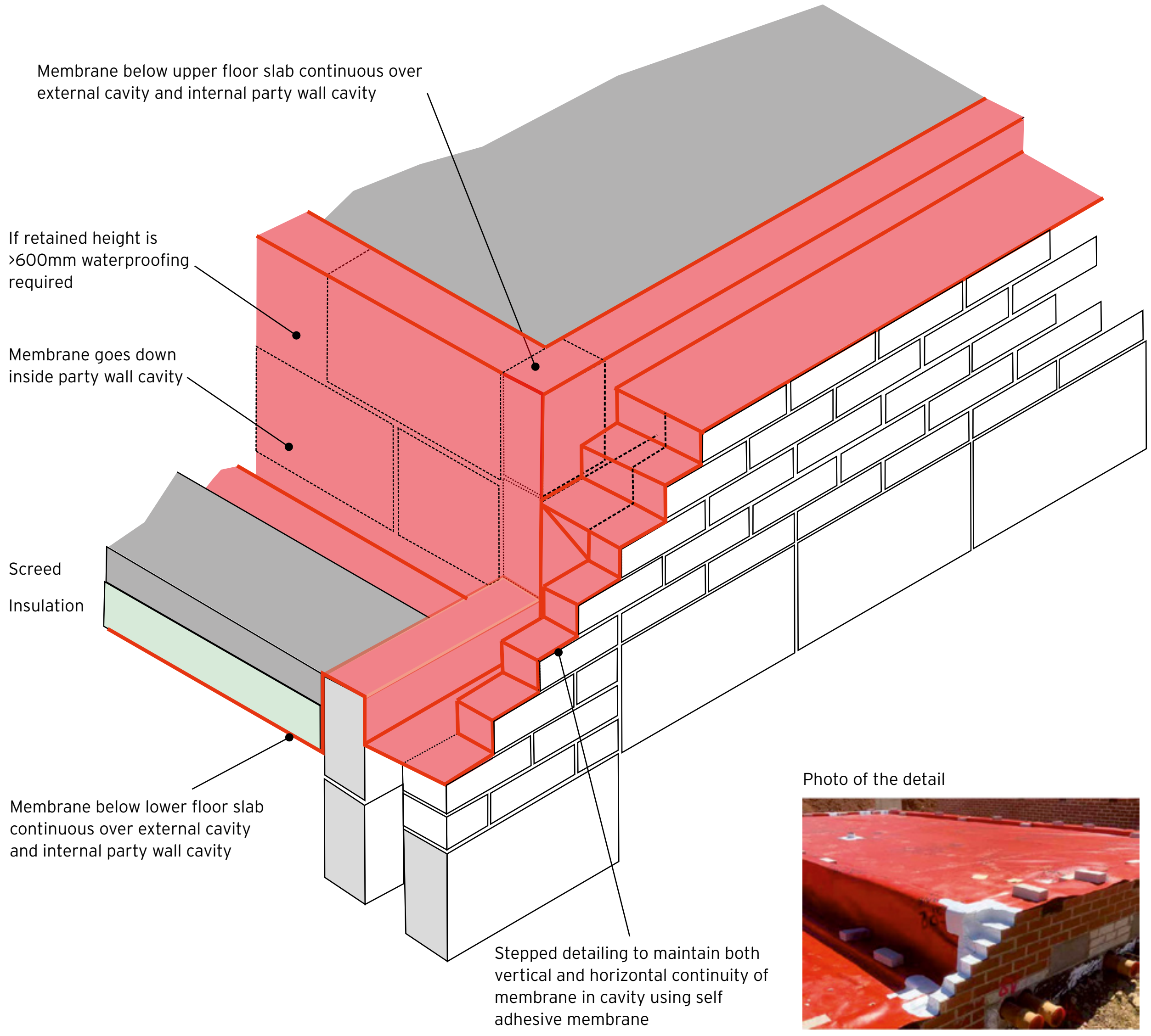


Figure C29 Change of level

Appendix D - Example ventilation calculations

Example calculation for open and clear ventilated sub floor void

Passive ventilation below buildings is designed to use wind effects on the sides of buildings to ventilate an underfloor void. It is also known as natural ventilation and with the increasing emphasis on energy efficiency in buildings it is the preferred option wherever possible (as opposed to systems that use active fans). The wind develops pressure and suction (Figure E-1) that drives fresh air through the void, thus diluting the gas emissions so they can be safely dispersed to the atmosphere.

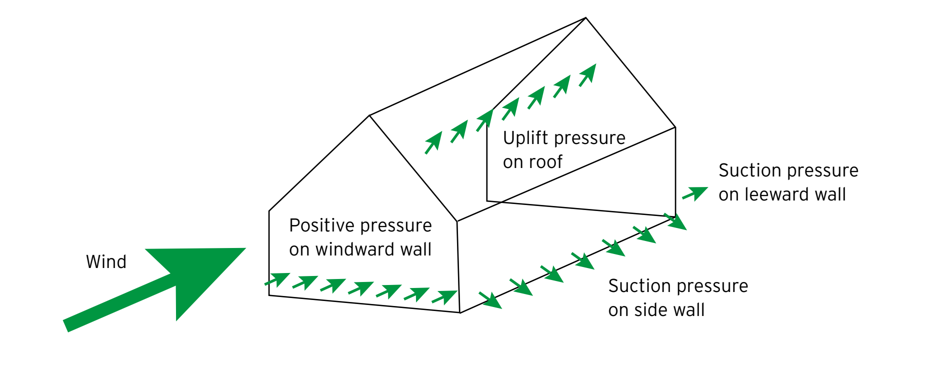


Figure D1 Wind pressure on building

The effect of differential temperatures between the outside air the underfloor void is ignored. In practice this can induce significant air flow and so provides an in built factor of safety in the design.

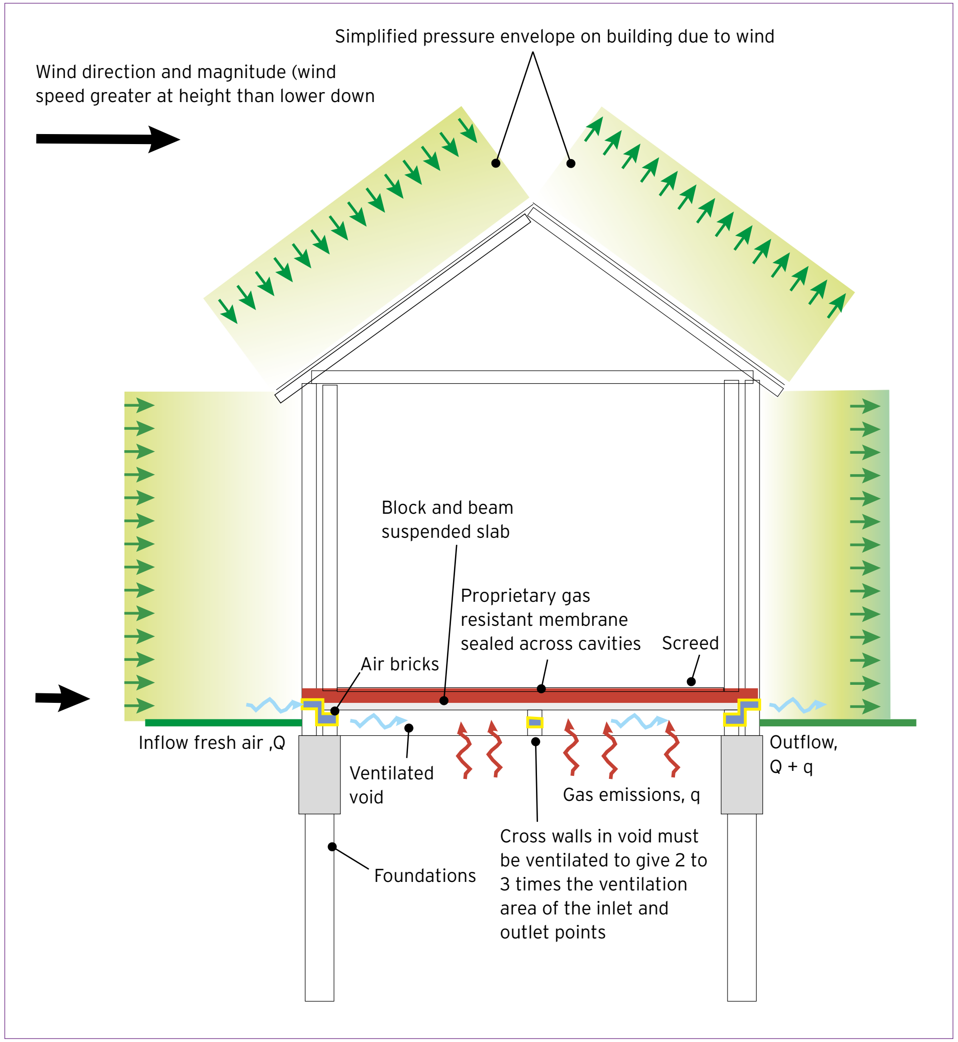


Figure D2 Calculations for an open sub floor void

STEP 1 Calculate fresh air flow required to dilute gas to design concentration

The fresh air flow, Q, required to dilute the gas emissions, q, in the void to a defined level can be estimated using the following equation from CIRIA Report 149.

Fresh air flow required (total under whole building), Q is given by:

$$Q = q\{(100-C_e)/C_e\}$$

Where:

q = surface emission rate of gas from the ground (total under whole building) – See Section 4.

C_e = equilibrium gas concentration in the void (in this case expressed as the % value not the mathematical value ie for 1% use 1 in the equation rather than 0.01).

Assume the surface emission rate of methane, = 0.35 l/h/m² (this is the limit for CS3 based on the Pecksen corelation from HGFR to surface emission rate)

Convert this to m^3 = 0.35/1000 = $3.5 \times 10^{-4} m^3/h/m^2$

Building is 6m wide by 30m long

So total surface emission rate of gas into void,
q = 6m x 30m x $3.5 \times 10^{-4} m^3/h/m^2$ = $0.063 m^3/h$

Required design concentration is 1% v/v of methane in the void and at outlets

Design fresh air flow rate required,

Q, = $0.063 m^3/h$ x [(100 – 1)/1] = 0.063 x 99 = **$6.2 m^3/h$**

The design of the ventilation system must provide this volume of air flow to provide sufficient dilution of the gas emissions. This applies to open void or void former systems.

STEP 2 Air brick vent area and spacing for an open void

The approach described in BS5925: 1991 is used to determine the necessary ventilation area and spacing of air bricks.

Determine the ventilation required for a housing development up to three storeys high located on the coast in Southampton. The height of the vents is 0.15m and the height of the building is 7m. The required flow of fresh air through the void is $6.2 m^3/h$ for a building that is 6m wide and 30m long. The underfloor void is 200mm high and the surface emission rate is $3.5 \times 10^{-4} m^3/h/m^2$

STEP 2.1 Reference wind speed

From Figure 5 in BS 5925: 1991 Code of practice for ventilation principles and designing for natural ventilation

Hourly mean wind speed, U_{50} 4.5m/s (measured at 10m height in open terrain)

Determine correction ratio from Table 9 of BS5925

Allow for the design wind speed being exceeded 80% of the time (ie this is the worst case value and gives the highest confidence that the passive system will operate) and consider an exposed coastal location.

So factor = 0.56

$U_m = U_{50}$ x 0.56 = 4.5 x 0.56 = **2.52m/s**

Determine factors K and a from Table 8 in BS5925 to allow for height of vent and nature of surrounding terrain.

Assume an urban environment so K = 0.35 and a = 0.25. These factors amend the mean hourly wind speed to allow for differing terrain and different heights. The pressure on the side of the building is governed by the height of the building but to be conservative in this case use the height of the vent as the design height.

Therefore reference wind speed $u_r = u_m \times K \times z^a$ (Where z = height of vent)

= $2.52 \times 0.35 \times 0.15^{0.25}$ = **0.55m/s**

The reference wind speed can also be used to estimate the driving pressure applied to a void former (eg geocomposite, polystyrene vent layers, gravel layer or pipe sin gravel) in the analysis of air flow through the void former.

Step 2.2 Vent area

Calculate required vent A_w area to give flow of fresh air, Q

Assume the discharge coefficient for a narrow opening, C_d =0.61, which is a typical value for narrow openings from BS 5925: 1991. (This is a factor that correlates theoretical performance to actual performance)

The orientation of buildings is not known so use a pessimistic value of ΔC_p

ΔC_p =0.4

Note for simple airbrick vents or similar there is usually some suction or pressure on the wall, regardless of wind direction. This is allowed for by using a very low value of ΔP, typically 0.4 to 0.6

Area of ventilation required for whole building, A_w, is calculated using the following equation from BS 5925: 1991

$$A_w = \frac{Q}{U_r \, x \, C_d \, x \sqrt{\Delta C_p}} \text{ x } 10^6$$

Q = 6.2m³/h and needs to be converted to m³/s = 6.2/3600 = 0.0017m³/s

$$= \frac{0.00017}{0.55\text{x}0.61\text{x}\sqrt{0.4}} \text{ x } 10^6$$ = **8012mm²** (note the factor 10^6 is to convert m² to mm²)

This is the total vent area along one long side of the building (the same area needs to be provided on two opposing sides).

It has not been normal practice in ventilated void design to increase the vent area to allow for reduced effective vent area for vents in series (multiple pairs of vents located on opposing walls), as described in BS 5925: 1991, which would increase A_w by a factor of 1.4 in most cases. This is because the flow of air through a relatively small underfloor void with vents located at relatively frequent regular intervals is similar to airflow through a network of parallel pipes. The total air flow through the underfloor void is the sum of the flow through the individual pair of vents (on opposing sides of the building), but the overall pressure and friction loss is the same as that through any one pair of vents. Thus there is little or no reduction in effective vent area as a result of vents in series.

Step 2.3 Air brick spacing

This is equal to 8012 mm²/30m = 267mm²/metre. This is less than the minimum venting area required in the Building Regulations of 1500mm²/metre so therefore the minimum vent area should be provided. This can be achieved by using normal air bricks with a vent area of 6000mm² at 4m centres (subject to detailed design to ensure even air flow across the void – typically this requires air bricks at 2m centres).

This step is part of the calculation for void formers to ensure that the inlets and outlets have sufficient area so that they do not impede air flow.

Step 3 Time to fill void

Check the time taken to fill the void to 5% methane if there is no wind.

Time to fill to 5% methane = (Volume of void x 5%)/Surface emission rate of gas below building.

The plan area is 6m by 30m and volume of void is 6 x 30 x 0.2 = 36m³.

Time to fill = (36m³ x 0.05)/(3.5 x 10-4m³/h/m² x 6m x 30m) = **28 hours**.

This is greater than the maximum period of still wind of 10 hours reported in the Partners in Technology report and so is acceptable.

Appendix E - Sealing of membranes

E.1 Sealing of penetrations

Step 1	Step 2	Step 3
Prepare the surface of the pipe or other penetration by making sure it is clean and free of debris, oil, etc; 	The base membrane should be carefully cut tight to fit around the pipe penetration (with a slight lip upwards) and so that there is no creasing in the surrounding base membrane.It should require effort to push the membrane down over the pipe 	If necessary prime the pipe, duct or column, etc as recommended by the supplier of the gas resistant self adhesive membrane (on surfaces such as metals, concrete, etc). This is not necessary for plastic pipes.

Images credited to JUTA UK Ltd and Neil Salvidge

Step 4	Step 5
For a 150mm pipe cut a 300mm by 300mm square piece of GRSAM with a 150mm dia hole at the centre. This should also be a snug fit to the pipe as shown in the photo – do not install at this stage – it will be installed later. 	Cut 100mm wide strips of GRSAM that are 150mm long (75mm adheres to the pipe and 75mm adheres to the base membrane. Preheat the GRSAM to activate the bitumen adhesive in the membrane. Apply the first strip to the penetration first and then fold it down to the base membrane and seal it, ensuring there is no void below it at the base. Sealing should be completed using the heat gun and roller. 

Images credited to JUTA UK Ltd and Neil Salvidge

Step 6	Step 7
Apply subsequent strips overlapping the previous on by 25mm, until the seal is complete all around the penetration. 	Take the 300mm square with the hole cut in it and locate it over the penetration and strips of GRSAM and seal to base membrane with heat and roller. Apply pressure to the GRSAM while continually applying heat to make sure it adheres to the base membrane and the penetration. 

Images credited to JUTA UK Ltd and Neil Salvidge

E.2 Sealing of corners

Corners can be formed using heat sealed joints and appropriate cutting of the membrane. The corner is then finished using self-adhesive membrane. The process is as follows:

Step 1

The base membrane is carefully and neatly cut to allow it to be folded tight into the corner with no voids below it – especially at the bottom. There must be enough membrane to pass across the cavity and external leaf of bricks.

Step 2

The membrane over lap is sealed using heat gun and pressure applied from the roller.

Step 3

The corner is reinforced using a preformed corner unit or by using self-adhesive gas membrane. The preformed corners can be heat sealed or can be made from self adhesive gas membrane. The example in the photo is sealing using sheet self-adhesive membrane. A 150mm by 150mm square is inserted into the corner after preheating and is sealed using heat and a roller.

Images credited to JUTA UK Ltd and Neil Salvidge

Step 4	Step 5
A self adhesive upstand is applied over the corner. And cut to that it fits neatly over the base membrane. It is again sealed using heat and a roller to apply pressure. 	A top cover section of self-adhesive is applied using heat and pressure from the roller. 

Images credited to JUTA UK Ltd and Neil Salvidge

Step 6		
A bottom cover section is applied using heat and pressure from the roller.		

Images credited to JUTA UK Ltd and Neil Salvidge

Appendix F - Example Verification Plan

Membrane installation: Specialist installer requirements

The appointed specialist installer for the gas membrane will need to demonstrate that a minimum of one on-site operative holds an NVQ Level 2 Qualification in Gas Protection Installation.

It is the responsibility of the specialist installer to:

- in advance of site works commencing, provide an **Installation Plan** for the gas mitigation measures;
- provide sub-grade acceptance forms for all areas of membrane installation; and
- complete QA sign-off sheets for all areas of membrane installation.

Concrete floor: Flooring contractor requirements

The flooring contractor must ensure that the requirements of design and this verification plan are met.

In addition, the flooring contractor is to confirm that the faces between pours have been adequately cleaned and scabbled, and that all concrete is placed in accordance with the specification (by others).

Records of the above can be provided via a combination of inspection reports, QA documentation and a photographic record (location referenced photos).

The flooring contractor is also to provide concrete supplier's QA sheets (mix design and QA tests).

Verification contractor requirements:

The appointed Verification Contractor for the site will need to be suitably trained and submit a statement detailing their qualifications, independence and relevant experience, a copy of which is to be included in the **Verification Report** for the site. The Verification Consultant is to be a CL:AIRE Accredited Specialist in Gas Protection Verification and will be required to provide a CL:AIRE Declaration under the Gas Protection Verification Scheme for each report.

The company completing the verification will provide detailed method statements for the work (**Verification Method Statements**).

On completion of all the verification works on all parts of the system the verification consultant shall prepare an overall **Verification Report** for the whole gas mitigation system. This shall, as a minimum, include the completion inspection records detailing the site areas inspected, sign-off records, quality of workmanship, equipment calibration records, membrane type, membrane detailing, integrity testing methods, non-conformances and repairs, as well as good resolution photographs and any matters requiring further investigation and/or rectification.

It is also the responsibility of the Verification Contractor to:

- conduct a visual inspection of the ventilated void and air bricks and confirm it is in accordance with the design drawings. Provide location referenced example photos
- conduct a thorough visual inspection of 100% of the membrane area prior to it being
- ensure 100% of all joints / penetrations of the membrane are subject to mechanical point stress testing ('pick testing') in accordance with the ASTM D4437-08:2013
- verify that the ventilated void has been provided to the design height
- verify that the air bricks have been installed at the locations specified in the design drawings
- present verification evidence of the above (together with the information provided by the Specialist Installer, see above) in the form of a **Verification Report**.

Service ducts: Developer requirements

The Developer is to provide confirmation that the internal annulus of any open portion of any service duct annulus has been sealed in accordance with the design drawings. Location referenced photos to be provided of all seals.

Final ground levels at airbricks: Developer requirements

The Developer is to provide confirmation of the placement of airbricks with reference to finished ground levels after completion of landscaping works to ensure theses have not been obscured. Location referenced photos to be provided.

Hold points in the process

The main contractor or developer has responsibility for ensuring that appropriate verification is done at the right times in the process. Hold points in the construction process have been determined, these are an important element in the Verification Plan as overlying construction should not proceed until the main contractor or developer has written confirmation that verification or QA sign off has been completed and that element of gas mitigation system is acceptable before it is covered up or the development occupied.

The hold points for the construction at the site comprise:

- verify depth of sub-floor void and spacing of vents/air bricks
- placement and sealing of the gas membrane across the entire building footprint
- placement of the geotextile protection fleece above the membrane
- hold points during concrete slab construction to be determined by structural engineer, but to include as a minimum: Inspection of reinforcement and formwork (including supports to both) prior to concrete pour to ensure gas membrane is not punctured
- sealing of service ducts (prior to occupation)
- ground level checks at airbricks (prior to occupation).

NHBC FOUNDATION

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