Good Practice for Risk Assessment for Coal Mine Gas Emissions

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Web: www.claire.co.uk Email: enquiries@claire.co.uk

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Authors

Steve Wilson, Environmental Protection Group / STRi Group Limited

Dr. Tom Henman, RSK Environment Limited

Alex Lee, WSP UK Limited

Richard Meredith, GeoEnvironmental Consulting Ltd

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Disclaimer

Preface

This document provides advice that could be regarded as essential reading towards understanding coal mine gas risk assessment. The intended audience of this document is those involved in commissioning and undertaking mine gas risk assessments to support proposed development, and local authority officers involved in regulating development management through the planning or building control regimes.

The decisions that underlie an assessment of coal mine gas risks should be reported in a transparent manner. In choosing the best approach a practitioner must be well-informed about mine gas risk and risk communication. Practitioners should seek to acquire as full an understanding as practicable of the potential issues and limitations of their data, together with those of the methods available for its assessment. Critical thinking is required in such assessments in order to improve the quality. Critical thinking is the process of independently analysing, synthesising, and evaluating information (Hughes and Lavery, 2014). The critical thinker is diligent in seeking relevant information, reasonable in the selection of criteria, adopts focused inquiry, and is persistent in seeking results which are as precise and accurate as the subject and the circumstances of inquiry require.

This document is a collation of current understanding of coal mine gas risks and seeks to assist in the formulation of appropriately robust mine gas risk assessments in the UK. Its contents cannot be considered as definitive, and the reader may wish to use additional methods to those presented. However, consideration of the guidance contained in this document and following the assessment procedures outlined, would demonstrate the reasonable practice and care expected of professional assessors.

Furthermore, proportionate resources should always be applied when delivering any risk assessment. Consequently, it is strongly advocated that on those occasions where potentially complex mine gas risks are present, a discrete and more detailed assessment is considered. Whether this is standalone or contained as a section of an existing report, the expectation is for greater transparency of decision making. In summary, purposeful reflective judgment is required that must be well-informed, clearly described and proportionate to the problem. This document consequently seeks to inform, provide a decision framework and present those factors an assessor would be expected to have considered if delivering with standard good practice.

Steve Wilson and Alex Lee are Society of Brownfield Risk Assessment Fully Accredited risk assessors for permanent gases and vapour intrusion (ASoBRA).

Tom Henman and Richard Meredith are registered Specialists in Land Condition (SiLC) and Suitably Qualified Persons (SQP) under the National Quality Mark Scheme.

All have many years' experience of assessing mine gas risk.

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1. Introduction

A well-publicised incident in Gorebridge (located in Midlothian, Scotland) in 2013/14 highlighted that in certain circumstances, gas ingress to residential buildings from mine workings can occur and potentially pose risks to human health (NHS Lothian, 2017). Research commissioned by the Scottish Government into the wider prevalence of similar cases (RSK Stirling, 2019) found a small number of incidents in Scotland, the rest of the UK and beyond since the 1950s. The research also identified that current standards and guidance on ground gas are limited in their coverage of specific factors affecting mine gas risks and recommended that these be supplemented. This guidance is intended to highlight some of the issues relating to mine gas risk assessment for development, signpost existing information and promote good practice.

The Gorebridge incident also highlighted the importance of integrating reasonably foreseeable change into the mine gas risk assessment process. For sites where potentially significant sources of mine gas are present, the risk assessment should be seen as a live document until the proposed design is fixed and off-site factors such as climate change and regional groundwater conditions are understood as far as possible. This document provides examples of what reasonably foreseeable change could look like and provides advice on how these factors should be incorporated into the assessment at appropriate times.

This guidance is principally concerned with the risk assessment of gas emissions from former coal mine workings in the UK (United Kingdom of Great Britain and Northern Ireland). However, there are many other forms of mines that could potentially result in emission of gas from the ground, for example oil shale, metalliferous and rock mining (CIRIA, 2019). The principles discussed in this report could be applied to other types of mines as well as beyond the UK context (although compatibility with non-UK jurisdictions has not been checked). It should also be noted that the Coal Authority does not hold information or define coal mining reporting areas for Northern Ireland.

> The term 'mine gas' used in this report specifically refers to 'coal mine gas' with the principal components being methane, carbon dioxide, carbon monoxide, hydrogen sulfide and deoxygenated air.

The presence of a development over coal workings or areas of non-coal mining, does not necessarily mean that there are risks due to gas emissions. There are specific circumstances when mine gas can pose a significant risk (acute or chronic) to development and this document describes how to identify when gas mitigation measures are likely to be required (in buildings) or not. If emissions do occur into buildings, the consequences can range widely from mild to severe health effects or even death. All recorded acute and chronic incidents have been caused by gas emission from open mine entries (shafts or adits) or from shallow mine workings combined with an open or highly permeable pathway for gas migration to the surface (deep workings may also be connected to shallow workings by shafts or adits). The same also applies where reported chronic and acute effects from other sources of methane and carbon dioxide have been reported, i.e. there needs to be a highly permeable pathway for gas to migrate along and a large volume of gas that can move freely (such as found in open workings and entries)

(Card *et al.*, 2019). This document describes these credible pathways and the impact of foreseeable events, including changes in groundwater level, climate change and changes to the conceptual site model (CSM) caused by development itself. It also considers how to address uncertainty in mine gas risk assessments and suitable application of the precautionary approach.

BS 8485:2015 + A1:2019 (British Standards Institution, 2015) and other ground gas-related standards and guidance emphasise the critical importance of the CSM. BS 8485 also recommends the use of detailed quantitative assessment of gas emissions in appropriate situations, such as sites with moderate to high gas hazards (as defined by the standard) or where buildings have complex foundations. This includes situations where mine gas may be present. The assessment of mine gas risk should not rely solely on gas monitoring data from boreholes, and it is important to have a robust assessment process that is followed by competent risk assessors who have experience in this field. There is the potential that coal mine gas risk assessments conducted by unqualified and inexperienced practitioners who place too much reliance on limited gas monitoring data without proper reference to an appropriately developed site specific CSM can result in significant underestimates (or overestimates) of the actual risk present.

It is also evident that a blanket assumption that mine gas risk is high for all buildings across all coalfields can have a detrimental impact on people selling existing houses that do not have gas protection installed. Such a potential for blight is causing anxiety and stress to those people involved in some cases and is a further reason for showing that an informed approach to mine gas risk is required. The blanket application of gas mitigation measures to all new development in coalfield areas would similarly be unnecessarily discouraging, and costly. Such an approach might also be either insufficient or too precautionary depending on the minimum standard applied to mandatory gas protection measures. The Scottish Government research report considers these issues in more detail (RSK Stirling, 2019).

There are several existing documents that provide advice either on mine gas risk or factors that may influence mine gas risk (see Chapter 7). This document pulls together the specific information relating to mine gas risk and highlights the most important considerations. It shows how the information from the existing documents can be used in an overall risk assessment framework that is not provided in any of the other documents. It should help assessors provide a consistent approach to mine gas risk assessment that sets a benchmark that is acceptable to regulators and clients.

2. Overall Risk Assessment Process

The overall risk assessment process for mine gas follows the broad framework provided by the UK government on land contamination risk management (LCRM[1]) (Environment Agency, 2020). The Coal Mining Reporting Area (also known as CON29M Coal and Brine Consultation Areas) is the known extent of coal mining activity and is used to determine whether a coal mining report is required for property transactions and the conveyancing process. The coalfield is divided into two areas, referred to as Development High Risk Area and Development Low Risk Area:

- the High Risk Area (15% of the coalfield) is where coal mining risks are present at shallow depth which are likely to affect new development; and
- the Low Risk Area (85% of the coalfield) is where past coal mining activity has taken place at sufficient depth that it poses low risk to new development.

If a site is within a Coal Mining Reporting Area (as defined by the Coal Authority, based on their current data and experience across Great Britain[2]) then a mine gas risk assessment should be carried out. This may be relatively simple process in the Low Risk Area with detailed assessments more likely to be required in the High Risk Area.

Further information on Coal Mining Reporting Areas (including locations) can be found on the Coal Authority Interactive Viewer[3]. This website also defines Development High Risk Areas where risks associated with mine workings are likely present at shallow depth and could impact surface development. Mine gas issues may, or may not be more significant for these areas, but they must be considered for all sites within the defined Coal Mining Reporting Areas.

Further information on the risk assessment process is provided in Chapters 12 and 13. The results for simple cases may be reported as a discrete section within a wider geo-environmental report. However, for more complex sites a discrete mine gas risk assessment report may be more appropriate.

The first stage of the assessment should be a desk-based review culminating in a preliminary risk assessment report. The Coal Authority has a statutory duty to maintain and make accessible a range of relevant information relating to coal mining in Great Britain. It is therefore essential to procure a current Consultant’s Coal Mining Report from the Coal Authority to inform desk-based assessments (for all sites within a defined Coal Mining Reporting Area).

Other sources of information described later in this document should also be consulted. Local knowledge can also be important (contaminated land officers, environmental health officers, building control and local authorities) may hold information on shafts, adits, etc that are not in Coal Authority records. At this stage it may be possible to

[1] https://www.gov.uk/government/publications/land-contamination-risk-management-lcrm

[2] Note that the Coal Authority does not define Coal Mine Reporting Areas in Northern Ireland, although mining has taken place there.

[3] http://mapapps2.bgs.ac.uk/coalauthority/home.html

determine the level of likely risk using the flow chart in Chapter 13 of this report and further site investigation and monitoring may not be required. If further ground investigation and monitoring is required, the Preliminary Risk Assessment should be used to inform the design of the investigation.

Uncertainties in the availability and quality of data should be considered explicitly by assessors at every stage in the risk assessment process, along with any assumptions made in the development of CSMs (see also standard disclaimers and notes associated with Coal Authority data and plans).

3. Competence

The reader is reminded in respect of competency that:

> *….. a professional [person] should command the corpus of knowledge which forms part of the professional equipment of the ordinary member of his profession. He should not lag behind other ordinarily assiduous and intelligent members of his profession in knowledges of new advances, discoveries and developments in his field. He should have such awareness as an ordinarily competent practitioner would have of the deficiencies in his knowledge and the limitations on his skill. He should be alert to the hazards and risks inherent in any professional task he undertakes to the extent that other ordinarily competent members of the profession would be alert. He must bring to any professional task he undertakes no less expertise, skill and care than other ordinarily competent members of his profession would bring but need bring no more. The standard is that of the reasonable average. The law does not require of a professional man that he be a paragon, combining the qualities of polymath and prophet.*
>
> Lord Bingham in Eckersley v Binnie 1998.

Anyone responsible for carrying out a mine gas risk assessment and mitigation design should be suitably qualified and experienced as required under the definition of ‘competent persons’ in the National Planning Policy Framework (MHCLG, 2021) in England and equivalents in the devolved governments. Land Contamination: Risk Management (LCRM) (Environment Agency, 2020) also requires that for ‘land contamination and planning you must use and meet the National Planning Policy Framework definition of a competent person’.

They should ideally be a Chartered professional member of an appropriate organisation (or be able to demonstrate equivalence) and have competence in geology, understanding of mining and the processes that can cause gas to be produced in mines, how it can migrate to the surface and into buildings, as well as gas risk assessment techniques. Additional accreditation (e.g. SoBRA fully accredited risk assessor for permanent gases or a similar level of qualification such as SQP, SiLC, or RoGEP - defined on next page and in Glossary) is one way of demonstrating professional competence.

Professional chartership shows a commitment to career development and skill building whilst binding members to the codes of ethics and professional standards of the institution of which they are a member. An important aspect of this is that members are required to recognise the limitations of their own expertise and when that of other specialisms is required.

Developers and clients have a role to play in upholding levels of professionalism and competence of those they appoint to undertake mine gas risk assessments as they are responsible for ensuring that their developments are safe and suitable for their intended uses. They need to satisfy the local authority / Coal Authority and other regulators that any unacceptable risks will be successfully mitigated through suitable and sufficient investigation and the implementation of appropriate remedial measures where necessary.

Developers should be aware that their actions or omissions could lead to liability being incurred under Part 2A, e.g. where development fails to address an existing unacceptable risk or creates a risk by introducing a new receptor or pathway. There is also a legal duty under the Construction (Design and Management) Regulations (HSE, 2015a) for clients to appoint competent designers. Developers can discharge potential liabilities by appointing suitably experienced and qualified professionals to advise them, and by taking care that the staff offering their services can demonstrate their competence and experience.

Procurers and specifiers of mine gas risk assessments should take care to reference current standards and authoritative guidance when specifying the work. Where inappropriate or out of date standards are referenced in specifications, complying with them could yield a sub-standard result. However, when competent professionals are appointed with reference to a well-defined scope and brief and provided with adequate resources to carry out the work, an outcome which achieves good practice would be expected.

Competence can be demonstrated with qualifications and experience in a specific technical or scientific discipline or application relevant to mine gas, or by multidisciplinary qualifications. These include for example:

- a Suitably Qualified Person (SQP) registered under the National Quality Mark Scheme (NQMS);
- the Society of Brownfield Risk Assessment (SoBRA) accreditation scheme (for permanent gases in the case of mine gas);
- Register of Ground Engineering Professionals (RoGEP);
- a Specialist in Land Contamination (SiLC);
- membership of a professional organisation relevant to mine gas assessment;
- a proven track record of dealing with mine gas issues.

A proven track record means a regulator or consultant who regularly deals with the technical aspects of mine gas. For example, someone with knowledge and experience of the development planning regime or someone who regularly deals with the technical aspects of land contamination.

4. The Precautionary Approach

CIRIA Report C665 states:

> *The risk assessment should include, as far as is practicable, known and potential changes in site use which could affect the gas regime or compromise the long-term effectiveness of gas protection and control measures. ……However, it is accepted that all possible events and future developments cannot be predicted and planned for in the design of protective measures*
>
> Section 10.3, p13 (CIRIA, 2007).

In essence reasoned professional judgment is required when undertaking a gas risk assessment, a principle that is reinforced in BS 8485 (British Standards Institution, 2015). Indeed, it has been (and remains) a principle that risks must be both foreseeable and credible if they are to feature in an assessment of risk. This continues to be reflected within contemporary guidance, such as BS 8576. This document notes that to determine where and how to monitor requires consideration of:

> *Credible pathways of possible exposure of the receptors, taking into account what is known about the geology and hydrogeology, building construction and services layout, etc.; and*
> *Foreseeable events such as flooding, changes in groundwater level, global warming [now generally referenced as climate change], extreme weather conditions [including the influence of climate change], the closure of mines, and possible changes to the gas regime caused by future development.*
>
> Section 6, p7 of BS 8576:2013 (British Standards Institution, 2013).

When seeking to identify deleterious effects, an observed risk must be:

- significantly distinct;
- occur at a concentration or level that may be deemed as significant;
- indicative of long term irreversible environmental change or acute immediate risk; but also be
- reasonably foreseeable.

Yet, when drawing conclusions on the foreseeability of an event it must also avoid unintentional bias. For example, underestimation of a risk, based on the low probability of a past event that is easily recalled; may be overconfident (prevents a decision maker from considering extreme cases) or even have an over simplified representation of a problem or a desirability for a positive consequence (optimism bias). For example, the perception that mine gas risk is a low probability event based on personal recall alone could result in it being simply risked away at a location where gas protection is warranted. It can also bring a desire to be overly cautious, prudent, or conservative in the estimates that may be related to harmful consequences. This bias is common in environmental risk analyses, which deliberately use ‘conservative’ models and estimates (Montibeller and von Winterfeldt, 2015). The consequence can be to recommend costly and unnecessary site investigation or remedial intervention under the guise of a ‘precautionary approach’.

Yet, it should be reminded that:

> *The precautionary principle is not intended to apply to 'hypothetical effects and imaginary risk'; rather, it should be based on a scientific examination of the issue. Indeed, this has been confirmed on numerous occasions by the Court of Justice of the EU (see e.g. Case T-13/99 Pfizer Animal Health SA v Council of the European Union [2002] ECR II-03305). The precautionary principle will not apply where the desired level of protection is defined, and the risk of harm can be quantified. This situation can be dealt with using 'normal' risk-management tools.*
>
> European Commission (2017)

Normal risk management tools as described in this document, together with a consideration of 'reasonableness', is important. It should not be reckless, yet neither should the precautionary principle be invoked simply by a broader negative outlook. Where an activity or substance poses a plausible threat of harm but there is insufficient scientific evidence, or a lack of agreement as to the nature or scale of the likely adverse effects, a precautionary approach can be justified.

A precautionary approach may also be warranted where the potential harms are known but the cause-effect relationships cannot be scientifically established. However, the reader is reminded that transparent auditable and informed decision making is always a necessity as is the avoidance of bias. The mere presence of coal workings does not mean that a mine gas risk exists, or that costly gas protection will be required. The application of available risk management tools should in most cases enable the desired level of protection to be defined and the residual risks clearly described and appropriately mitigated.

5. Recorded Coal Mine Gas Incidents in the UK

Potentially hazardous mine gases can, in some instances, enter buildings (or other enclosed spaces) where they may accumulate to present a risk. The main gases of concern from old coal mines include methane, carbon dioxide, carbon monoxide and oxygen deficient air. Other gases such as hydrogen sulfide and radon may also need to be considered in specific sites where there are known issues (See Table 7.1 of CIRIA Report C758D for information on the principal gases found in UK abandoned mine workings (CIRIA, 2019)).

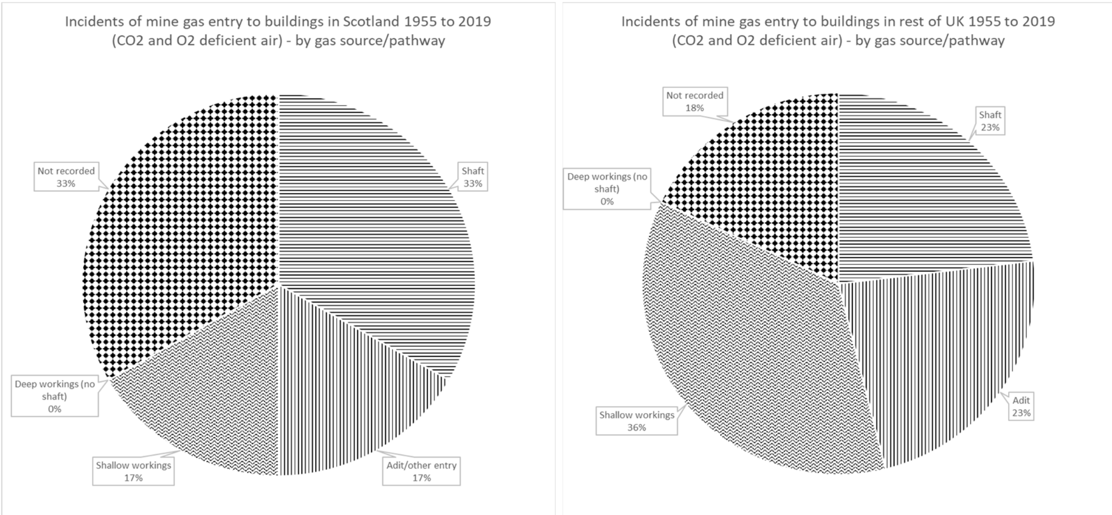
In Great Britain, parts of all the major coalfields have been affected at some time by surface emissions of mine gas. However, not all colliery closures necessarily lead to gas emission problems (UN Economic Commission for Europe, 2019). The United Nations report indicates that in the UK over 900 deep mines were closed in the UK from 1947 to 1998 during which time only 75 surface gas emission incidents were recorded (although many more could have remained undetected).

During the 1990s there was an average of about three new incidents per year, of which over 60% were attributed to leakages of gas through old, abandoned mine entries (this related to all gases). While methane ignitions (from various sources) have occurred in residential buildings (Wilson *et al.*, 2009), there have been no fatalities in the UK (but there have been injuries and in other countries there have been fatalities as well). In contrast, blackdamp (carbon dioxide and nitrogen) emissions have led to a number of deaths in the UK (RSK Stirling, 2019). At some sites, the Coal Authority has schemes in place to manage mine gas.

A study commissioned by the Scottish Government (NHS Lothian, 2017) researched incidents related to carbon dioxide emissions from old mines dating back to the 1950s. The report includes a list of incidents that are summarised in Figure 5.1a for Scotland and 5.1b for the rest of the UK (excluding incidents where entry to old workings or emissions into open air occurred) and relates specifically to gas entry to buildings. The data show that where the source or pathway for the gas was stated, it was related to either shafts (or other entries) or shallow coal workings.

None of the incidents were caused by carbon dioxide emissions from old deep mines through the ground above (except where shallow workings were connected to deeper ones). Many of the incidents relate to issues such as residents reporting headaches, breathlessness or an inability to light appliances (milder versions of symptoms seen in more severe carbon dioxide poisoning). Such reported effects are often the instigator of investigations and remedial works, although the report cautioned that based on the nature of carbon dioxide ingress/depleted oxygen events and their health effects, it is possible that some chronic events may have gone unrecorded.

The incident data suggest that overall, the consequences of the hazard are severe but the probability of significant mine gas entry into buildings is low. The greatest risk occurs where mine entries and/or shallow workings are present directly below a site. However, when the consequences are realised, the cost and disruption caused by having to retrofit gas protection to buildings is significant (see example on page 11).



a: Scotland **b: Rest of UK**

Figure 5.1: Incidents of carbon dioxide entry to buildings from mine workings (a) Scotland (b) rest of UK (percentages refer to the proportion of the total incidents that were related to the source/pathway). For a larger version, see page 67.

The United Nations report identifies that uncontrolled mine gas emissions are generally associated with one of the following scenarios:

- A point source emission from a specific abandoned mine entry affecting a few square metres of ground;
- A localised emission where gas has escaped from a specific mine entry and migrated along shallow, permeable migration pathways affecting a few tens of square metres of ground; or
- An extended area of emission where gas is migrating to the surface through the permeable ground overlying an extensive area of shallow, gassy mine workings directly beneath the permeable strata (or via a fault zone from deeper strata).

Therefore, the presence of these factors and their influence on the risk is what needs to be addressed in any mine gas risk assessment for new or existing developments. The presence of pathways, such as permeable superficial deposits or fault zones of fractured rock, that can allow emissions from deeper workings should also be considered. Mine gas problems are generally not encountered where coal mining is at depth (>150 m), unless deep mine shafts or faulted rock link the surface with underground workings (Sizer *et al.*, 1996). The migration pathways may also be affected by other geological structures such as anticlines and laterally extensive low permeability strata, that can trap gas or cause lateral gas flows, with emissions at remote points on the ground surface.

Other authors (Appleton, 2011) have similarly suggested that the most significant occurrences of methane and carbon dioxide emissions to surface have been where there are shallow mine workings and/or adits and shafts. The occurrence of widespread diffuse gas emissions above old workings is therefore critically dependent on intervening ground conditions, as well as the nature of mine gas formation within such workings. For example, a sufficiently thick layer of competent clay can prevent such emissions into development if it is not penetrated by foundations or service trenches (but it can also concentrate emissions at high permeability penetration points (natural or otherwise).

Example of disruption caused when mine gas emissions require remediation

A housing estate in Northumberland was constructed over shallow mine workings and close to several mine entries over a 10 year period from the mid-1960s to 1970s. This was at a time when the full implication of mine gases was probably less well understood than it is today. The houses are a mix of two-storey and bungalows. The site is underlain by Coal Measures with a thin layer of overlying superficial deposits of Glacial Till that are absent in places (i.e. it does not form an effective barrier to gas emissions).

A coal seam outcrops nearby the site and dips below the estate. The old workings are at a depth of 12 m to 16 m depth and the rock overlying the workings is predominantly sandstone (described as broken in some cases, i.e. fractured). This will provide a permeable pathway for mine gas migration to the surface.

Mine gas ingress (in this case oxygen deficient air) first became apparent in November 1980 when issues with lighting gas appliances in properties in one road were found. Similar issues were encountered in 1985 and 1987 at other properties in nearby roads. Initially, attempts were made to physically seal these properties to prevent gas ingress by retrofitting gas membranes, but this was not entirely successful.

Grouting below properties was also used to try and prevent the gas emissions but was not completely successful. Gas monitoring/alarms were installed in dwellings, which is not recommended as a long term solution to ground gas ingress (CIRIA, 2020).

In 1988 the Coal Authority installed an active ventilation system which draws air through the old mine workings by way of an air intake installed in the grounds of a local school (Northumberland County Council, 2012). The airflow is driven by a fan located over the entrance to the nearby former Ridley drift mine (located in open space) which connects to the workings.

This active ventilation system has fulfilled its purpose since that time by protecting a wide area with numerous properties within it and is still operational today. However, the incident has been disruptive to residents, caused stress and anxiety and there are significant costs involved (although the works are covered by the Coal Authority). The sustainability of long term active measures is also questionable.

6. Gas Hazards

Whilst the consideration of risk associated with methane is based on the occurrence of an explosion, the risk associated with the presence of carbon dioxide and oxygen depleted air is based on health effects related to toxicity and asphyxiation. The assessment of gas monitoring results in the ground should not be based on the exceedance of arbitrary application of limiting concentrations intended for use in occupied spaces. Such values are useful as initial screening tools (e.g. >1% methane, >5% carbon dioxide or <19.5% oxygen), but exceedance of those concentrations in the ground does not automatically imply an elevated risk of hazardous gas emissions occurring. Where gas concentrations exceed those levels in the ground in coal mining areas a robust assessment of the likely source of gas and gas flow from the ground is required (e.g. Card *et al*., 2019).

Guidance is provided in CIRIA Report C795 (Wilson *et al.*, 2020) on choosing appropriate limiting concentrations that may be used by risk assessors when considering either results of internal monitoring or modelling of gas flow from the ground into buildings. Additional information on the hazard potential of carbon dioxide is provided by the Health and Safety Executive (HSE, 2015b).

7. Useful Information Sources

There is a wealth of information available to assist consultants seeking to act with ordinary care in carrying out site investigations for mine gas and mine gas risk assessments. The key UK references that anyone carrying out a mine gas risk assessment should have access to are:

- Hooker P.J. and Bannon M.P., 1993. Methane: its occurrence and hazards in construction. CIRIA Report 130;
- Department of the Environment, 1996. Methane and other gases from disused coal mines: the planning response technical report. The Stationary Office;
- BS 8576:2013. Guidance on investigations for ground gas – Permanent gases and Volatile Organic Compounds (VOCs);
- BS 8485:2015 + A1:2019. Code of practice for the design of protective measures for methane and carbon dioxide ground gases for new buildings;
- CIRIA, 2019. CIRIA Report C758D, Abandoned Mine Workings Manual; and
- Coal Authority, 2019. Guidance on managing the risk of hazardous gases when drilling or piling near coal. The Coal Authority, Health and Safety Executive, British Drilling Association, Federation of Piling Specialists and the Association of Geotechnical and Geo-environmental Specialists. Version 2, April 2019.

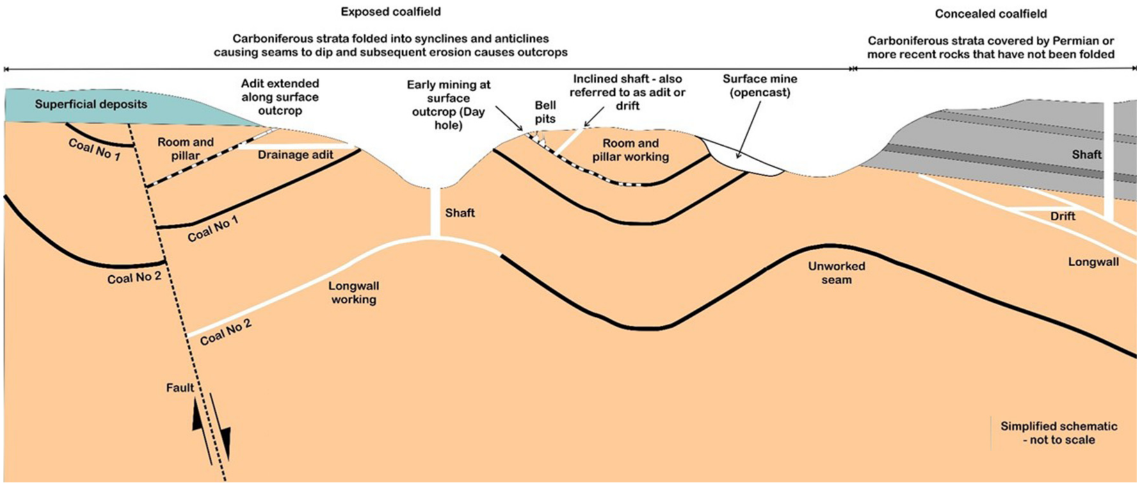
The Coal Authority Interactive Viewer also provides extensive site specific information for use in mine gas risk assessments and the Coal Authority archives hold information such as mine abandonment plans, shaft/adit decommissioning records and groundwater monitoring data, etc[4]. Note the older documents in this list contain a wealth of technical information that is still relevant today.

[4] It only became a legal duty for mine owners to prepare accurate mine abandonment plans as a consequence of the Coal Mines Regulation Act, 1887. The majority of mine workings pre-dating this act are unrecorded. The Coal Authority estimates that there are 172,000 recorded mine entries in the UK and a similar number of unrecorded ones.

8. Mining History and Methods

A summary of the main methods of accessing and mining coal is provided in Figure 8.1. For more information refer to CIRIA Report C758D (CIRIA, 2019). The development of coal mining techniques through the ages and the implications for mine gas risk are described in Appendix 1: Table A1.1.

> It is important to understand the different methods of working coal, the effect this has on the likely presence of a mine gas hazard being present below a site and the corresponding risk of emissions into buildings. At the very least, CIRIA Report C758D is considered to be essential reading for anyone undertaking mine gas risk assessments as it contains a wealth of additional information on coal mining methods that is beyond the summary of key issues provided in this report.



1. Early mining of coal from surface outcrops. Also occurred during 1920s/30s in some areas (e.g. from cellars in northeast England). Small scale or with short adits driven into slopes or hillsides where coal outcropped (short due to lack of ventilation and roof support). These workings were not recorded. The further from the outcrop and deeper the seam, the less likely they are to be present.
2. Adits used to extend workings deeper into outcropping seams. Often located in the side of river valleys or on hillsides. Also driven to allow gravity drainage of seams that were reached by other adits or shafts. Adits were also driven as inclined shafts to reach deeper coal seams.
3. Bell pits used where the coal seam had a shallow dip and superficial deposits were thin or absent. Shaft diameter 1 m to 1.3 m with coal removed from around it. Maximum depth of around 12 m, but there may be several located parallel to the seam outcrop. These workings were not recorded.
4. Shafts to reach deeper coal horizons. At first, single shafts, but later two or more shafts used. By the end of the 18th Century, some shafts had been constructed up to 250 m depth with a diameter of 4 m. Some modern shafts extend to depths of 1000 m. Drainage levels may have air shafts.
5. Horizontal drifts were sometimes driven underground from one seam to reach another seam.
6. Room and pillar workings originally developed to allow extension of bell pits and rarely extended more than 40 m from a shaft. The excavations to remove coal were supported by pillars of unmined coal. Layout was arbitrary at first, but became progressively more systematic, with later workings extending large distances from shafts and having distinct rectilinear patterns. Pillar robbing (removing the coal) at the end of mine operation was common. Little used in more recent coal mining.
7. Longwall mining involves a coal face (the longwall) that is up to 300 m long and accessed by roadways perpendicular to it. The coal face area is supported temporarily and as the works advance, the roof behind is allowed to collapse to leave an area of waste.
8. Surface mine or opencast. Extraction of coal in open excavation by stripping off the covering soils to expose seams.

Figure 8.1: Summary of the history of methods of coal mining. For a larger version, see page 68.

9. Sources of Gas in Coal Mines

Building an understanding of the source terms in the CSM is a fundamental aspect of all risk assessment. Methane is generally not ‘generated’ in coal mines in the same way that it is in landfill sites. The methane is produced as part of the coal formation process. It is produced by a complex series of geochemical processes (initially bacterially mediated decomposition, followed by high pressure and heat driven changes that vary with depth of burial and the length of heat exposure (coal maturation)).

Coal can contain a significant amount of methane, the majority of which is normally adsorbed on coal seam surfaces. Additional methane can be present as a dissolved phase in interstitial porewater and local groundwater and as gaseous methane. The free gas phase is typically about 5 to 10% by volume of the total methane in coal (Backhaus *et al.,* 2002), although the variability of mine ‘gassiness’ generally is widely acknowledged.

The methane may also be present in the rocks surrounding a seam. The maximum amount of gas that a coal can store is known as its retention capacity. Its retention capacity is influenced mainly by pressure, coal rank (quality / maturation level), and the moisture and mineral matter content.

Methane can also be produced (and driven out of coal) as a product of self-heating reactions when temperatures rise above about 50^{o}C, but this contribution is likely to be insignificant in most cases.

The methane in coal is not generally mobile (on non-geological timescales) and is not emitted to the surface in sufficiently large amounts to pose a risk unless mining takes place.

When the coal is mined (or a borehole drilled into an intact seam) the coal is fractured and the stored gas desorbs into the mine workings or borehole (the rate and length of time over which desorption takes place is highly variable in practice). The desorption occurs because of a reduction in the lithostatic and groundwater pressure. This can also occur when unworked seams above and below a worked seam are disturbed by ground movements.

Abandoned mines can continue to release methane until the workings are completely flooded or the gas reserve is depleted (WSP, 2011). Abandoned mine methane (AMM) emissions are characterised by a high rate of release immediately following closure, then falling to much lower rates of emission over a period of 8 to 10 years. In one study emissions completely stopped after 15 to 20 years although the majority of methane currently vented by the Coal Authority surpasses this timescale (Duda and Krzemien, 2018).

For most documented mine workings, there will be factual records of gas occurrences and production during the operational life of the mine, as well as anecdotal comments on the degree of gas hazards recognised at various levels, even down to individual phases of operation in some cases. The Coal Authority holds a significant database of post-closure monitoring of known gas emission points under its control (mainly methane venting).

Dissolved methane in mine water (and also more generally in Coal Measures strata) may in some cases be a credible gas source to be considered in a risk assessment. To be credible there must be the potential for the methane to degas in significant quantities (e.g. when groundwater flows from a point of high pressure head to one where it is low and allows degassing inside a confined space).

This process caused an explosion at a pumping station in Abbeystead (Hooker and Bannon, 1993). It can also be an issue to be considered if boreholes or other conduits (e.g. shafts, faults) allow upward flow of confined groundwater through an aquiclude at a rate sufficient to pose a hazard to buildings or infrastructure at or close to the surface.

Carbon dioxide generation can occur in mine workings due to the oxidation of coal (and to a more limited extent due to the oxidation of wood such as pit props and gaseous methane present in the mine atmosphere). From the moment that coal is exposed to air, it is subject to low temperature oxidation (weathering) by atmospheric oxygen.

This process is exothermic and can lead to self-heating and ultimately combustion if the heat produced by the reaction (mainly chemisorption of oxygen at the coal surface and emission of carbon dioxide) cannot be sufficiently dissipated by heat transfer within the coal seam or ground. The same processes also occur in colliery spoil heaps or backfill and can cause ground gas to be present in those situations.

Wang *et al.* (2003) suggested that coal oxidation at low temperatures is a complicated process that involves four phenomena:

- Oxygen transport to the surfaces of coal particles;
- Oxygen transport within coal pores;
- Chemical interaction between coal and oxygen; and
- Release of heat and emission of gases.

Carbon dioxide emission is also accompanied by emission of low molecular weight organic gases (C1 to C5, e.g. methane and ethane), carbon monoxide and hydrogen, all of which are flammable. This is especially so above about 50°C. In low quality coal it may also produce dimethyl sulfide. Low rank coals are more prone to oxidation than higher rank coals. This is mainly due to their higher porosity and greater internal surface area.

The main factors that may affect the oxidation of coal and hence generation of carbon dioxide emissions are summarised below:

- The lower the rank of coal[5] the greater the risk of oxidation and carbon dioxide emissions;
- A greater seam thickness increases the risk;
- Availability of oxygen. A sustained source of oxygen is required, and availability can be rate limiting. Static flooded workings will limit the supply of oxygen and subsequent transport of gas. Creation of large scale mine water flows could increase gas production and encourage degassing as mine water becomes

[5] Coal rank may be determined following the guidance in ASTM D388 – 19a, Standard Classification of Coals by Rank

depressurised. Boreholes can introduce oxygen into unflooded workings (especially if using air as a flushing medium);

- Time since exposure. The longer the time coal has been exposed the lower the risk. Oxidation history has a significant effect on the reactions between coal and oxygen at low temperatures. It was observed that a weathered or oxidised coal consumes oxygen at a rate far lower than a freshly mined or crushed coal;
- Ambient temperature. The higher the temperature the greater the risk. Although the mean annual temperature at 1 m depth in the UK varies from 12.7°C (southern England) to 8.8°C (northern Scotland), with a seasonal range of 10.3°C and 7.9°C respectively (Busby, 2015), temperatures in mine workings can vary greatly for these average values. In general terms the ground temperature shows seasonal variations to a depth of just 15 m, at which point the temperature is equal to the mean annual air temperature. Below 15 m in undisturbed ground, the temperature is stable and increases with depth, by an average of 2.6°C for every 100 m (BGS, 2020). Most modern data for subsurface temperatures relate to flooded workings. Dry, shallow workings will generally be better connected to the surface and show more variability in temperatures. Workings affected by self-heating and / or combustion will have a very different temperature profile than long abandoned, thin seam pillar and stall workings;
- Moisture content. Low moisture content reduces risk. It has been found that wet coal is more reactive than dry coal at room temperature (Cliff *et al.,* 2014).
- Ash content. As ash content increases the possibility of spontaneous combustion reduces because of the reduction in inert material that can act as a heat sink (Onifade and Genc, 2019).

Oxygen deficient atmospheres in old mines occur mainly because the oxidation of coal uses up the oxygen. Therefore, the risk of generation of an oxygen deficient atmosphere within old workings is generally controlled by the same factors discussed above for carbon dioxide.

It is noted that there are many other causes of oxygen deficient atmospheres, which can occur in almost any type of confined space or void. Other gases can displace the oxygen in air. This depends on the nature of the coal and the workings as different chemical reactions can occur in difference surfaces. Therefore, the presence of low oxygen needs careful assessment based on the CSM. Oxygen deficient atmospheres are regularly reported as the cause of fatalities in many industrial and commercial settings.

Carbon dioxide can also be produced when acidic mine water from workings reacts with carbonate in rocks or if it flows through open cast mine backfill. It is also possible that carbon dioxide can be produced in the opencast backfill, because of acidic rainfall percolation and oxidation of sulfide minerals present in the spoil / rock material. The reaction rates are normally low and rarely pose a risk of significant gas emissions. However, if large flows of acidic groundwater occur (e.g. if displaced by grouting works or groundwater levels rise and overflow into shallower workings or permeable rocks) it can cause emissions that are sufficient to pose a hazard to development at the surface.

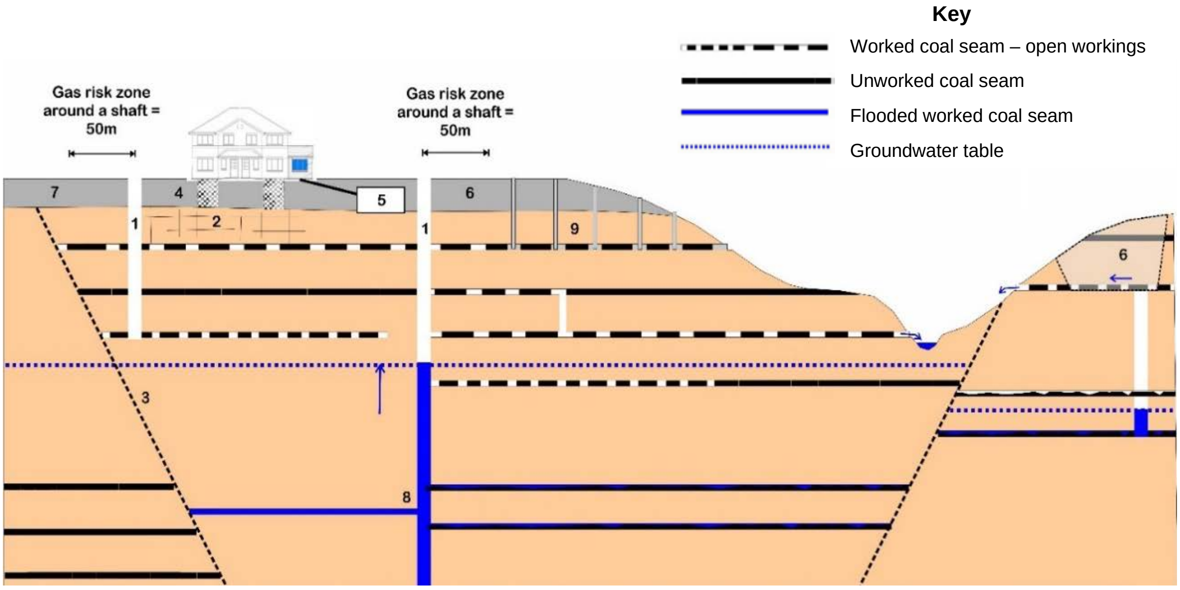
Anaerobic degradation of organic material (including coal) is not normally a significant contributor to gas in mines. Mines may also enhance the emission of radon gas and mining aspects should therefore be considered by an appropriate radon risk assessment that is a standard requirement for any new development[6].

> Once a mine becomes flooded desorption of methane reduces significantly and when the water pressure is greater than the desorption pressure it stops completely. A study of abandoned mine sites in the USA has observed that if a mine floods after closure, methane emissions are negligible, while if no flooding occurs, emissions are likely to occur (Kirchgessner *et al.,* 2000). Carbon dioxide emissions from flooded workings will also be negligible (see Chapter 11).

[6] https://www.ukradon.org

10. Mine Gas Sources, Migration Pathways and Barriers

A summary of the main processes that can produce mine gas is provided in Figure 10.1. This figure also summarises the most likely migration pathways and factors that can provide barriers to limit or prevent gas reaching the surface.



Causes of gas in mine workings

A. Desorption of gas from coal and rocks. Methane – a large proportion is released during or shortly after mining.

B. Oxidation of coal. Carbon dioxide and oxygen deficiency, also methane and ethane. If it self-heats and temperature exceeds about 50°C then carbon monoxide, ethylene and hydrogen can be produced. In low quality coal dimethylsulfide may also be produced.

C. Decomposition (aerobic) of old wood (pit props). Carbon dioxide but contribution probably small.

D. Decomposition of coal or wood anaerobically – negligible contribution to mine gas.

E. Acidic mine water drainage reacting with carbonate in rocks around a seam or shaft or in surface mine backfill.

F. Gases that are naturally present. Radon.

Drivers for gas migration (may or may not be present)

G. Change in barometric pressure causes expansion or contraction of gas in mine workings.

H. Rising groundwater pushes gas out of ground via shafts, faults or fractured rock. Impact depends on rate of rise and available pathways. Can also cause pockets of trapped gas that are pressurised.

I. Thermal gradient. Varies seasonally and can, for example, cause increased emissions in summer.

Pathways that allow gas migration (may or may not be present)

1. Old shafts or unsealed site investigation boreholes connected to unflooded workings.
2. Fractured rock above shallow workings.
3. Fault zones connecting to unflooded workings.
4. Stone column foundations
5. Deep drainage or soakaways (drainage trenches and networks may also allow shallow lateral migration. Attenuation tanks and soakaways can facilitate secondary storage of significant volumes of gas).
6. Permeable backfill to surface mines and shafts below backfill.

Barriers to gas migration (may or may not be present).

7. Sufficient thickness of low permeability rock or drift cover.
8. Flooding of workings or shafts. Stops desorption once water pressure exceeds desorption pressure and limits availability of oxygen and transport of gases.
9. Grouting (if designed as gas mitigation) reduces the potential for gas migration. Incompletely grouted works and grout holes can act as sources or pathways for gas migration so grouting may not completely remove risk.

Figure 10.1: Sources of mine gas, pathways and barriers to migration. For a larger version, see page 69.

Figure 10.2 shows the potentially numerous occurrences of pathways and gas reservoirs that may be introduced as part of the development construction.

It also shows the interactions that may be present between site investigation holes, grout holes, stone columns and drainage. It is a real example and shows the complexity of the situation that can occur on some development sites.

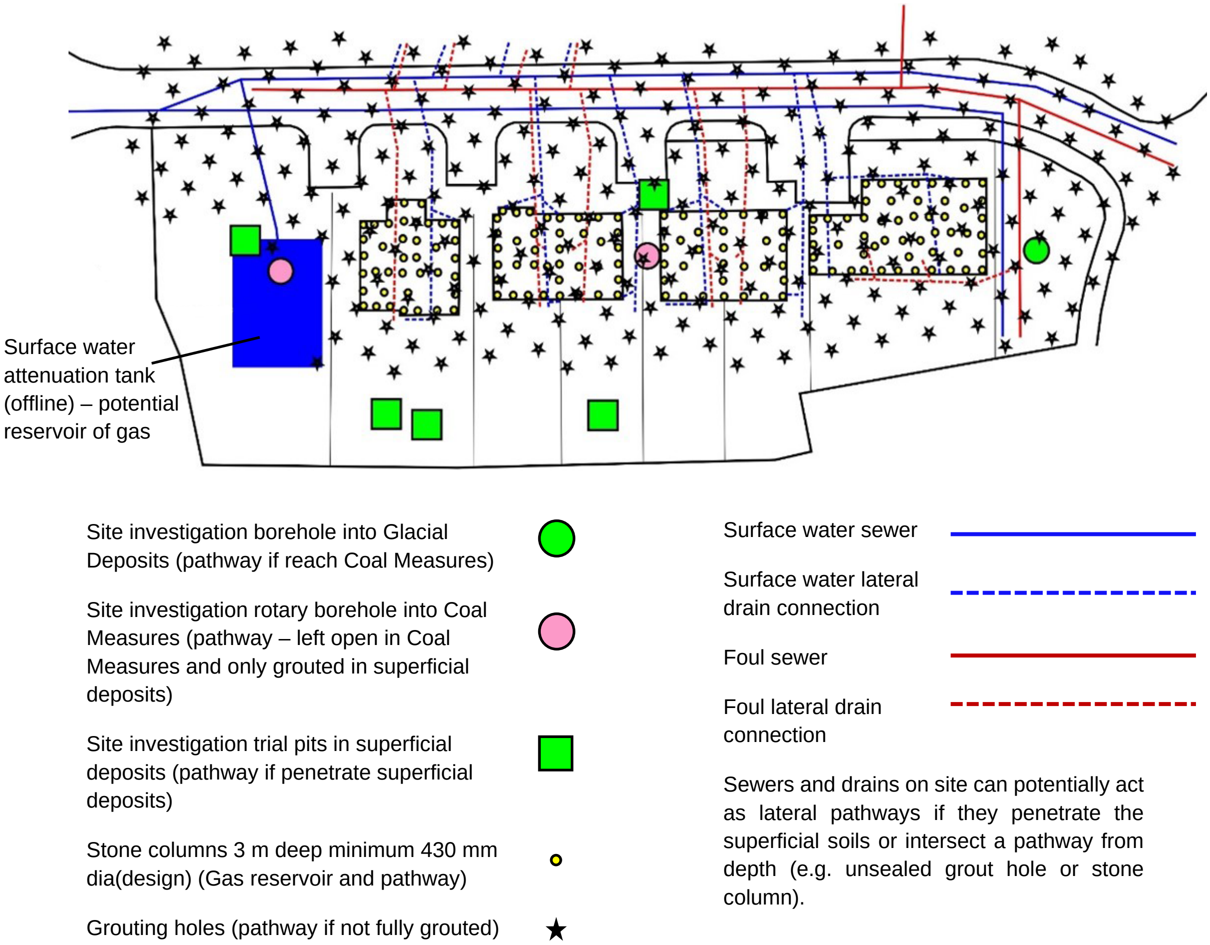


Figure 10.2: Complexity of pathways and gas reservoirs introduced by the development construction. For a larger version, see page 70.

The risk of gas migration is greatest from shallow workings (defined by the Coal Authority as less than 30 m from the surface (Coal Authority, 2012)). In this situation gas migration may occur through fractured rock above the workings.

Fracturing and permeability may be increased because of 'crown-hole' collapse above shallow pillar and stall workings. These features can migrate up to 10 times the worked seam thickness through overlying strata. By their nature, these are unrecorded features but the risk of them being present can be assessed using desk study information and the ground investigation data (this is required as part of the stability assessment for developments).

Below 30 m the risk of mine gas emissions reduces with increasing depth of the workings. Gas migration through the overlying ground from deep workings is not likely to cause significant emissions at the surface (Appleton, 2011) unless there are shafts, faults or other pathways linking the workings to the surface (which are typically well recorded for more modern, very deep mining).

Significant pressure driven gas migration will not occur from workings below 200 m depth (Pokryszka *et al.,* 2005). This is based on the assumption that rock above the workings will be highly fractured because of the subsidence to a height between 150 m and 170 m above the seam and that this releases gas from coal during mining (the point at which the highest methane emissions will occur).

For older workings in the UK that have now been closed for over 15 years (i.e. the vast majority) a shallower depth is reasonable, given that the Lower and Middle Coal Measures tend to be dominated by mudstones. In such situations, diffuse gas migration over a wide area from below depths of 150 m is not likely.

> The risk of significant emissions at the surface from deep workings below 150 m is low unless there are shafts, faults or other pathways linking the workings to the surface.

Faults require careful consideration as potential pathways for gas migration from deeper workings. Faults are visualised on maps as a singular plane but in practice they tend to cover a wider area or zone that can vary from a few metres up to hundreds of metres across. Coal may not have been worked right up to the fault (because of the poor mining conditions).

Faults may comprise more fractured permeable rock. Equally, the processes of faulting may have resulted in the fractures being infilled with lower permeability gouge (crushed rock or soil produced by fault movement).

Weathering (e.g. precipitation of minerals from infiltration of water, clay smearing, etc) can reduce the permeability of the fracture zone such that it may act to reduce or entirely eliminate surface to subsurface connectivity.

Where workings are shallow enough for gas migration to occur through the overlying ground a sufficient thickness of low permeability superficial soils or low permeability rock below buildings may reduce the risk. However, the depth of any foundations and the risk of penetrating such barrier layers should be considered. For example, vibro stone columns may provide a preferential pathway for gas migration. BRE Report 391 (Watts, 2000) notes that where ground contains toxic waste, or where inflammable or toxic gas generation may take place, stone columns may act as vertical vents. The foundation designer should consider all reasonably foreseeable consequential effects for building occupants. Similar advice is also provided in NHBC Standards (NHBC, 2020).

The risk of the most commonly used types of piled foundation in the UK (bored cast in place or driven precast concrete piles) forming a pathway is unlikely except where the barrier layer is already unacceptably thin. The risk of piles forming pathways can be assessed using the information in Wilson and Mortimer (2017). Lateral movement of the pile head in driven piles (pile whip) can occur (Talbot and Card, 2019), but this is likely to be in limited situations. It should not be used as a blanket reason not to use driven piles where there are mine gas issues nor to increase the gas risk classification on a site.

One of the most common causes is overdriving in hard ground conditions (Coal Authority, 2019). Other causes are driving into stiff over-consolidated clays, incorrect alignment of the piling hammer and use of raking piles (not likely in development sites). Whip can be avoided by good installation practice and avoiding use of driven piles in unsuitable ground conditions. Driven hollow steel piles may form preferential pathways up the inside of the tube if they are left open (they are often infilled with sand and/or concrete which limits or prevents significant gas migration).

The effect of any penetrations of a barrier layer providing a pathway should also be assessed. In the authors' experience, if a low permeability layer is to be relied on in a risk assessment, a minimum confirmed thickness of low permeability material below the base of the proposed development (including buildings, substructures, foundations or drainage infrastructure) would likely be in the order of 5 m. Allowing for construction thicknesses and trench depths this is likely to require a 10 m thickness of low permeability layer from the pre-development ground level. However, such judgements should always be evaluated on a site specific basis taking account of the CSM and uncertainties within it.

The risk of gas migrating via any ungrouted boreholes (Environment Agency, 2012), ground source heat pumps or similar also requires consideration, even when barrier soil layers / low permeability strata are present.

> It is important to consider the effect of foundation construction and other below ground infrastructure on migration pathways and the integrity of any barrier layers, and the implication for the mine gas risk assessment. If the foundation type is unknown at the time of the risk assessment or changed subsequently, then the CSM and risk assessment must be updated at detailed design stage. Reports should be transparent as to the foundation (and other) design features that are included in the assessment. If final designs change, then the gas risk assessment will require updating (even if the risks do not change significantly).

The risk posed to development by gas migrating via shafts reduces with distance from the shaft because of dispersion and dilution by atmospheric air ingress to the ground. It is also influenced by geology, shaft backfill, lining and capping. Typically, this risk is considered minimal beyond a radius of 50 m (based on the authors' experience) unless there are specific pathways that could cause gas to migrate further without significant dispersion (such as adits or service conduits). Conversely there is a much greater risk of gas migration within 20 m of a shaft.

Adits are shallow inclines into the ground and the risk will be highest where development is located in areas above or to either side of the adit and there is shallow cover. The risk of gas emissions to the area opposite to an adit will be minimal. Note that just because a shaft, drift or adit has been sealed does not automatically mean the risk from mine gas is low. It is only recently that records for shaft filling were taken, and many historic shafts were just filled with material that was available nearby. Infilling and capping have normally been carried out for stability reasons and may not prevent gas migration. This should be considered carefully in any mine gas risk assessment.

When considering likely migration pathways and influences on the rate of gas emissions, the impact of grouting works for the development and future grouting works in off-site connected workings should be considered, if reasonably foreseeable. Grouting can push gas out of workings, or it can potentially divert flows of acidic mine water that can cause generation of carbon dioxide. It is noted that grouting designs are often prepared separately and at different times to other engineering designs and plans for built development. Appropriate assessment of grouting impacts may not be possible during the initial stages of a mine gas risk assessment and the risk assessment may need to be updated once the grouting plan is finalised (and both then subject to iterative change as appropriate).

> Grouting plans should consider mine gas risks both during and after grouting, including off-site receptors (preferably by understanding and referencing an existing mine gas risk assessment). If grouting boreholes are to penetrate an impermeable barrier that is relied on to minimise gas risk this should be recognised and dealt with in the design, supervision and verification of the works.

11. The Effect of Changing Groundwater Levels on Mine Gas Risks

A crucial part of mine gas risk assessment is understanding groundwater conditions and the likely impact they could have on gas emissions at the surface. A summary of the issues is provided in Figure 11.1. However, generic statements that 'rising groundwater levels will increase the risk of gas emissions' should be avoided and a site specific assessment should be made on whether groundwater rise is likely, and if it is, what the likely significance will be.

Useful information in this respect can be obtained from the Coal Authority, research publications and the British Geological Survey (BGS). The Coal Authority holds a great deal of information on coalfield groundwater levels and the status of groundwater recovery post mine abandonment (some data are freely accessible for Northumberland via the interactive viewer, other information is available on request).

The BGS Future Flows and Groundwater Levels project has also addressed these issues by carrying out a consistent assessment of the impact of climate change on river flows and groundwater levels across England, Wales and Scotland[7].

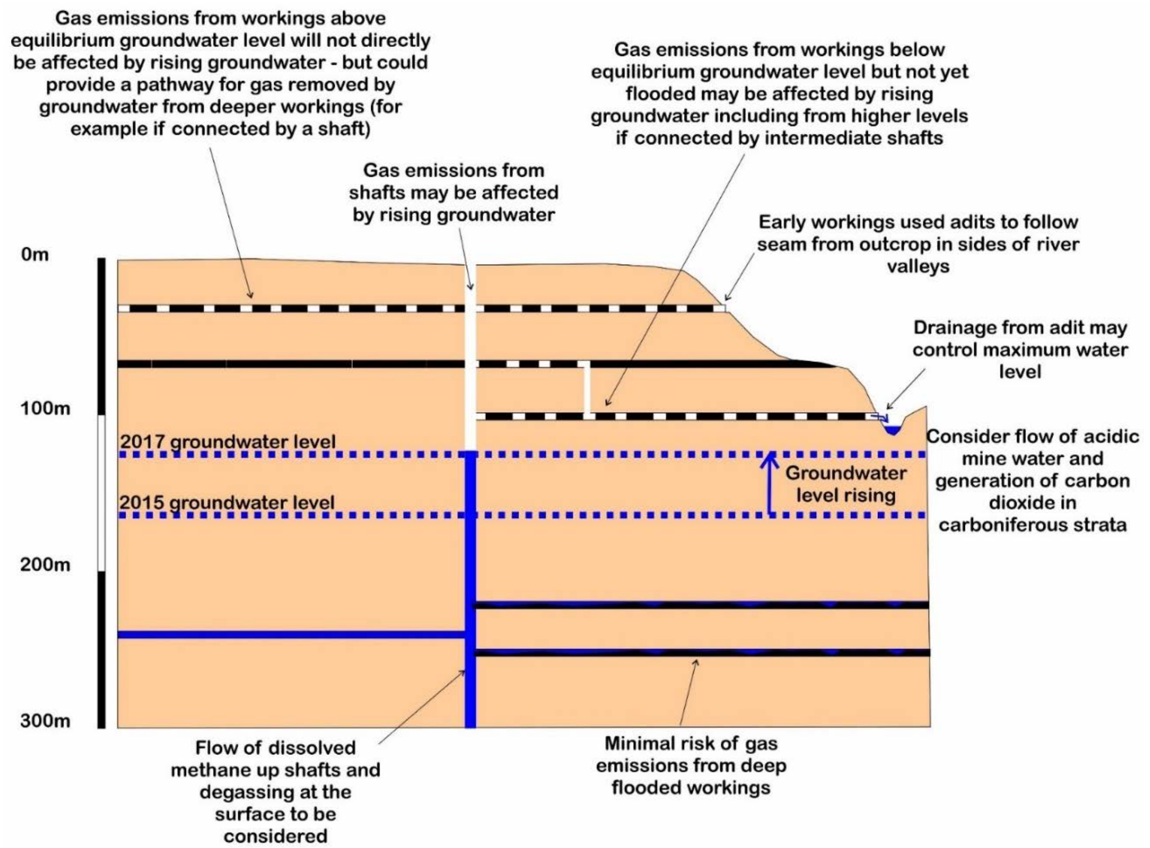


Figure 11.1: Example groundwater conditions and influence on mine gas risk - generalised schematic of Midlothian Coal Field (based on groundwater conditions in Todd *et al.,* 2019). For a larger version, see page 71.

[7] https://www2.bgs.ac.uk/groundwater/change/FutureFlows/home.html

Where mined seams are located below the natural groundwater table, pumping is required to keep the operational workings free of water. After mining stops, the pumping usually stops, and groundwater levels will rebound back to natural pre-mining levels (although the Coal Authority is required to maintain some pumping to protect strategic public supply aquifers from contamination by rebounding mine water). As the water rises into unflooded workings it can push any accumulated gas out of shafts or adits and possibly up fracture zones.

The likelihood of water causing dispersed emissions through overlying rock that pose a hazard at the surface is low and reduces with increased depth of the workings. The rebound of groundwater can however be complex because individual mines in relative proximity often stopped pumping at different times, but have a linked network of voids, shafts and tunnels that affect the flow and storage of water and movement of any mine gas.

Key factors relating to groundwater are:

- In some areas of coalfields in the UK groundwater levels are fully recovered and are unlikely to be capable of creating sustained gas flows out at the surface. The Coal Authority holds detailed information on coalfield groundwater levels and for Northumberland details of groundwater recovery is available online via the Coal Authority viewer.
- If workings are above the natural groundwater levels then rising groundwater is not likely to push gas out of them. However, the interconnection with deeper workings that could become flooded should be considered and is known to have caused issues on some sites.
- Once workings are flooded the risk of gas emissions from them is significantly reduced and in many cases will be minimal. The flow of acidic minewater and its contact with carbonate rocks elsewhere resulting in carbon dioxide generation and migration via fractured rock above longwall workings may require consideration as well as flow of dissolved methane. Acidic minewater coming into contact with metals in the workings has also been known to cause hydrogen generation. This may require a detailed hydrogeological assessment.
- Post mine closure groundwater pumping may remain ongoing to maintain groundwater at a level that prevents groundwater or surface water pollution. The impact on gas emissions if pumping stops in future should be assessed.
- If groundwater levels are still recovering the levels in relation to former workings, then the rate of the rise should be assessed, if possible, to determine the influence on gas emissions.
- Partially flooded workings where the groundwater level can vary above and below some workings present a high risk situation in relation to mine gas. Conversely, deep permanently flooded workings pose minimal potential for gas emissions.
- Consider the potential impact on groundwater flows if nearby sites are developed and any mine workings below them are grouted.
- Climate change may affect groundwater levels in the longer term (see Appendix 3).

There may be uncertainty in the assessment of groundwater recovery if data are not available, and this should be considered in the risk assessment.

> The potential for gas emissions is greatest where groundwater levels are still recovering or fluctuate above and below any workings.

12. Mine Gas Risk Assessment Process

The process for mine gas risk assessment follows the broad framework for any ground gas risk assessment as shown in BS 8485:2015 + A1:2019 (British Standards Institution, 2015). The specific requirements for mine gas risk assessment within the BS 8485 flow chart are shown in Figure 12.1.

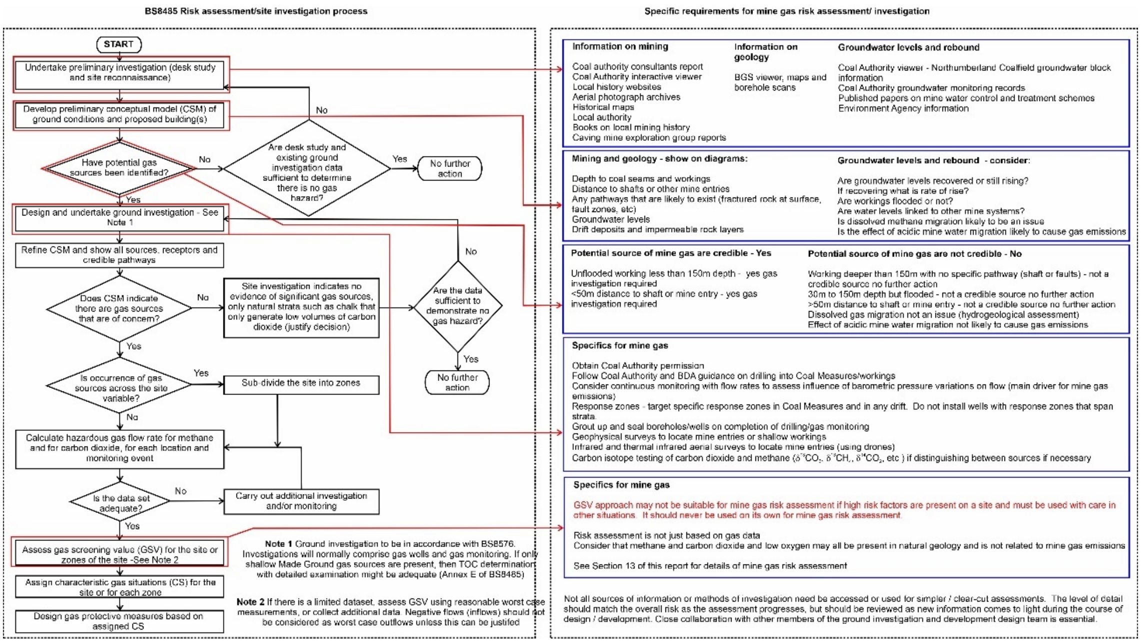


Figure 12.1: Flow chart for gas risk assessment with specific considerations for mine gas assessment. The left hand side has been adapted from BS 8485 and the right hand side shows how the specific considerations for mine gas assessment described in this document follow the generic flow chart from BS 8485. For a larger version of this image, see page 72.

12.1 Collect Desk Study Information and Critically Assess it to develop Preliminary CSM (preliminary risk assessment)

> This is one of the most important parts of a mine gas risk assessment. Without a robust and well-presented desk study and preliminary CSM any other site investigation or gas monitoring data cannot be interpreted correctly.

A desk study for a mine gas risk assessment should consist of more than just ordering data from an online data service provider. It should also include obtaining data from the following sources:

- Consultant's Coal Mining Report from Coal Authority (A CON29M report is not sufficient as it is only intended for property conveyancing and the Consultant's report includes additional information). Note that where the Coal Authority reports state that there are no records of mine gas emissions, this does not mean that there is no risk of emissions occurring. It should not be relied upon in isolation from other information and data;

- Historical mine plans and other information from the Coal Authority, e.g. mine entry datasheets and interpretive reports, and mine abandonment plans, which should be consulted where appropriate. The Consultant's Coal Mining report will give an indication if any such information is available[8]. The Coal Authority also has a database of gas monitoring data and information regarding previous incidents, and it should be contacted to see if such data are available. Coal Authority Mine Gas Emissions report provides bespoke information on the details of any mine gas incident that has been treated by the Coal Authority. Note that there are still a small number of small operational coal mines that are either privately owned or fully licensed by the Coal Authority;
- Shaft or adit records that may be available in the borehole scans on the British Geological Survey viewer;
- Local museums (e.g. Durham Mining Museum website, http://www.dmm.org.uk);
- Internet search of local history groups, railway enthusiast sites (collieries often had their own railway sidings), etc.;
- Information on groundwater recovery within the coalfield from Coal Authority, research studies or journal papers;
- Consultation data from the local planning authority and environmental regulator (Environment Agency / Natural Resources Wales / Scottish Environment Protection Agency / Northern Ireland Environment Agency); and
- Infrared aerial photographs.

Once the information has been collected it must be interpreted to produce a preliminary risk assessment and not just described factually. It is good practice to develop a schematic CSM on all sites as described in Clause 5.4 of BS 8485 (British Standards Institution, 2015) and in BS EN ISO 21365 (British Standards Institution, 2020). BS 8576 (British Standards Institution, 2013) specifically requires geological cross sections to be provided as part of the CSM, preferably to natural scale.

The interpretation of the data should be site specific and avoid generic statements. For example, it may be possible to discount mine gas risk simply based on the known depth of workings and groundwater recovery (see Appendix 4: Case Study 1). Examples where the mine gas risk can be discounted at an early stage include where workings are deeper than 150 m with no specific pathway (shaft or faults), where shallower workings (30 m to 150 m) are permanently flooded or where there is >50 m to a mine entry. However, any such assessment should be based on a thorough understanding of the CSM for the site. There will be a requirement to undertake more detailed assessment where there are credible potential sources of mine gas emissions (unflooded working less than 150 m or there is <50 m to a mine entry).

[8] Prior to 1840, there was no requirement for mining plans to be prepared and it was not until 1850 that the Inspection of Coal Mines Act 1850 required a coal mine owner to keep a plan at each mine. In 1872, the Coal Mines Regulation Act and the Metalliferous Mines Regulation Act made the deposition of plans of abandoned mines with the Secretary of State a statutory requirement, therefore an assessment will always be required for the potential for unrecorded workings to be present.

Although in most cases care has to be taken with the location of shafts because of the inaccuracies in location, the historical information can, in some cases, identify the location of former shafts quite accurately (see Appendix 4: Case Study 2).

> The preliminary CSM should be a synthesis of information about a site together with some interpretation, assumptions and hypotheses – BS EN ISO 21365. It is a mental construct of all the gathered information and should take account of foreseeable future changes or events.

The definition of the preliminary risk assessment should also seek to identify any aspects of the development foundation and drainage design (or any other factors) that could influence gas risk. Consideration should be given to any limitations on the information and a requirement to revisit the mine gas risk assessment once the design of a development is finalised should be clearly stated. For example, if a layer of impermeable soil is expected to provide a barrier to gas migration the impact of foundation types should be assessed and, if necessary, limitations placed on the depth or type of foundations that are suitable. Similarly, the use of deep drainage in trenches may increase gas risk and shallow surface based sustainable drainage systems (e.g. permeable pavements, shallow swales or basins) may be more suitable to minimise mine gas risk.

Every effort should be made to fully understand the historical, current and likely future situation at a site and failure to do so can result in inappropriate risk assessment and recommendations. For example, on one site information on gas emissions from a colliery adit was incorrectly interpreted. It was assumed that a mine gas emission incident had resulted in a gas extraction system being installed into a former adit. On this basis, gas protection measures were recommended in a nearby development. Investigation with the Coal Authority found that the gas extraction system in the adit was installed as a commercial coal mine methane (CMM) extraction system for the purpose of generating electricity. The 'gas emission incident' was a leak from the pipework in the extraction system. Further investigation also found a detailed geological log for the adit that included coordinates along its length. This information was plotted to show that the adit did not go anywhere near the site being assessed. Accordingly there was minimal risk of mine gas emissions to the development (regardless of the future activity of the CMM scheme) and the recommendations for gas protection were not warranted.

12.2 The Site Investigation

The design of a site investigation for mine gas assessment should be based around the results of the desk study and preliminary risk assessment. There is a wealth of guidance on site investigation that is relevant to mine gas investigation, including:

- Association of Geotechnical and Geoenvironmental Specialists (AGS), 2015. UK Specification for Ground Investigation, Second Edition.
- BS 5930:2015 + A1:2020. Code of practice for ground investigations.
- BS 8576:2013. Guidance on investigations for ground gas. Permanent gases and Volatile Organic Compounds (VOCs).
- BS 10175:2011 + A2:2017. Investigation of potentially contaminated sites. Code of Practice.

- Coal Authority, 2019. Guidance on managing the risk of hazardous gases when drilling or piling near coal. The Coal Authority, Health and Safety Executive, British Drilling Association, Federation of Piling Specialists and the Association of Geotechnical and Geo-environmental Specialists. Version 2, April 2019.
- CIRIA, 2019. CIRIA Report C758D, Abandoned Mine Workings Manual.
- Environment Agency, 2012. Good Practice for Decommissioning Redundant Boreholes and wells.
- Scottish Environment Protection Agency, 2014. Good Practice for Decommissioning Redundant Boreholes and wells.

Specific considerations for mine gas investigations include:

- During privatisation of the coal industry in 1994 the Coal Industry Act transferred ownership of unworked coal and coal workings, including shafts and adits, (previously vested in the National Coal Board and British Coal) to the Coal Authority. In the interests of public safety and to ensure the proper exchange of relevant information, the Coal Authority, as owners, requires that any activity which intersects, disturbs or enters any of its property interests requires its prior written authorisation. For site investigation works such as drilling boreholes or digging trial pits into coal workings this will be in the form of a permit;
- Drilling may also need to comply with the Borehole Sites and Operations Regulations, 1995. The regulations require notification to the HSE of borehole sites and operations where the boreholes are 30 m deep or more, and within a Mining Area. A Mining Area is defined as land which lies within 1000 m, measured in any direction in three dimensions, of any mine currently being worked or disused, or land where a licence to mine minerals has been granted for coal, natural gas, coal bed methane, or other minerals, in natural strata. Mines include shafts for access, ventilation or pumping, underground roadways, adits, and stopes but do not include opencast mines or quarries. Boreholes used for the storage of gas in natural strata reservoirs from which oil or coal bed methane has previously been extracted are also included as mining activities;
- A sufficient number of boreholes should be drilled to an adequate depth to determine whether former workings are present at shallow depth. These may be required to assess ground stability issues but should also consider data collection requirements for mine gas risk assessment. Often boreholes are drilled to at least 30 m, but blanket application of this depth is not recommended. The design depth of boreholes should be site specific, based on the information in the preliminary CSM / ground model;
- A sufficient number of boreholes should be drilled to an adequate depth to determine the significance of potential migration pathways and the variation in any superficial deposits that may act as a barrier to mine gas migration;
- Investigation of shafts may require close spaced probes, trenches or geophysical methods and must be carefully planned to mitigate the health and safety risks;
- Gas monitoring at the base of the hole, every 1 m, as drilling progresses can provide useful information for gas risk assessment. The absence of gas during

drilling should not be relied upon on its own to indicate there is no potential risk from mine gas. Gas monitoring for health and safety reasons is typically a condition of a Coal Authority permit to drill into Coal Measures. It should not however be seen as the only monitoring that is required to assess long term gas emission risk but can be useful to identify the depth that gas is entering a hole (if gas is detected) and in refining the CSM. This is straightforward in window sampler and cable percussion holes in superficial or weathered rock deposits up to depths of about 10 m. It becomes less practical with depth (because the time to pump the gas sample increases). It is not practical where the ground is prone to collapse and drilling needs to proceed quickly, nor in rotary probeholes because of the time required to withdraw the drill string every 1 m of penetration. It could however be targeted in probeholes around depths where sources or pathways are anticipated or where changes in drilling observations (speed, flush loss, etc) indicate it may be useful. Alternatively, if gas monitoring for health and safety is only carried out at the top of the hole during drilling the depth profiling (if required) can be completed in suitable gas monitoring wells;

- Careful logging of rock cores is necessary to identify fracture spacing, infill and direction;
- Logging of nearby rock exposures can provide useful information on fracturing;
- Gas monitoring well response zones should be designed to ensure that they are within a single source or migration pathway, i.e. within made ground, any superficial deposits, in a worked coal seam or in the surrounding Coal Measures strata. Response zones should not span multiple strata or worked seams and surrounding strata. The response zone for each monitoring well should be designed after completion of drilling when the ground conditions in the well are known. This requires close communication between the drillers and the site geotechnical/geo-environmental engineer or engineering geologist;
- If the superficial deposits are likely to be sufficiently thick and impermeable to provide an effective barrier to gas migration from depth, then gas monitoring may only be required in those deposits or in strata above in order to show gas migration is not occurring from deeper workings. The thickness of the barrier, potential variations, the risk of gas emissions from mine workings / entries occurring, foundation and drainage depths, the likely depth of desiccation that could realistically occur to clay soils, gas flow rates through the barrier, etc should be taken into consideration. The influence of anything that has or could comprise the barrier should be assessed (e.g. boreholes);
- A sufficient number of gas monitoring readings should be obtained to characterise the mine gas regime below the development. Advice is provided in BS 8576. Spot monitoring is often insufficient to allow assessment of mine gas risk. It should be carried out during periods of rapid and sufficiently large drops in barometric pressure. Where continuous monitoring is used the advice provided in CL:AIRE TB17 (Wilson *et al.,* 2018a) can be used to assess if the data are sufficient (this should not be used for spot monitoring). Where the CSM indicates a lower risk then spot monitoring may be suitable on its own. Continuous monitoring is more likely to be required on high and moderate risk sites to support more detailed risk assessment;

- Surface emissions measurements and flux chamber testing can provide valuable information when combined with gas monitoring data from wells. The density of tests and number of visits should be sufficient to allow assessment of risk (e.g. grid spacing on surface emissions points, visits during falling barometric pressure, etc);
- If workings are shallow and flooded, then timeseries groundwater monitoring may be necessary to confirm variations do not result in levels dropping and exposing the workings to air;

> It is vital that after the site investigation or gas monitoring is complete that any boreholes, probeholes or wells are decommissioned (backfilled) and sealed in a manner that prevents them acting as migration pathways for mine gas (See Coal Authority (2019), Environment Agency (2012) and Scottish Environment Protection Agency (2014) guidance as well as note 4 in BS 8576). If trial pits are to be excavated into impermeable drift deposits, they should be located outside building footprints (if known) or alternatively the effect of the pits on gas migration should be considered in the risk assessment.

12.3 Gas Monitoring

Guidance on gas monitoring is provided in BS 8576 (British Standards Institution, 2013) and other ground gas guidance referred to in this document. Early awareness of the required period of monitoring and open discussions with the client about the timescales are important. As discussed above, the response zones should be designed based on the preliminary risk assessment and the findings during drilling of boreholes. Emissions from mine workings are likely to be sporadic with fluctuations over long time periods and this needs to be taken account of in the gas monitoring programme. If spot monitoring is completed it requires data on weather conditions and barometric pressure variations prior to and during the monitoring period, along with a sufficient number of closely spaced visits, so the relationship between the gas concentrations and flows and changes in pressure can be assessed. The barometric pressure data can be purchased from online weather sites for the nearest weather station. Continuous monitoring may allow a more robust risk assessment in many cases. In both cases (spot and continuous) the monitoring should cover a number of periods within the worst case zone described in CL:AIRE TB17 (Wilson *et al.,* 2018a).

The gas monitoring protocol for spot monitoring is particularly important where the data are to be used for mine gas assessment. Peak flow rates and gas concentrations should be recorded at the start of monitoring and then at 1 minute intervals until steady values are achieved. Gas monitoring instruments must measure all the principal permanent gases (methane, carbon dioxide and oxygen). It is not acceptable to monitor only for oxygen with the assumption that the creation of carbon dioxide will have caused the depletion of oxygen. Such data are insufficient to support a robust risk assessment.

Gas spot monitoring should be completed for at least 10 minutes at each well for flow rates and a further 10 minutes for gas concentrations (or until gas concentrations or flows reach a steady sustained state for more than 2 minutes). The gas concentration and flow rates should be recorded at 1 minute intervals. This requires at least 20 minutes of monitoring at each location, but experience has shown that often reductions from peak values take at least 10 minutes to fully dissipate to true steady state values. It may also take this amount of time for carbon dioxide to increase to peak values and oxygen to reduce to minimum values if carbon dioxide has accumulated at the base of the well and monitoring is being carried out from a single gas tap at the top of the well.

Gas sampling and isotope testing (^{13}C or ^{14}C) can sometimes be useful to differentiate mine gas from other sources (see Appendix 2) albeit application of the latter is not ordinary practice but may be warranted in complex situations where other sources of gas are present.

BS 8576 contains a clear recommendation that a factual report should be prepared following each monitoring or sampling event (this does not mean a full report but a record of the field data). Providing factual monitoring reports in advance of the interpretative mine gas risk assessment assists the practitioner in demonstrating that a complete and auditable set of factual data has been obtained and draws a clear distinction between data and interpretation. Interpretation may then involve the identification of unrepresentative data for valid reasons (such as flooded monitoring wells on certain dates), which could then be justifiably excluded from the risk assessment. The assessor is then well placed to review the sufficiency of the data set, continue with the risk assessment, or recommend that additional monitoring data are obtained if necessary.

In no circumstances should monitoring data be omitted from factual monitoring reports.

13. The Risk Assessment

The Gas Screening Values and the design and specification procedure for identifying suitable mitigation measures as described in BS 8485 (British Standards Institution, 2015) should be used **with extreme caution** in mine gas risk assessments. These methods are unlikely to be appropriate for sites with complex CSMs or affected by high risk factors, except as one strand in a multiple lines of evidence approach. This is because of the following:

- Clause 1 Scope, Note 2 advises that it does not provide advice on oxygen depletion which is an important consideration for mine gas;
- Table 4, Note B, for higher Characteristic Situations the gas hazard is too high to allow the use of the empirical Gas Screening Value method. Mine gas emissions are the highest risk category of ground gas emissions and use of gas monitoring data alone can underestimate the risk (see Appendix 4: Case Study 3). Where mine gas emissions are likely to require mitigation, it is therefore important to base the design on detailed quantitative methods as described in BS 8485 Clause 6.2.2; and
- The Characteristic Situation is an empirical approach that was developed based on data from wells installed in soil-based sources. Mine gas emissions involve flow through open voids and fractured rock which the method was not intended to be applied to.

Consequently, site specific assessment is required when seeking to consider shafts or other entrances or flow in fractured rock from shallow workings. A multiple lines of evidence approach is required. Further information on applying this approach to ground gas assessment is provided in CIRIA Report C795 (Wilson *et al.*, 2020).

The mine gas risk assessment should also consider the potential for hazardous atmospheres in below-ground confined spaces in soils impacted by mine gas, both during construction and following development. Fatalities have occurred when mine gas has accumulated in deep trenches excavated into colliery spoil. The design of drainage systems where a mine gas risk is present should remove the need to enter trenches or manholes during construction or maintenance. In this respect shallow surface landscaped sustainable drainage system features will be beneficial.

Particular care is required when an assessor relies on the continuity and integrity of a barrier to gas migration such as a layer of low permeability clay when sources of mine gas have been identified within influencing distance of the site. This is because a development could be highly sensitive to a compromise in the effectiveness of the barrier in these circumstances. The influence of the development construction should be considered (see Chapter 10). The site investigation and assessment should provide sufficient confidence that the barrier will remain effective over the lifetime of the development, taking into account potential future changes.

A decision support tool for mine gas risk assessment is provided in Figure 13.1. This is provided to assist risk assessors in providing consistent and transparent decision making. It should not be followed blindly (and without recognising the advice provided in the rest of this document). It is not a substitute for assessors applying their professional judgement and ultimately making the decisions themselves.

> Use of gas screening values and the points score system in BS 8485 is not considered appropriate in isolation for assessing mine gas risk on sites with complex CSMs or that are affected by high risk factors where mass advection of soil gas could occur.

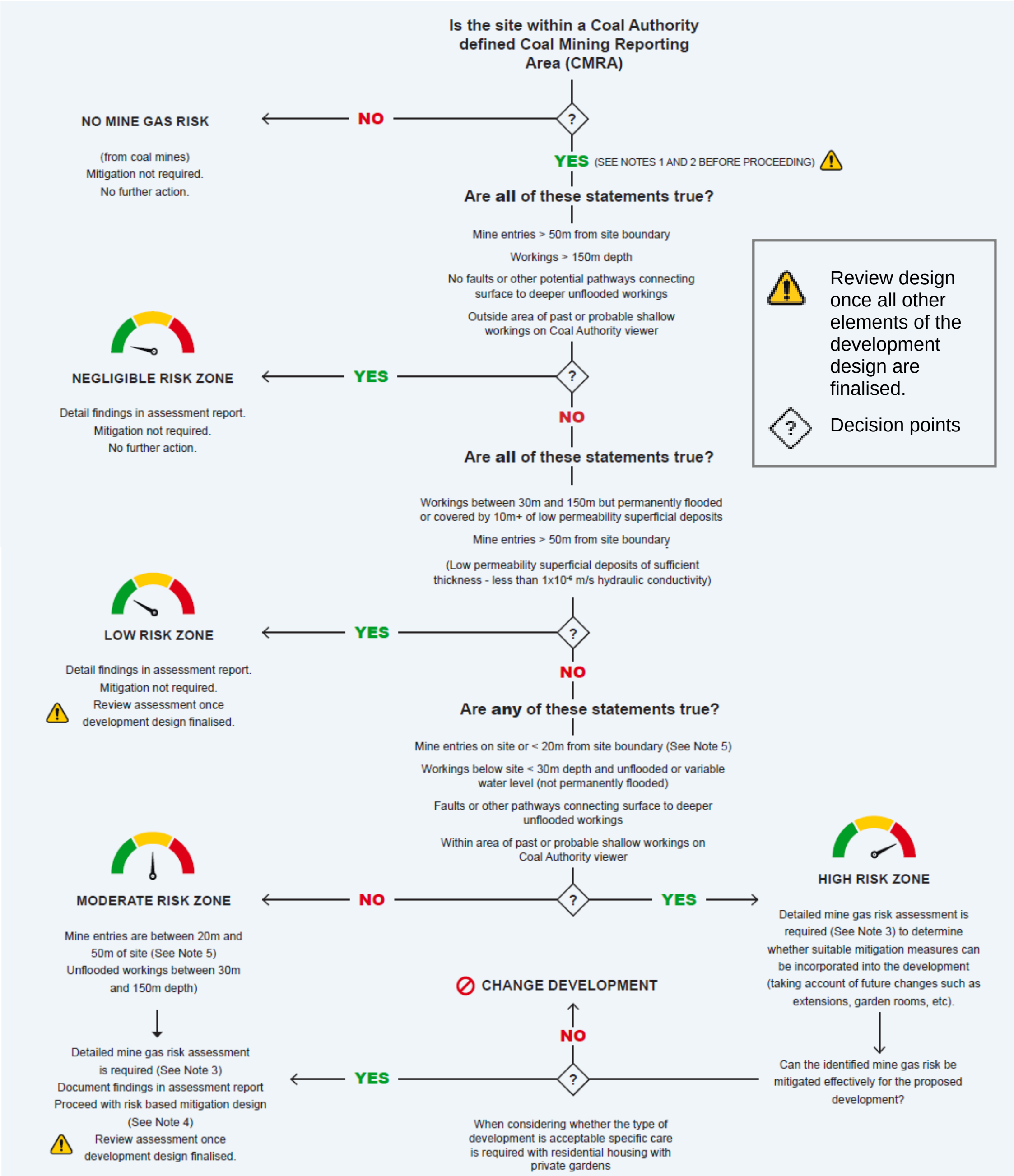


Figure 13.1: Decision support tool for mine gas risk assessment. For a larger version, see page 73.

Please refer to notes on the following page.

Notes for Figure 13.1: Decision support tool for mine gas risk assessment

Note 1: Preliminary Information Requirements

Before proceeding further with the decision process the following should be in place:

1. Sufficient information to develop an initial schematic CSM. This should be a site specific visual CSM (i.e. geological cross section showing development proposals including foundations, mine entries and workings with relevant seam levels). Examples of visual CSMs are provided in Appendix 4: Case studies.
2. Comprehensive desk study information collected from sources including Coal Authority Consultants Report and other data.
3. Data have been checked and are sufficiently robust to allow the preliminary mine gas risk assessment and design of any site investigation if required.

Note 2: Decision Process

- The decision process is started with a desk-based study. The process is followed and at any point if site investigation data are required to confirm any specific factor then a suitable investigation should be designed, the data collected and then the decision process restarted.
- For example, where workings are considered permanently flooded at shallow depth, groundwater level monitoring may be required to confirm likely variations will not cause levels to drop below the level of the workings. Likewise, site investigation may be required to confirm the thickness and nature of any low permeability layer to determine if it can be relied on as a barrier to potential gas migration.

Note 3: Detailed Mine Gas Risk Assessment

- Detailed mine gas risk assessment will require suitable site investigation and use of a multiple lines of evidence approach to risk assessment.
- Consider - depth and permeability of drift deposits and if >5 m to rockhead from underside of foundations and drainage trenches (including any deep soak away or attenuation tanks).
- Model and assess gas migration rates through the ground using approaches in the Ground Gas Handbook (Wilson *et al.,* 2009).
- Assess whether shafts or other pathways are connected to unflooded deep or shallow workings.
- Assess risk of gas migration from shaft or adit (consider filling, capping type, any venting and geology and relationships between flow rates and meteorological conditions).
- Detailed assessment of gas monitoring data looking for correlations of flow rates with barometric pressure, temperature, groundwater levels and whether elevated flows are likely to be associated with mine gas emissions, consideration of gas ratios and other potential sources of gas.
- Assess volume of potential gas reservoir that could accumulate in workings.
- Assess impact on the gas risk of any grouting works to shallow mine workings. Consider relevant uncertainties from Table 14.1.
- Consider credible future changes that could impact on mine gas risk (water level changes or grouting in connected workings).
- Consider risk to external areas (gardens, landscaped areas) e.g. sheds. The rate of gas emissions from open fractures or shafts can overcome the ventilation in these types of buildings.
- Consider floor construction and resistance to gas ingress.

Note 4: Design of Gas Protection System

- Design gas protection measures (see CIRIA Report C801 - Site Guide for Hazardous Ground Gases (Mortimer *et al*., 2021) for guidance on procurement and competence). The points system in BS 8485 should not be used, site specific detailed risk-based design is required.
- Specify requirements for floor slab construction (with respect to gas protection).
- Specify appropriate gas membrane.
- Design venting layer if required based on estimated gas expansion and flow rate from mine workings during fall in barometric pressure (see CL:AIRE TB17 (Wilson *et al.,* 2018a) for critical events).
- Consider implications of residual uncertainty on mitigation design.

Note 5: Adits

- Adits require specific consideration of their direction in relation to the development. In cases where the adit entry is close to the development (between 20 m and 50 m or less than 20 m) but it dips in the opposite direction, it might not be considered a pathway for mine gas emissions and may be considered low risk.

13.1 Assessment of Gas Monitoring Data

Depleted oxygen concentration and presence of carbon dioxide or methane on their own are not good indicators of mine gas risk as these can occur in intact Coal Measures or overlying superficial deposits where they are not indicative of elevated surface emissions. This is because they can be caused by redox reactions and biological oxidation with very low reaction rates. Methane can desorb in small quantities into a monitoring well in intact Coal Measures and cause high concentrations. Oxidation of the coal can occur in the side walls of the well and again small volumes of gas can cause high concentrations in the well head space. The small volumes of gas and elevated concentrations are not representative of large volumes of gas in the surrounding ground. It is therefore necessary to assess gas concentrations and flow rates in conjunction with the CSM. The following may be useful:

- Presenting gas monitoring data as ternary plots can be useful in assessing gas risk but has to be used with care (an example is shown in Figure 13.2). Advice on ternary plots is provided in Ground Gas Information Sheet No 1 (Wilson *et al.,* 2018b). Further details are provided below with respect to mine gas risk and carbon dioxide.
- Carbon dioxide and depleted oxygen are commonly recorded in monitoring wells installed in either unworked strata with no credible pathway to workings or in superficial deposits. This is caused by carbon cycling processes that occur in the vadose zone such as biological oxidation and the concentration varies with temperature, soil moisture, nutrient availability and oxygen supply. If oxygen and other electron acceptors such as nitrate and sulfate are depleted methane can be produced under reducing conditions close to the water table. This may be oxidised as it diffuses higher up the soil column to a point where oxygen can ingress. If this is the case, the monitoring results will plot within the zones identified in Figure 13.3. Steady state flow rates from unflooded wells will be low and consistently less than 1 l/h. These processes are widespread in soils and rocks across the UK and do not cause any significant surface emissions of gas from the surface (although due consideration of underground spaces is required).
- Where a well is installed above workings and oxygen depletion is observed without any corresponding increase in carbon dioxide or methane, it may be an indication that soil air is being displaced by oxygen deficient air migrating from below. Other gases such as hydrogen sulfide and carbon monoxide can also replace oxygen in air if they are present in sufficient volumes. This depends on the nature of the coal and the workings as different chemical reactions can occur in difference surfaces. However, they are toxic at much lower concentrations than required to deplete oxygen to unacceptable levels. Sampling and testing for trace gases can be useful in the assessment.
- Where carbon dioxide is present without any corresponding decrease in oxygen:nitrogen ratio (i.e. no consumption of oxygen) it may be an indication that soil air is being displaced by carbon dioxide migrating from below. In this case the gas monitoring results will plot well above the stoichiometric line for biological respiration in Figure 13.3.

- Low flow rates (steady state from unflooded wells) with variations that have little correlation to variations in air temperature or barometric pressure indicate a low potential for mine gas emissions (at the monitoring locations).
- Regular occurrence of higher flow rates in both the negative and positive direction indicates possible air flow from mine workings or nearby entries. There may be a strong correlation with changes in air temperature and/or barometric pressure and/or wind speed. The correlation is likely to be stronger for open shafts and will reduce as the permeability of any infill reduces. BS 8485 (British Standards Institution, 2015) states:

  > *If a negative flow is recorded it should not automatically be discounted. Rather, an assessment of whether, under different temporal conditions, a similar positive out-flow of gas could occur should be undertaken, consistent with development of the CSM. Only when the reason for the negative value is reasonably understood, and a positive flow can be credibly ruled out, should a negative value be discounted.*

  This is particularly relevant to mine gas assessment.
- Variation of gas concentrations with barometric pressure or temperature alone is not a good indicator that mine gas emissions are occurring.
- Methane diffuses out of coal extremely slowly (over geological timescales) and this means that the closer a seam is to the surface the less methane coal contains. Shallow seams tend to have much lower methane content than deeper seams.
- Continuous monitoring data are often useful when assessing mine gas risk and advice on their interpretation is provided in Talbot and Card (2019).

13.2 Ternary plots

Often carbon dioxide from mine workings is of concern and methane may not be present. Carbon dioxide is produced widely in unworked Coal Measures and other strata by aerobic biological (microbial) respiration (or oxidation) of organic material, represented as follows:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

(CH_2O being a general representation of typical 'organic matter')

This means that as oxygen is consumed and the oxygen concentration reduces, the carbon dioxide concentration increases in the same proportion. The zone this trend occupies is shown on the bottom left hand corner of the ternary plot in Figure 13.2. Note that the plot has methane, carbon dioxide and balance + oxygen axes to define the zone (they are not normalised – see Ground Gas Information Sheet No 1 (Wilson *et al.,* 2018b) and balance is assumed to be nitrogen).

There may also be trace amounts of methane caused by anaerobic decomposition in small anaerobic hotspots, or the reduction of carbon dioxide by methanogens in more widespread reducing environments. Oxygen concentrations will also be depleted, but in this scenario oxygen deficient air is unlikely to be emitted quickly from the ground and it does not pose a risk to surface development. However, similar concentrations can also occur when coal is oxidised and therefore the assessment has to take into account the location of the monitoring response zone and potential CSM pathways, as well as flow rates as described above.

The most appropriate and consistent way of presenting data in a ternary plot is to use methane, carbon dioxide and balance + oxygen as the axes (not normalised data). Detailed consideration of the variation in gas flow rates with atmospheric pressure, including under worst-case conditions, and both negative and positive flows, is also required.

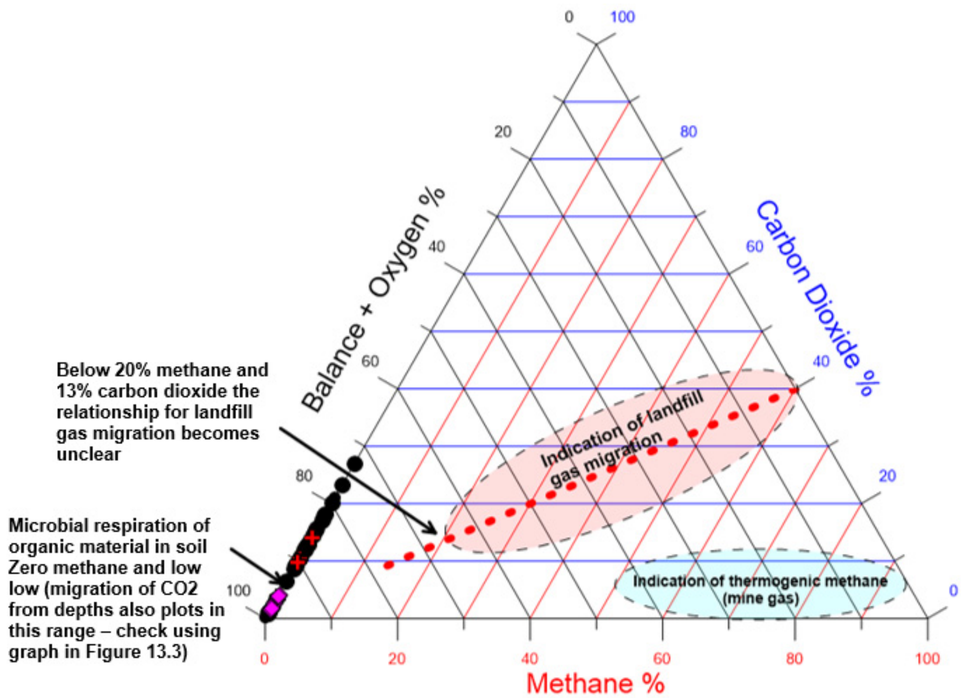


Figure 13.2: Ternary plot showing aerobic soil respiration, thermogenic methane and landfill gas migration zone (after Wilson *et al.*, 2018b). For a larger version, see page 74.

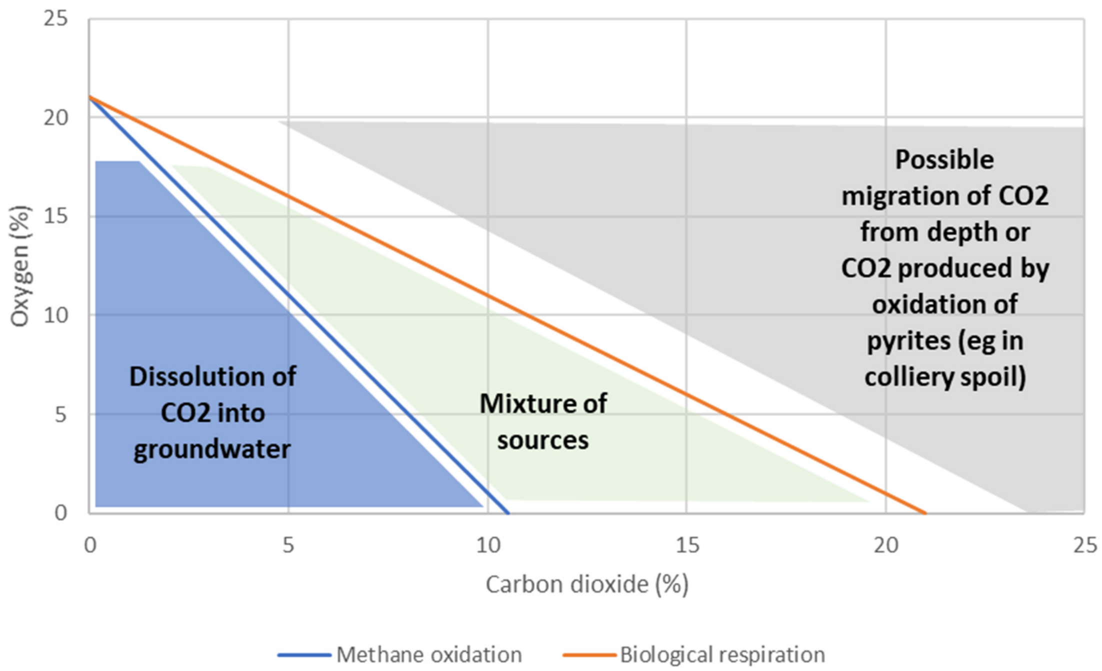


Figure 13.3: Stoichiometric assessment of carbon dioxide and oxygen. For a larger version, see page 75.

14. Identifying and Managing Current and Future Uncertainties

There will always be an element of uncertainty in any ground gas (or other contaminated land) risk assessment. Table 14.1 highlights some potential areas of uncertainty in mine gas risk assessment and possible ways of reducing them. It is important to recognise that this requires site specific investigation and assessment for relevance and credibility. Generic statements are not appropriate (see Appendix 4: Case Study 3).

Although a precautionary approach should be applied to any risk assessment, this is not an excuse to invent hypothetical or extremely unlikely hazards or consequences and thus to recommend the mitigation of improbable or irrelevant risks. The data collected may also feed into a multiple lines of evidence approach as described in CIRIA Report C795 (Wilson *et al.*, 2020).

Table 14.1: Consideration of potential uncertainties.

Aspect	Further assessment options
Seasonal or tidal effects on groundwater levels not sufficiently understood	If the data gap is likely to significantly affect the risk outcome, then consider additional spot monitoring over a longer time period and/or continuous monitoring including groundwater levels
Effect of worst case conditions not adequately characterised, i.e. falling atmospheric pressure	As above
Absence of shallow mine workings or shafts/ adits not sufficiently investigated	May be addressed through additional desk study or site investigation, typically alongside a geotechnical assessment of settlement, or using remote sensing or geophysical methods
Ground gas source(s) not sufficiently understood	Consider additional lines of evidence e.g. further site investigation, bulk gas analysis, groundwater sampling and testing for dissolved gases, gas isotopic analysis
Preferential pathways to mine workings at depth or characteristics of overlying low permeability deposits not adequately characterised	Consider whether additional lines of evidence will significantly alter the outcome of the assessment and if so, collect further data e.g. further site investigation, geophysical surveys, surface monitoring surveys, flux box testing etc.
Mine stabilisation works will be needed to support the proposed development	The likely effect of this on the CSM needs to be considered. Gas monitoring is likely to be a requirement of Coal Authority licensing and should be evaluated. Additional site investigation/ gas monitoring/ risk assessment may be required post-grouting.

Aspect	Further assessment options
Future increases in groundwater levels, e.g. due to groundwater rebound following cessation of mine water pumping not sufficiently understood	Consider effects within CSM and in particular whether groundwater is fully recovered or if not, how rising groundwater levels could affect interconnection of workings. However, assessment may be limited by availability of existing data for workings in wider area.
Is it credible that subsequent development on adjacent sites could affect the mine gas risk	Effects such as ground sealing and future mine stabilisation should be considered within the CSM
Is it credible that future effects due to climate change could affect mine gas risk	A range of potential effects that are relevant to a site could be considered within the CSM and assessment – see further discussion below
Future changes to a building could increase the potential for mine gas entry or accumulation	Consider the impact of changes to the building in the risk assessment, e.g. reduced ventilation of occupied spaces, blocking of underfloor vent points by extensions

The Scottish Government report (NHS Lothian, 2017) noted that application of the National Quality Mark Scheme (NQMS) for land contamination to gas risk assessment reports could be beneficial since this specifically requires that uncertainties in risk assessments and their implications are explicitly documented.

For reference, BS 8485 also states that uncertainty should be taken into account in the mitigation design. This might be taken into account in an increase in the number of levels of protection, gas protection score, or uprating certain elements of the gas protection measures. However, this is not a substitute for an adequate risk assessment / CSM development and is an option that is chosen on an informed basis by a risk assessor.

It is extremely important that the influence of climate change, foundation and other development factors and grouting on mine gas risk are considered. Further advice is provided in Appendix 3. The Scottish Government research (NHS Lothian, 2017) reported that '*there can be a disconnect between ground gas and geotechnical/ structural assessments for building design*', which undermines the precautionary nature of the gas mitigation design.

15. Key Conclusions and Recommendations

The presence of a development over coal workings or areas of non-coal mining, does not necessarily mean that there are risks due to gas emissions. If emissions do occur into buildings, the consequences can range widely from mild to severe health effects or even death. The consequences of the hazard are severe but the probability of significant mine gas entry into buildings is low. All recorded acute incidents have been caused by gas emission from open / unsealed mine entries (shafts or adits) or from shallow mine workings combined with an open or highly permeable pathway for gas migration to the surface (deep workings may also be connected to shallow workings by shafts or adits). The potential for gas emissions also increases where groundwater levels are still recovering or fluctuate above and below any workings. Once a mine becomes completely flooded, the risk of gas emissions reduces significantly. The risk of significant emissions at the surface from deep workings below 150 m is low unless there are shafts, faults or other pathways linking the workings to the surface.

There are specific circumstances when mine gas can pose a significant risk (acute or chronic) to development, and this document describes how to identify when gas mitigation measures are likely to be required (in buildings) or not. The blanket application of gas mitigation measures to all new development in coalfield areas is unnecessarily discouraging and costly for development and may be either insufficient or too precautionary depending on the minimum standard applied.

Mine gas risk assessments should be transparent and should include all data used in Appendices so that the complete document is readily auditable.

Key recommendations and information, which are detailed in this guidance, are provided below:

1. Reference should be made to the main information sources that are available to assist assessors carrying out site investigations for mine gas and mine gas risk assessments.

2. Mine gas risk assessments and mitigation design should be carried out by ‘competent persons’ as defined in the National Planning Policy Framework in England and equivalents in the devolved governments.

3. It is important to understand the different methods of working coal, the effect this has on the likely presence of a mine gas hazard being present below a site and the corresponding risk of emissions into buildings. At the very least, CIRIA Report C758D (CIRIA, 2019) is considered to be essential reading for anyone undertaking mine gas risk assessments.

4. Development of a CSM is a vital part of any mine gas risk assessment as well as its use in the interpretation of any gas monitoring data.

5. Risk assessment using the gas screening values and the ‘points system’ in BS 8485 on its own is not likely to be appropriate where there is a risk of mine gas emissions on sites with complex CSMs or where mass advection of soil gas

could occur. Detailed quantitative assessment of gas emissions may be necessary.

6. It is important to consider the effect of foundation construction and other below ground infrastructure on migration pathways and the integrity of any barrier layers, and the implication for the mine gas risk assessment.
7. It is vital that after the site investigation or gas monitoring is complete that any boreholes, probeholes or wells are decommissioned and sealed in a manner that prevents them acting as migration pathways for mine gas.
8. Potential areas of uncertainty in mine gas risk assessment and the effects of future changes should be considered. It is important to recognise that this requires site specific investigation and assessment for relevance and credibility. Generic statements are not appropriate (see Appendix 4: Case Study 3). Although a precautionary approach should be applied to any risk assessment, this is not an excuse to invent hypothetical or extremely unlikely hazards or consequences and thus to recommend the mitigation of impossible risks.
9. One of the most significant issues at the Gorebridge incident in Scotland was the disconnect between the gas risk assessors and the development designers. Mine gas risk assessment reports should be transparent as to the foundation (and other) design features that are assumed or included in the assessment. The reports should make it clear that if final designs change, then the gas risk assessment will require updating (even if the risks do not change significantly).

16. Glossary

Term	Definition
Adit	Non vertical mine access roadway (usually walkable) driven from the surface and used for removal of mineral, ventilation, pumping water etc. See also Drift; Sough; Level; Day Level
Advection	Movement of chemical constituents in a fluid (including liquid and air) down a pressure gradient
Asphyxiation	To deprive of oxygen often leading to unconsciousness or death
Bell Pit	A shaft down to the coal seam which was widened at the base to remove the coal. Shaped like an upside-down bell
Blackdamp	A mixture of gases formed when oxygen is removed from mine air and is replaced by carbon dioxide, also known as 'stythe' or 'chokedamp'. The main components are carbon dioxide and nitrogen, but the precise composition of blackdamp will vary from mine to mine
Broken Ground	Area of disturbed ground usually associated with the collapse of overlying strata into former coal workings
Carbonaceous	Consisting of, containing, relating to, or yielding carbon
Coalfield	An area in which deposits of coal are found
Coal Measures	Coal-bearing part of the Upper Carboniferous System
Coal Rank	Coal rank is the measure of the degree of 'coalification' of a coal from low-ranking lignite to high-ranking anthracite. As the rank increases the carbon content also increases).
Coal or Mine Workings	Areas of underground strata from which coal is being or has been mined. Coal workings can be open and void, partially collapsed and semi void, totally collapsed with little void space or infilled with fill material. See also - Broken Ground
Competent person	A person with a recognised relevant qualification, sufficient and relevant experience, and chartered membership of a relevant professional organisation
Conceptual Site Model (CSM)	An illustrative representation of the ground conditions and the physical, chemical and biological processes that control the generation, transport, migration and potential impacts of mine gas to receptors
Day Level	Non vertical mine access roadway driven from the surface. See also 'Adit'
Desorption	The release of gas from coal where it has been stored on the surfaces of the internal structure

Term	Definition
Diffusion	Movement of a fluid from an area of higher concentration to an area of lower concentration. Diffusion is a result of the kinetic properties of particles of matter. The particles will mix until they are evenly distributed
Drift	See also 'Adit'. Non vertical mine access roadway. Particularly known as a drift when driven as a major access
Drilling	The intrusive process by which ground is penetrated by percussive, rotary or rotary percussive or resonance techniques to obtain samples or data, provide access for installations and ground stabilisation etc.
Fault	A fracture or fracture zone in rock along which there has been an observable displacement
Firedamp	Mining term used for methane and associated alkanes
Gas screening value	An indicator of the level of gas risk. It is determined by considering the individual hazardous gas flow rates from monitoring data (flow rate x gas concentration) together with consideration of data reliability, temporal and spatial variations and shortages of data and the CSM for gas (e.g. likely sources of gas).
Groundwater	Water present in the cavities and spaces in soils and rocks
Ground Investigation	Exploration and recording of the location and characteristics of the subsurface. Specialist intrusive investigation on a site with the associated monitoring, testing and reporting. This may comprise boreholes, trial pits, penetration tests, laboratory tests and geophysical methods
Grout	Refers to a mixture of cementitious material and aggregate to which sufficient water is added to produce pouring consistency without segregation of the constituents but will gain strength over time
Level	See also 'Adit'. Non vertical mine access roadway. Often known as a level when driven for mine drainage
LEL	Lower Explosive Limit, the lowest concentration of a specified gas in an air mixture that can explode if an ignition source is introduced.
Mine Entry	See also 'Adit' and 'Shaft'
Outcrop	The area over which a coal seam (or other rock type) occurs at bedrock level – whether exposed at ground surface, or buried beneath superficial deposits
Oxidation	To convert into an oxide; combine with oxygen
Permeable Ground	Rock or superficial deposits that will allow gas and/or water to pass through it with relative ease
Piling	Construction of deep foundations by driving a preformed pile (usually concrete or steel) into the ground or by casting concrete in a pre-bored shaft which may be cased or uncased

Term	Definition
ppm	Parts per million
Preferential migration pathway	A pathway of high gas permeability through a soil or other medium that connects a source to a receptor and allows greater gas flow than would occur through the surrounding ground
Pyrite or Iron Pyrite	An iron sulfide with the formula FeS_2. Nicknamed 'fool's gold' due to its resemblance to gold. Often found in association with coal seams
Risk Assessment	The formal process of identifying, assessing and evaluating the health and environmental risks that may be associated with a hazard.
Rockhead	Interface between soil (superficial deposits) and the underlying solid rock
RoGEP	The Register of Ground Engineering Professionals provides external stakeholders, including clients and other professionals, with a means to identify individuals who are suitably qualified and competent in ground engineering
Shaft	Vertical or almost vertical opening used for access to the mine, removal of mineral, ventilation of a mine, or pumping water, etc
Shallow mine workings	Shallow workings are usually defined as those at a depth of less than 30 m (Coal Authority, 2012).
SiLC	A registered Specialist in Land Condition is a senior practitioner who has a broad awareness, knowledge and understanding of land condition issues, providing impartial and professional advice in their field of expertise.
Site Investigation	The overall process of determination of the physical characteristics of sites as they affect design, construction and stability of neighbouring ground or structures
SoBRA	The Society of Brownfield Risk Assessment has developed this registration scheme in order to recognise and reward the technical skills associated with land contamination risk assessment. The SoBRA scheme does not demonstrate that an individual is an expert, but it shows that the individual possesses the critical technical, scientific and communications skills required to design, perform and/or critically evaluate land contamination risk assessments.
Sough or Slough	Non vertical mine access roadway. Particularly known as a sough when driven for mine drainage. See also 'Adit'
SQP	A Suitably Qualified Person is a registered experienced professional in the field of land contamination management.
Stinkdamp	A mining term for hydrogen sulfide
Stythe	See blackdamp
Superficial deposits	Soil materials overlying rockhead. The most recent deposits, mostly unconsolidated (e.g. sand, silt, clay, mud, etc)

Term	Definition
UK	United Kingdom of Great Britain and Northern Ireland. Refers to the areas and legislative frameworks for England, Scotland, Wales and Northern Ireland.
Whitedamp	A mining term for carbon monoxide

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Appendix 1: History of Mining Methods and Implication for Mine Gas Risk

Table A1.1: History of mining methods and implication for mine gas risk.

Period and type of working	Implications for mine gas risk assessment
From about the 12th Century early mining of coal was from surface outcrops. This also occurred during the 1920/30s in some areas (e.g. from cellars in northeast England). The workings were small scale and known as Day holes (day is a mining term for surface). Short adits (day levels) were also driven into slopes or hillsides where coal outcropped but these would have been short due to a lack of understanding of ventilation and roof support. This type of working is not generally recorded at the time. The further from outcrop a site is, the less likely they are to be present.	The potential for mine gas emissions occurring from unrecorded early workings is greatest close to coal outcrops at the ground surface, where there is a thin or no covering of overlying superficial deposits. There may be a mine gas risk from shallow local unrecorded workings in some urban areas where sites are being redeveloped.
Adits were used to extend workings deeper into outcropping seams. They were often located in the side of river valleys or on hillsides. In some places once the ventilation and support technology was available they extended deeper along seams. Adits were also driven to allow gravity drainage of seams that were reached by other adits or shafts (also known as drainage level, day levels or level rooms). Adits were also driven as inclined shafts to reach deeper coal seams and some of these were constructed in the 20th Century. Maps and plans exist for many adits. More comprehensive records sometimes exist for major adits, especially those more recently driven.	Adits can present an important pathway for migration of mine gas from large scale workings to the surface (at a single, concentrated location). Gas emissions can be affected by collapse fill and flooding within adit and connected workings. Gas emissions through strata overlying an adit are very unlikely to be significant (compared to flows along the adit).
Bell pits were used by the 13th Century where the coal seam had a shallow dip and superficial deposits were thin or absent. It was more widely adopted over adits to reach deeper seams from the 16th Century. A 1 m to 1.3 m diameter shaft was sunk to the seam and then the coal removed from around it. The excavation extended until the roof became unstable or when ventilation became restricted, or groundwater inflow exceeded bailing capacity. Maximum depth was typically around 12 m but there may be several located parallel to the seam outcrop nearby. These workings were not recorded.	The potential for mine gas emissions occurring from unrecorded early workings is greatest close to coal outcrops at the ground surface, where there is a shallow or no covering of overlying superficial deposits, which is where bell pits are most likely. Bell pit shafts can form pathways from the coal seam directly to the surface. Collapses are commonplace and can lead to subsidence and fracturing of overlying strata.

Period and type of working	Implications for mine gas risk assessment
Shafts were used to reach deeper coal horizons from the 16th Century onwards. At first crude pumping methods were used in a single shaft. From the 17th Century it was increasingly common to use additional entries to increase ventilation, but shaft depths rarely exceeded 60 m. The Coal Mines Act of 1862 made it law that mines had at least two shafts. Over time pumping methods improved and by the end of the 18th Century some shafts had been constructed up to 250 m depth with a diameter of 4 m. Further legislation specified that shafts had to be separated by 3 m and then 13.6 m of natural material. Some modern shafts extend to depths of 1000 m. Drainage levels may also have air shafts associated with them.	The potential for mine gas emissions from deeper workings reduces with increasing depth. The main area of risk is around former shafts or adits or where faults provide a preferential pathway to the surface. Historical maps, aerial photographs (including infrared) and Coal Authority records should be assessed to determine the location of shafts on or close to a site where mine gas risk is being considered. A geological cross section drawn to natural scale, showing the depth of the potentially worked seams and overlying geology, is a vital part of a mine gas risk assessment to allow an understanding and assessment of gas emissions from a worked seam.
Horizontal drifts were sometimes driven underground from one seam to reach another seam.	Workings at different levels may be connected underground which could influence the risk of mine gas emissions at the surface.
Room and pillar workings originally developed to allow extension of bell pits and rarely extended more than 40 m from a shaft. The excavations to remove coal were supported by pillars of unmined coal. They were not planned, and the layout was arbitrary. By the end of the 17th Century workings rarely extended more than 200 m from a shaft. The method became progressively more systematic with later workings extending greater distances from shafts and having distinct rectilinear networks of interconnected roadways supported by pillars of unworked coal. Pillar robbing (removing the coal) at the end of mine operation was common. Local styles and terminology developed in different areas (e.g. pillar and stall, post and stall). By the 19th Century the pillars were generally square and rooms were between 1.8 m and 4.6 m wide (extraction ratios 30% to 70%). Later workings had rooms between 6 m and 9 m wide and extraction ratios of 50% to 60%. It was little used in more recent mining.	The depth and extraction ratios of room and pillar workings will influence the potential for large voids being present for gas accumulation and the potential for migration via fractured rock above the workings. Investigations to assess the risk of voids being present where gas can accumulate should be sufficient to minimise the risk of all the holes encountering intact pillars. Room and pillar workings are typically at shallower depths <100 m and can remain stable for many years after mining has ceased.
Longwall mining was originally developed in the Shropshire coalfield in the 17th Century and was then developed and mechanised. A coal face	The depth and longwall length will influence the potential for large voids being present for gas accumulation and

Period and type of working	Implications for mine gas risk assessment
(the longwall) that is tens or up to 300 m long is accessed by roadways perpendicular to it. The coal face area is supported temporarily and as the works advance the roof behind is allowed to collapse to leave an area of waste (known as the goaf). The roadways are advanced with the face. More modern mines have two parallel roadways about 200 m to 300 m apart and retreat mining was developed in the 1960s where the roadways are advanced to the full extent first and the coal extracted by working backwards. A development of using a short coal face up to 45 m long and a single roadway was known as short wall mining but was not widespread. It can result in the goaf not collapsing completely so it can contain large voids where gas can accumulate.	the potential for migration via fractured rock above the workings. Longwall mining is typically >100 m deep (Todd *et al.,* 2019) which means the potential for gas emissions via the overlying ground is lower than with shallower workings unless shafts/adits/faults create pathways.
Surface mining methods are in effect quarrying for coal (known as opencast mining). The overburden is stripped back to expose the coal seam which is excavated. They are generally located where the overburden is relatively thin and are worked until the depth of overburden makes them uneconomic. Several seams may be worked in one pit. The overburden is normally stockpiled and then used to reinstate the excavation.	Sometimes seams previously worked by room and pillar methods are worked by open cast methods, effectively removing the old workings from below a site. However, the potential for older workings around the opencast area providing a source/pathway for mine gas to enter the backfill should be considered. Carbon dioxide emissions up the backwall of open cast sites has occurred where the excavation has intercepted old workings. Freshly backfilled opencast can produce very high concentrations of carbon dioxide in monitoring wells (sometimes methane too), with correspondingly low oxygen concentrations. Gas emission rates from the undisturbed surface would likely be very low, but consideration should be given to potential enhanced migration pathways and the impacts of fluctuating water levels within the backfill.

Appendix 2: Gas Sampling and Isotope Testing

Trace gas testing and isotope testing can sometimes be useful to differentiate gas from different sources (e.g. if the gas source may be landfill or mine gas, or if biological oxidation of organic material in drift deposits is occurring). Where it is necessary there are three commonly used methods to distinguish between gas sources in the ground:

1. Analysis of the composition of the gas in terms of the main and trace constituents (e.g. methane, carbon dioxide, ethane, propane, hydrogen sulfide, carbon monoxide, etc). Its composition may then be compared to the composition of known sources in published references. Thermogenic gas (including methane from coal) has a greater proportion of higher chain hydrocarbons (ethane, propane, etc) than biogenic gas, which has little if any at all. The methane to ethane ratio of thermogenic gas such as mine gas will be less than about 100 and for biogenic gas it will be greater than about 1000.

2. Analysis of the stable isotope ratios of the atoms in the gas. Methane is made up of one carbon atom and four hydrogen atoms. The stable isotope ratio of carbon ($^{12}C/^{13}C$) and for hydrogen ($^{2}H/^{1}H$) can be compared to various published ratios for gases from known sources and may enable identification of mixed sources.

3. Radiocarbon dating of ^{14}C. The half-life of ^{14}C is known and by measuring the quantity of ^{14}C the age of the gas can be estimated. Geologically old carbon dioxide or methane will contain no ^{14}C, while carbon dioxide and methane derived from terrestrial organic matter grown in the last 60 years or so will be enriched in ^{14}C (from atmospheric nuclear bomb tests in the 1950s and 60s). This helps distinguish between gases that have been generated in different geologic time periods (e.g. it can be useful when trying to distinguish between gas generated recently, such as from landfills and that generated many millions of years ago in coal). Such radiocarbon testing has historically been expensive compared to the other methods and has typically only been used in more complex situations. New methods developed by the Scottish Universities Environmental Research Centre have simplified the process and made it more accessible and cost effective. However, some care is still required, such as where Glacial Till is present, as the last glaciation in the UK was about 10,000 to 12,000 years ago and biological oxidation of organic matter in the till will produce carbon dioxide with a radiocarbon date around that time. This can then be misinterpreted as due to mixing of older gas with modern gas from shallow soil organic matter, which can give a similar ^{14}C value.

The main factors that affect the trace constituents and the isotopic signature are the age and processes that generated the gas. The gas composition and stable isotope ratios can also change as a result of chemical processes that might occur as gas migrates through the ground. Bacteria in the ground can oxidise methane to carbon dioxide in the right conditions and this will change the isotopic signature (methane will be enriched in ^{13}C). The complexity of interpretation and the time and cost involved, need to be balanced against the significance of the uncertainties that are driving the more intensive analyses such as those described above. This type of testing is the exception rather than the norm. Isotope testing has limited commercial availability in the UK, especially ^{14}C. It is possible to send samples to other countries for testing where it is offered as a commercial service.

Appendix 3: Future Changes

The risk assessor should distinguish between and consider two different types of future change in the context of the assessment:

- Future changes which will become crystallised (accurately defined) before construction commences. Typically, these would be changes in the understanding of ground conditions due to supplementary investigation, grouting work and monitoring or changes to development design e.g. revisions to layout, earthworks levels, foundation, or drainage design. The mine gas risk assessment should be considered a ‘live document’ in these circumstances and should be updated by a competent person when the design is fixed and before construction commences.
- Future changes which are not likely to be fully definable by the design team before construction commences but which may have an effect on the assessment (e.g. climate change, changes in regional groundwater level, off-site engineering works and adjacent development). Incorporating these potential changes relies on good engineering judgement and communication with relevant stakeholders (e.g. Coal Authority, Environment Agency / Scottish Environment Protection Agency / Natural Resources Wales, Building Control, Local Authority) who may have more knowledge of off-site conditions. These are less likely to be definable in detail and more likely to result in some uncertainty being incorporated into the risk assessment.

A3.1 Climate Change

It is accepted that the climate is changing, and this will affect future weather patterns and seasonal norms. At some (but not all) sites the impacts of climate change may influence the risk posed by the presence of mine gas and this should be considered on a site specific basis in any ground gas risk assessment.

The likely effects of climate change in the UK that are relevant to ground gas risk are:

- Increase in frequency of warm spells;
- Increase in frequency of heavy rainfall events and increase in rainfall intensity. The UK climate is becoming wetter, but the magnitude depends on location;
- Increase in dry spells in summer.

For other countries there may be different impacts depending on location in the world.

The data on the effects on atmospheric pressure drops or windstorms are inconclusive. However, barometric pressure drops of at least 24 mb in 24 hours are not unusual in the UK at present and might reasonably be expected to continue to occur in the future. Such barometric changes are capable of significantly influencing gas emissions in many cases.

Increased atmospheric temperatures in summer could reduce or even reverse gas flow up shafts (as temperatures in mines are less likely to rise significantly or by as much as at the surface). The increased dry weather could also cause a drop in groundwater levels that may expose previously flooded workings in some cases. This will depend on the site specific hydrogeology and extent of climatic change actually experienced.

The increased rainfall will generally increase flood risks (predominantly surface water flooding and possibly in some situations groundwater flooding), but these will vary greatly depending on site specific locations (relative to the flooding waterbody). There is no evidence of current flooding having a significant influence on mine gas migration / emissions, but there may be site specific factors that lead to a potential future risk under specified future flooding conditions. It is noted that most developments will be accompanied by a separate flood risk assessment that should provide valuable information in this regard.

A useful tool for assessing the risk associated with rainfall and groundwater levels is continuous monitoring of gas concentration, flow rates and groundwater levels combined with meteorological data from the same timeframe. The greatest risk is where groundwater is shallow and responds more quickly to rainfall, for example, where a site lies in a valley and rainfall in a large surrounding catchment feeds groundwater below a site. Groundwater at depth in coalfields is less sensitive to short intensive rainfall events but rebound will ultimately be affected by longer term changes in aquifer recharge driven by seasonal climatic changes.

A site specific assessment of the impact of climate change should consider whether the effects listed above are likely to increase mine gas risk such that the level of gas protection to be provided is sufficient to keep risk acceptably low. Generic statements that climate change could increase risk are not appropriate. In many cases the effects from climate change will not significantly change the risk.

Risk assessment should consider changes in future building use that can reasonably be expected to occur without requiring an improvement to the gas protection. Any risk assessment should include sensitivity analysis that considers changes in ventilation (e.g. fitting double glazing, blocking of chimney/opening up chimney, etc). This should be looked at in context of what is possible and the likely effects on a building on a site by site basis. The air changes per hour used in the standard risk assessments are already very cautious and may well cover such scenarios. The impact on driving pressure from the stack effect can also be taken into account on a site specific basis.

There is a trend in the industry to just state that 'future changes will increase gas risk' with no thought as to whether that is credible on a specific site. On many sites it is the generation rate or migration rate in the ground that will be the limiting factor and not the building parameters.

An assessment of the impacts of climate changes should provide the following:

- A balanced consideration of credible and foreseeable events vs 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, global warming, extreme weather conditions, the closure of mines, and possible changes to the gas regime caused by future development, as discussed above.

Any gas risk assessment should be precautionary, but this is not an excuse to invent hypothetical consequences that cannot occur on a site. The presence of gas in the ground does not mean that it poses a risk to development, nor that it will automatically become a risk because of climate change.

A3.2 Foundation Design and Other Development Risks

The gas risk assessment should take into account **any reasonably foreseeable changes** that will be caused by the development and that could affect the CSM and hence the level of risk assessed. However, it should be recognised by assessors that knowledge of details such as foundation or drainage design, may be incomplete at the time the gas risk assessment is undertaken to support a planning application, or it may be subject to later design development. In the Gorebridge case itself, it was identified that a contributory factor to the incident was that the gas risk '*assessment did not apparently anticipate the additional risk associated with the impact of treatment measures used to stabilise the site, including extensive grouting of the area, and use of vibro stone columns to provide support to the house foundations*'. Grouting of mine workings on a nearby site may also have contributed to the gas emissions. The Scottish Government research (NHS Lothian, 2017) reported that '*there can be a disconnect between ground gas and geotechnical/ structural assessments for building design*', which undermines the precautionary nature of the gas mitigation design.

Good practice entails review and updating of the gas risk assessment whenever a change is made to foundation design, particularly in the case of adoption of piling or stone column techniques. The Environment Agency has previously published guidance (Environment Agency, 2001) applicable to such 'foundation works risk assessments', which includes consideration of the impacts of different piling methods on ground gas migration. More recently, Wilson and Mortimer (2017) looked at the available evidence on the influence of piles on the permeability of the surrounding ground and hence the creation of preferential pathways for gas migration.

Other aspects of the development, for example ground improvement, construction of deep buried services, ground source heating/cooling etc. should also be evaluated for any impact they may have on the CSM, gas risks and associated uncertainties. Regulators in Environmental Health and Building Standards should be aware of such considerations and when mine gas risk assessments may need to be revisited. More importantly risk assessors should highlight any assumptions made in the risk assessment that could be invalidated by the development design (e.g. if an impermeable layer is acting as a barrier to gas migration the maximum allowable depth of foundations, trenches, etc should be stated by the assessor).

Assessors should be mindful of the following examples of foreseeable development change:

- If the assessment is based on a preliminary or draft development layout, changes to the sensitivity and location of receptors ought to be reasonably foreseeable;
- If the site contains shallow workings, ground stabilisation by drilling and grouting works ought to be reasonably foreseeable;
- If the site contains steep gradients, cut/fill earthworks and consequent changes to thicknesses of cover material ought to be reasonably foreseeable;
- If the site contains soft or loose shallow ground, vibrated stone columns or conventional piling ought to be reasonably foreseeable;
- If the proposed development requires piped drainage and attenuation, the introduction of pathways associated with storage in attenuation tanks and shallow lateral movement via a piped network ought to be reasonably foreseeable;
- If drainage trenches are required a reduction in the thickness of an impermeable cover layer ought to be reasonably foreseeable.

A further factor of concern is that site investigation boreholes themselves may create preferential pathways for gas migration to surface (see Appendix 4: Case Study 4). This is particularly the case where boreholes have been installed into workings (for geotechnical, mining or geo-environmental purposes) through overlying deposits of low permeability that would otherwise create a barrier to gas migration to shallow strata or the surface. Once a borehole is completed or monitoring well headworks are damaged locating boreholes can be an extremely difficult exercise. Therefore, borehole positions should be accurately located and decommissioned and sealed appropriately as standard at the earliest opportunity.

> It is good practice for the decommissioning and sealing of boreholes and monitoring wells to be detailed in remediation strategies and verification reporting. All holes should be sealed including those that have not had monitoring wells installed.

A3.3 Mine Stabilisation Works (grouting)

The impact of mine stabilisation works (grouting) on mine gas risk should be considered. This will include any stabilisation works below the site itself and any future ones off site. There is no specific distance that can be used as a limit for off-site migration because this depends entirely on the geology, likely depths and interconnection between mine workings, etc.

The grouting works, if done correctly below a site, can reduce gas risk (Sizer *et al.*, 1996). However, the design must minimise the risk of residual voids providing gas migration pathways and needs to consider the risk of gas from ungrouted areas outside the building footprints that could migrate via deep trenches.

No grouting can 100% guarantee to fill every single void, however small voids typically have only a low gas generating or accumulation potential, especially if flooded.

Poorly grouted injection wells and/or injection tubes can provide preferential pathways to the surface if they coincide with residual voids. It is good practice in grouting to top up wells where the grout has settled overnight. This should be verified under a Construction Quality Assurance procedure. There is one example in the authors' experience where there was an area of the site where shallow workings were grouted to maintain stability. However, there were deeper workings in a seam below that were not a stability concern and were not grouted. The site investigation boreholes to the deeper mine workings across the majority of the site had been left open and presented a potential pathway for gas migration to the surface.

Grouting can displace gas in the short term (although normally it vents via ungrouted drill holes as the work progresses). Probably of more importance is whether it will cut off existing venting or migration pathways and cause gas emissions to increase elsewhere.

Displacement or diversion of acidic mine water may also be significant if it can react with carbonate rocks and increase generation of carbon dioxide.

Appendix 4: Case Studies

The following case studies highlight the danger of relying on gas monitoring data alone without consideration of mining factors, response zones of wells, presence of site investigation boreholes and the critical importance of the CSM.

A4.1 Case Study 1: North Lanarkshire Coalfield, Scotland

The CSM is summarised in Figure A4.1. The site history indicated that there were no mine entries nearby and this was confirmed on the Coal Authority viewer, which also indicted that shallow workings were not likely. This was consistent with the geology because there are no shallow or outcropping coal seams. A search of data on groundwater levels in the coalfield indicated that deep workings should now also be flooded. The nearest mine entry to the deep workings was 405 m from the site, a distance beyond that considered to pose a risk of emissions to the site. The site investigation data included gas monitoring from wells installed in the Glacial Till. Carbon dioxide concentrations up to 6.7% were detected but methane was not detected. The hazardous gas flow rates for carbon dioxide were all less than 0.07 l/h which was consistent with the gas being produced by biological oxidation processes in the Glacial Till. This cannot generate sufficient gas to pose a risk to any development.

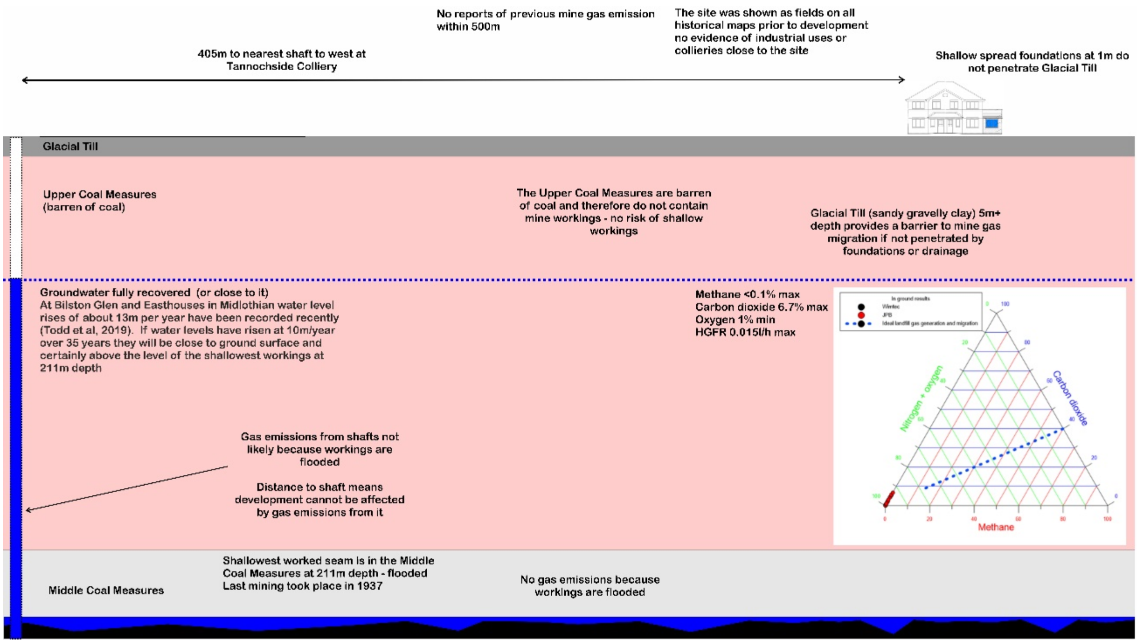


Figure A4.1: CSM for a site with deep flooded workings and no nearby shafts. For a larger version, see page 76.

All the lines of evidence were consistent and demonstrated that there was no risk of mine gas emissions affecting the building. Therefore, it was considered not necessary to require a gas membrane to be retrofitted to the building.

Key CSM elements:

- Assessment of geological profile and mine records to show mine workings are at depth;
- Records show that there are no known mine entries and assessment of geology shows no risk of unrecorded entrances or shallow workings; and
- Literature review on groundwater recovery in the coalfield that showed any workings would be permanently flooded (including allowance for a reasonable drop in level due to climate change).

A4.2 Case Study 2: Northumberland Coalfield

The CSM is summarised in Figure A4.2. An existing warehouse was being converted to a gym. The desk study for the site and the information on the Coal Authority viewer indicated that the site was located within a former colliery and where shallow mine workings were potentially present at about 25 m depth. There were multiple mine shafts within the site, one of which was indicated to be close to a corner of the building. The site was underlain by Made Ground over Fluvioglacial Deposits of sand and clay and then Coal Measures. Groundwater was at rockhead, and any seams would be permanently flooded. The Coal Authority viewer indicated that groundwater levels were recovered in this area.

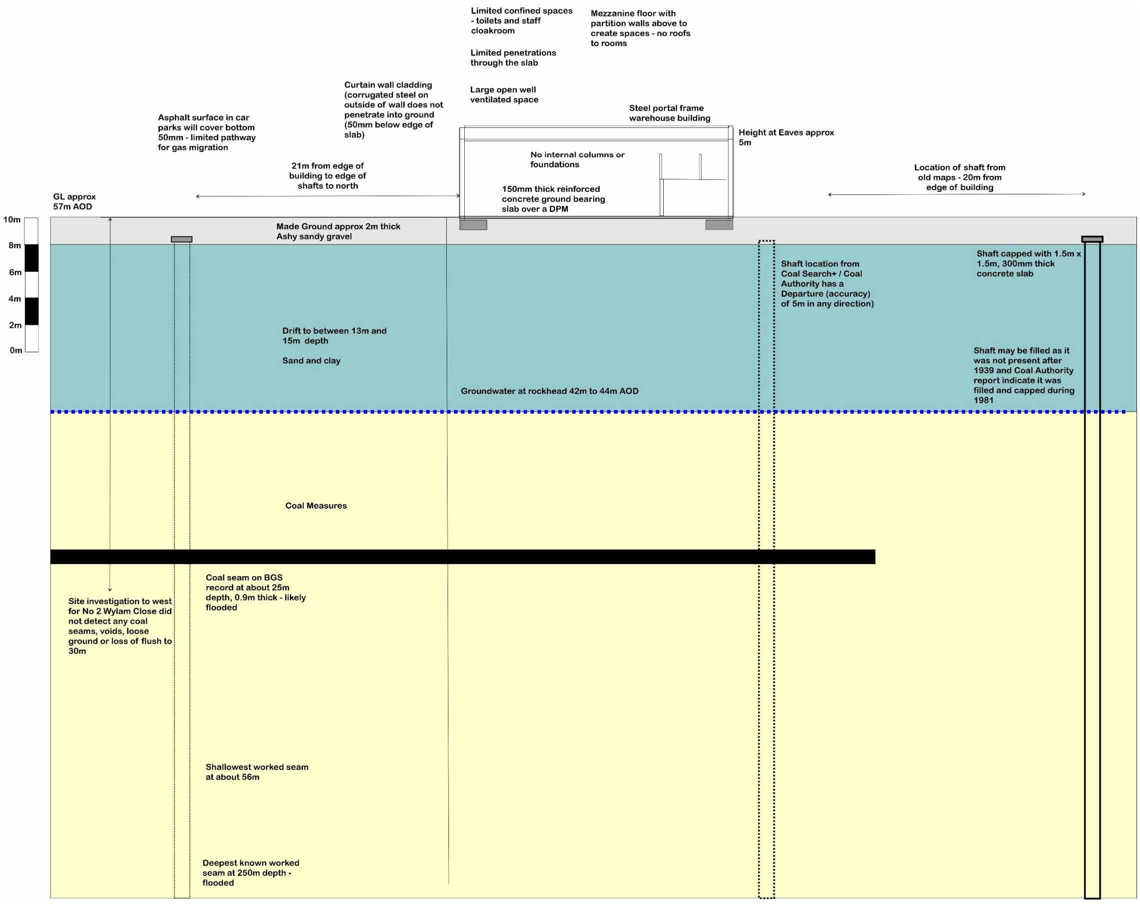


Figure A4.2: CSM for existing building within former colliery. For a larger version, see page 77.

There was some uncertainty about the location of the shaft closest to the building. One indicator was that it was below the corner. However, by comparing numerous maps and records and overlaying them (old Ordnance Survey maps, high resolution aerial photos and coordinates from mine shaft records) it was concluded that the shaft was actually 20 m away from the building.

Gas monitoring wells were only installed in the Made Ground. Limited spot monitoring had been completed. Methane was not detected, and the maximum carbon dioxide was 1.1%. A maximum borehole flow rate of 0.1 l/h was recorded and thus the gas screening value was less than 0.07 l/h (i.e. no risk from ground gas).

Crucially the concrete floor was in good condition with a 0.5 mm thick damp proof membrane (DPM) below it. There were no internal columns that penetrated through it and inspection and assessment of the reinforcement provision showed full depth cracks would not be present (it was only a small area). The external metal cladding walls did not extend into the ground and thus there was no perimeter gas migration pathway. The building was to remain as a large open space with no new enclosed spaces and there were limited penetrations by pipes. On the basis of this information the risk of mine gas emissions affecting the building was assessed as negligible.

In order to confirm this continuous gas monitoring was completed (for four weeks) immediately below the slab using vapour pins, in the area closest to the shaft . A maximum carbon dioxide concentration of 0.58% and a flow rates of 0.1 l/h were recorded. The flow rate in particular was very low and showed no correlation with falls in atmospheric pressure. Using data science analysis methods it was demonstrated that mine gas emissions from the shafts were not affecting the building. The impact of future changes in groundwater levels were considered but the geology, current groundwater levels in relation to the depth of workings and the building construction meant that this was not a concern and would not adversely affect the mine gas risk.

Key CSM elements:

- Assessment of geological profile to show significant thickness of low permeability superficial soils;
- Detailed review of mine entries shown on old maps, in Coal Authority records and evidence on aerial photos;
- Information from Coal Authority on groundwater block recovery (including allowance for a reasonable drop in level due to climate change);
- Absence of any correlation between carbon dioxide concentrations below the floor slab and changes in barometric pressure; and
- Building construction has a reasonable resistance to gas ingress and is essentially a large and well ventilated space with limited small rooms.

A4.3 Case Study 3: Yorkshire Coalfield

The CSM is summarised in Figure A4.3. The desk study for the site and the information on the Coal Authority viewer indicated that the site was located in an area where shallow mine workings were potentially present and that there were three mine shafts within the site. The seam was identified as being prone to spontaneous combustion. The presence of potentially collapsed workings in the coal seam was identified during the site investigation with weak fractured rock and Made Ground above. The seam was 1.5 m thick and was as shallow as 8 m bgl. Groundwater levels varied from above to below the worked seam.

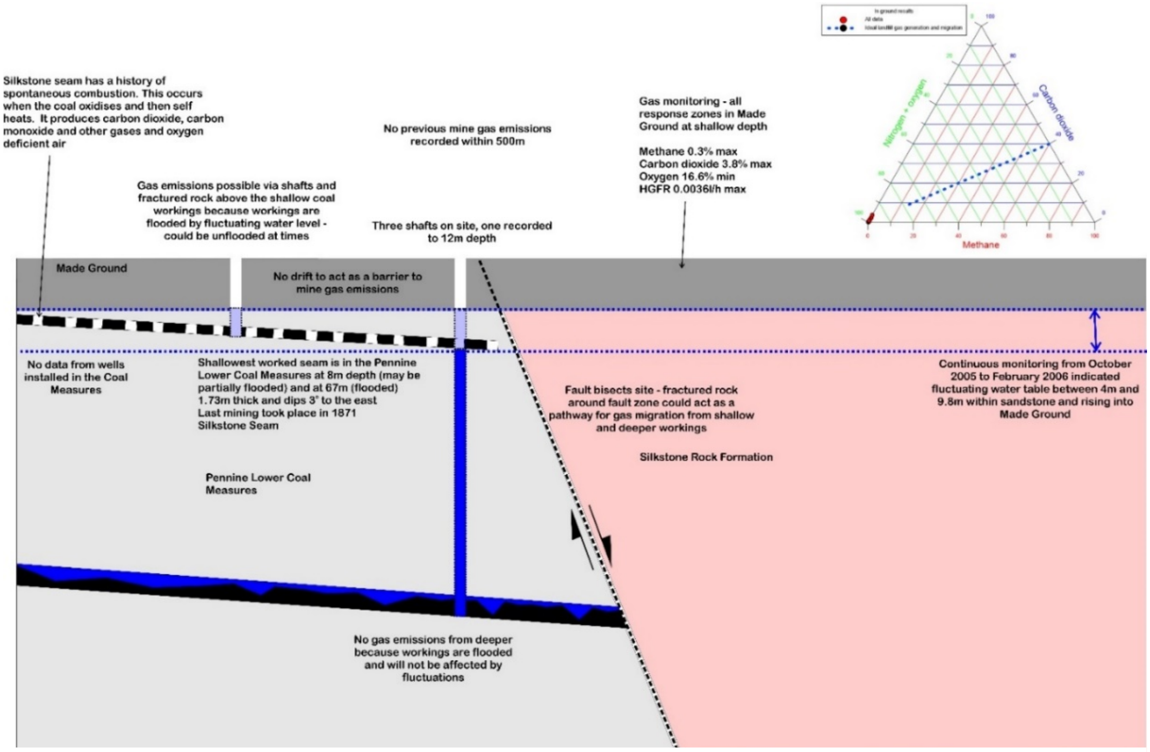


Figure A4.3: CSM for a site with shallow mine workings and shafts. For a larger version see page 78.

Gas monitoring wells were only installed in the Made Ground. Limited spot monitoring was completed. A maximum gas screening value of 0.022 l/h was recorded with methane concentrations less than 1% and carbon dioxide concentrations less than 5%. Based on the gas monitoring alone the site could have been classified as Characteristic Situation 1 whereby gas protection measures would not be required. The ternary plot of the data in this case again indicated low risk and that the gas being monitored was from biological oxidation in the Made Ground. However, wells had not been installed into the Coal Measures. Whilst it is sometimes acceptable to monitor in a shallow layer overlying Coal Measures in order to demonstrate that gas migration from depth is not occurring, in this case it was not acceptable because of the limited amount of gas monitoring data and the presence of shallow workings and shafts. It was considered that in this case even a period of prolonged continuous monitoring completed after any grouting works would be unlikely to change the risk classification and in any event would not be acceptable in terms of timescale for this development.

The site was considered as high risk with respect to mine gas (shafts within 20 m of site and workings less than 30 m deep). Further consideration of the CSM indicated that the groundwater levels were of concern as they could allow gas to accumulate in the workings when low and then push it out of shafts or through the thin fractured rock when it rose again. The workings were so shallow that it was not considered likely that grouting would fully remove the risk. It was therefore considered prudent to increase the classification to Characteristic Situation 2 as a precautionary approach.

Key CSM elements:

- Presence of shallow mine workings and shafts in the site;
- Absence of any low permeability superficial soils that would reduce or prevent surface gas emissions; and
- Groundwater fluctuations over the depth range where the shallow workings are present.

A4.4 Case Study 4: Complex CSM with Multiple Gas Sources and Pathways

The CSM is summarised in Figure A4.4. Construction of a major infrastructure and mixed end use development was planned near to a former landfill and in an area underlain by former mine workings at depth. Initial assessment using the empirical gas screening value approach as per BS 8485 indicated the site to be Characteristic Situation 1 based on borehole monitoring data alone. Recognising the limitations of the gas screening value approach in BS 8485 and the complexity of the CSM, a lines of evidence approach was adopted by the gas risk assessor, which included continuous and spot monitoring of boreholes for gas concentrations and flow, groundwater sampling for dissolved gases and surface monitoring/ flux box testing. This detailed assessment was able to discount the landfill as a gas source of concern to the development but identified the workings at depth to comprise a significant source of ground gases at the site. Overlying sandstone was identified as a reservoir for gases that had migrated from the underlying workings and a potential migration pathway. Above this stratum the cohesive Glacial Till presented a low permeability barrier for the upward migration of ground gases to occur, except for granular lenses that presented potential localised shallow ground gas lateral migration pathways.

A key factor for the development was that any existing unsealed site investigation borehole or monitoring well that penetrated the Till represented a direct vertical gas migration pathway from the workings and sandstone to the proposed development. The assessment concluded that it would be appropriate to determine the site as equivalent to Characteristic Situation 2, because of the presence of the deep boreholes, provided that all the deeper rotary boreholes and shallow installations that potentially penetrate the superficial deposits were located, over drilled and grouted from the base. However, if all such boreholes could not be located and remediated it was recommended that an increase to equivalent Characteristic Situation 3 should be considered. The detailed gas protection design for the buildings was then developed on a site specific risk basis.

Extensive work was undertaken to locate and grout the many boreholes that had previously been drilled on the site as part of site investigation for the development and associated with historical development. However, difficulties were encountered in locating all of the boreholes and enabling works in the development footprint encountered evidence of unrecorded boreholes. This raised questions of uncertainty in the assessment and following intervention by the local authority contaminated land adviser, it was agreed by all parties that suitable gas protection measures should comprise gas membranes combined with underfloor ventilation achieving 'very good' performance as per BS 8485.

This example clearly demonstrates the outcome of a higher level of risk and mitigation design being required following more detailed assessment to refine a complex CSM, as well as the importance of borehole decommissioning to address preferential pathways for gas migration.

Key CSM elements:

- Workings at depth but gas migration into an overlying sandstone layer that acted as a reservoir for gases to accumulate;
- Overlying low permeability superficial deposits acting as a barrier to gas migration to upper surface;
- Multiple pathways present from unsealed boreholes penetrating the superficial deposits that had to be systematically identified and decommissioned; and
- Earthworks in some parts of the development had the potential to reduce the thickness of the superficial deposits such that gas migration to near surface could occur.

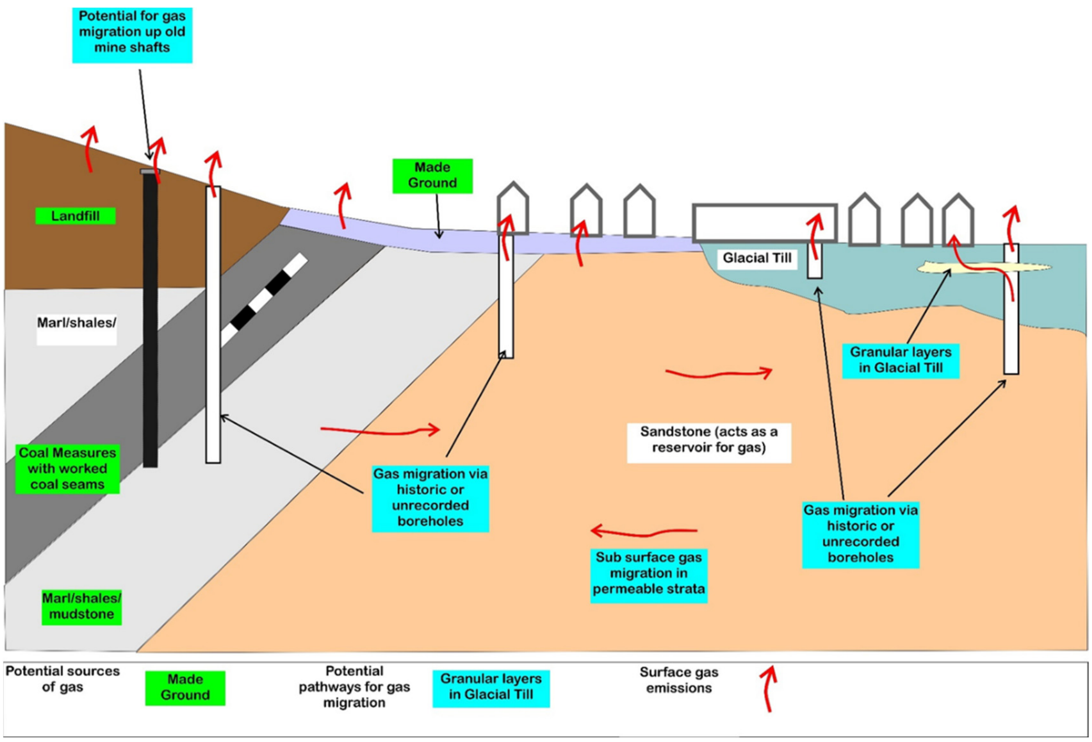
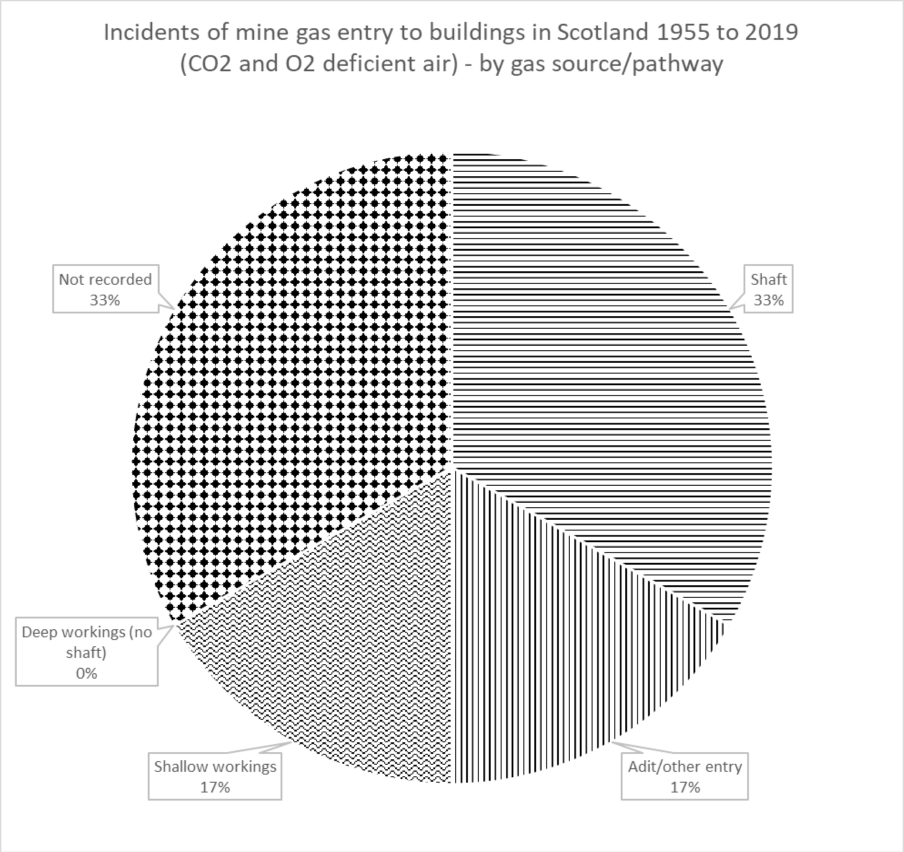
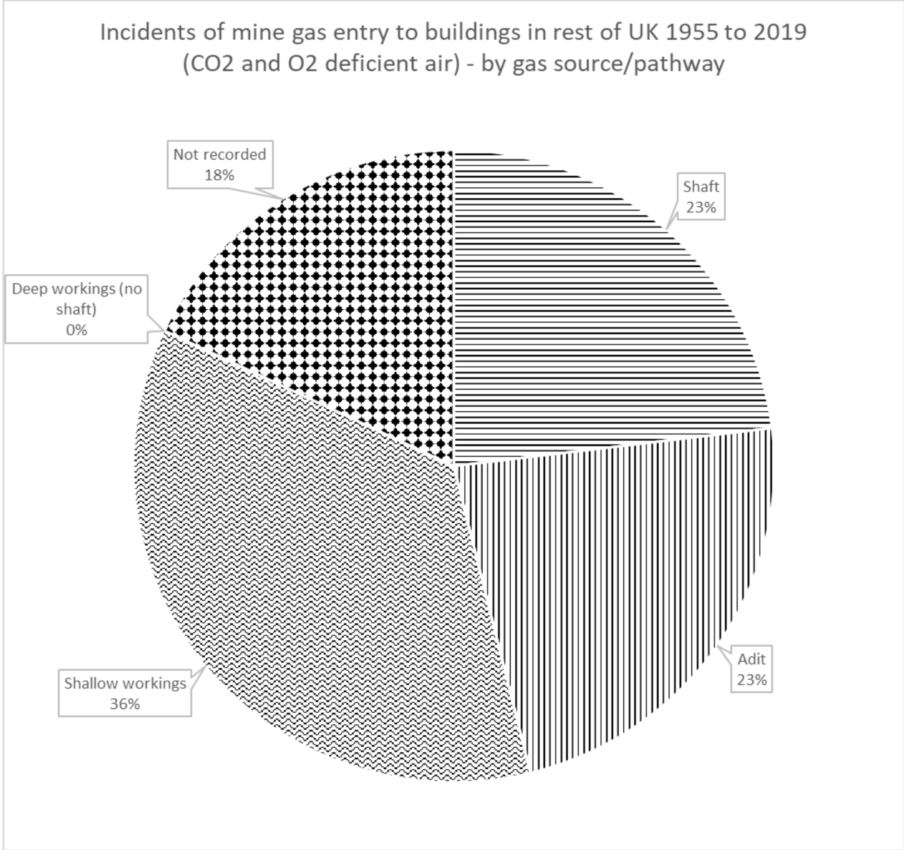


Figure A4.4: CSM for a site with old site investigation boreholes. For a larger version, see page 79.

Appendix 5: Figures



a: Scotland



b: Rest of UK

Figure 5.1: Incidents of carbon dioxide entry to buildings from mine workings (a) Scotland (b) rest of UK (percentages refer to the proportion of the total incidents that were related to the source/pathway) – page 10.

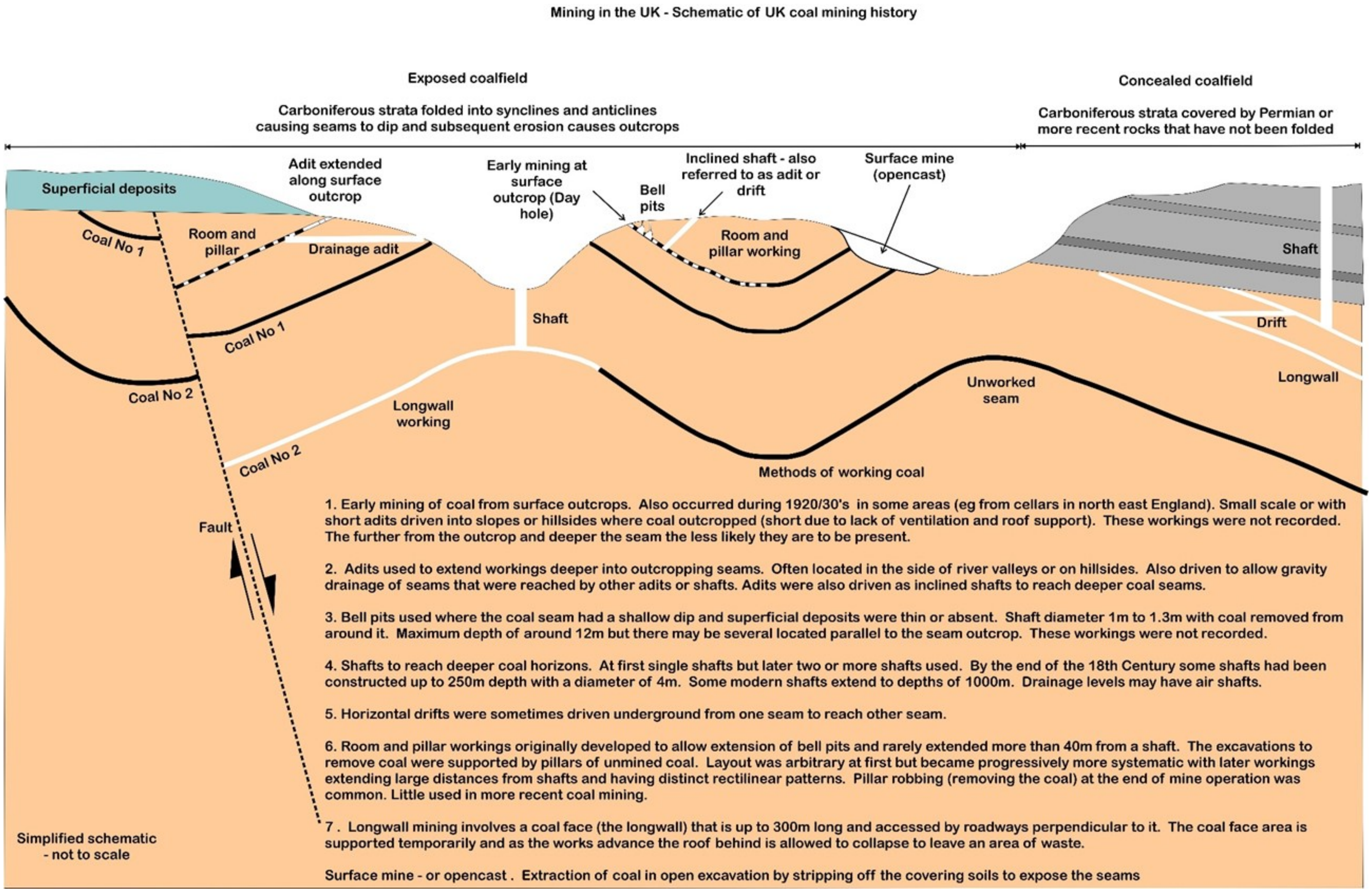


Figure 17.1: Summary of the history of methods of coal mining – page 14.

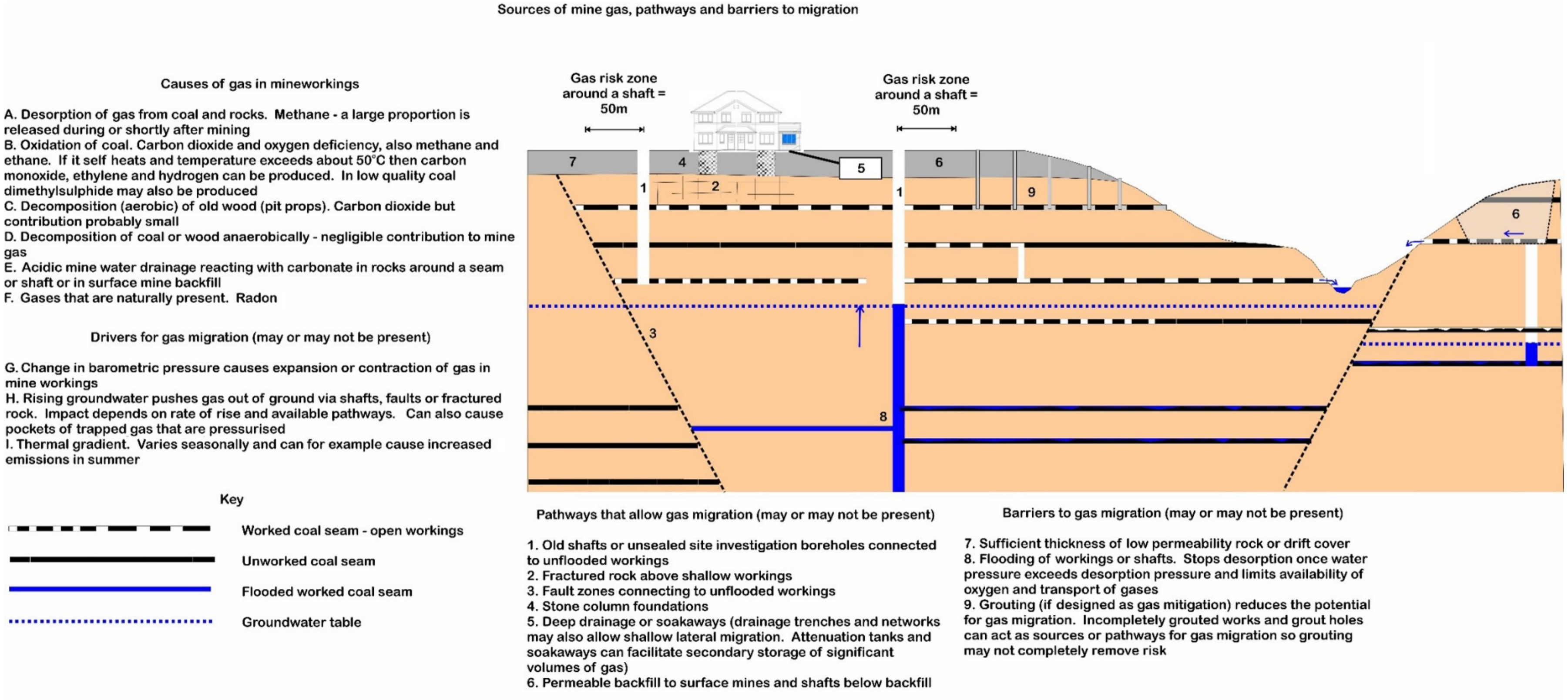


Figure 10.1: Sources of mine gas, pathways and barriers to migration – page 19.

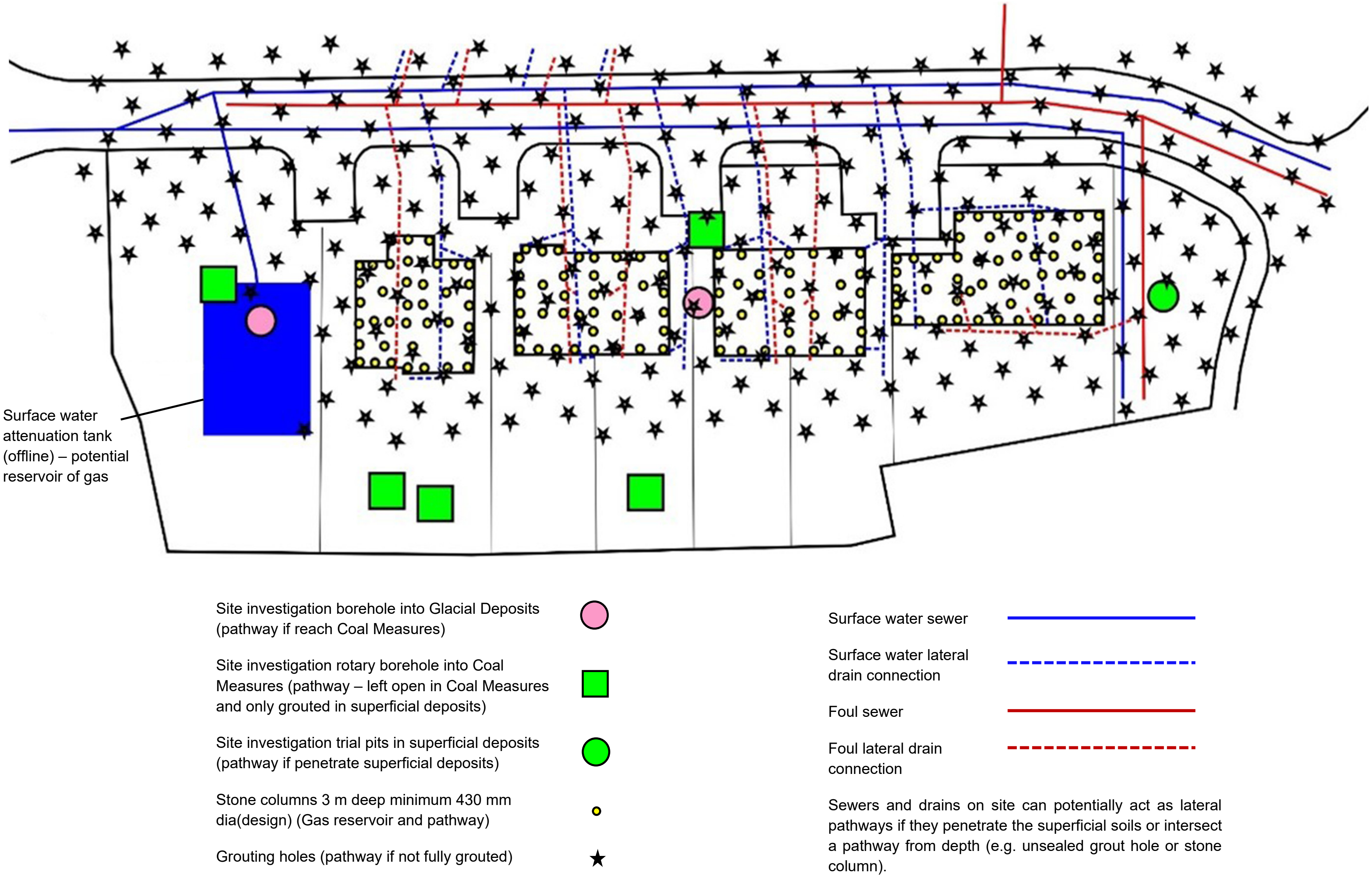


Figure 10.2: Complexity of pathways and gas reservoirs introduced by the development construction – page 20.

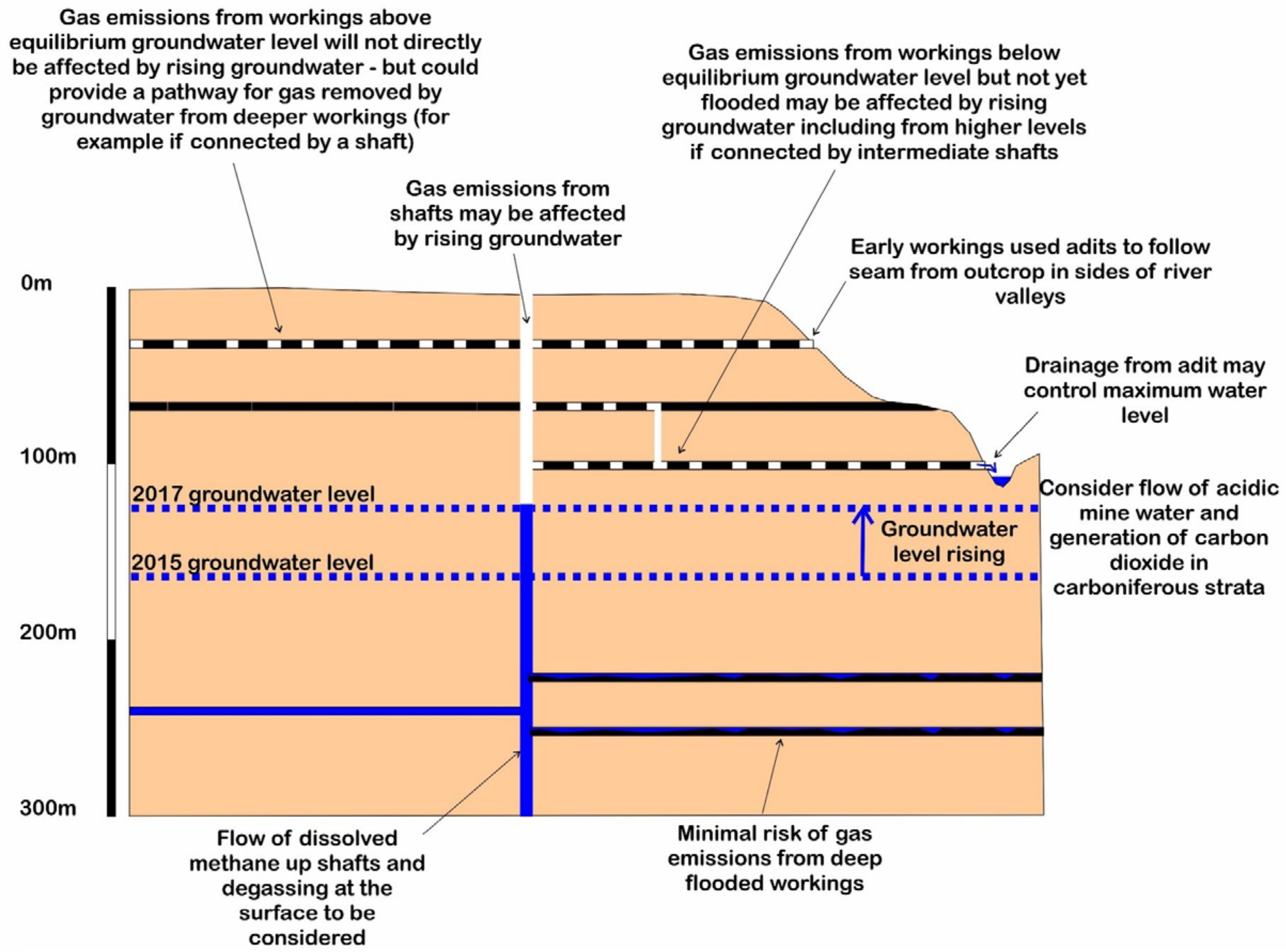


Figure 11.1: Example groundwater conditions and influence on mine gas risk (based on groundwater conditions in Todd et al., 2019) – page 24.

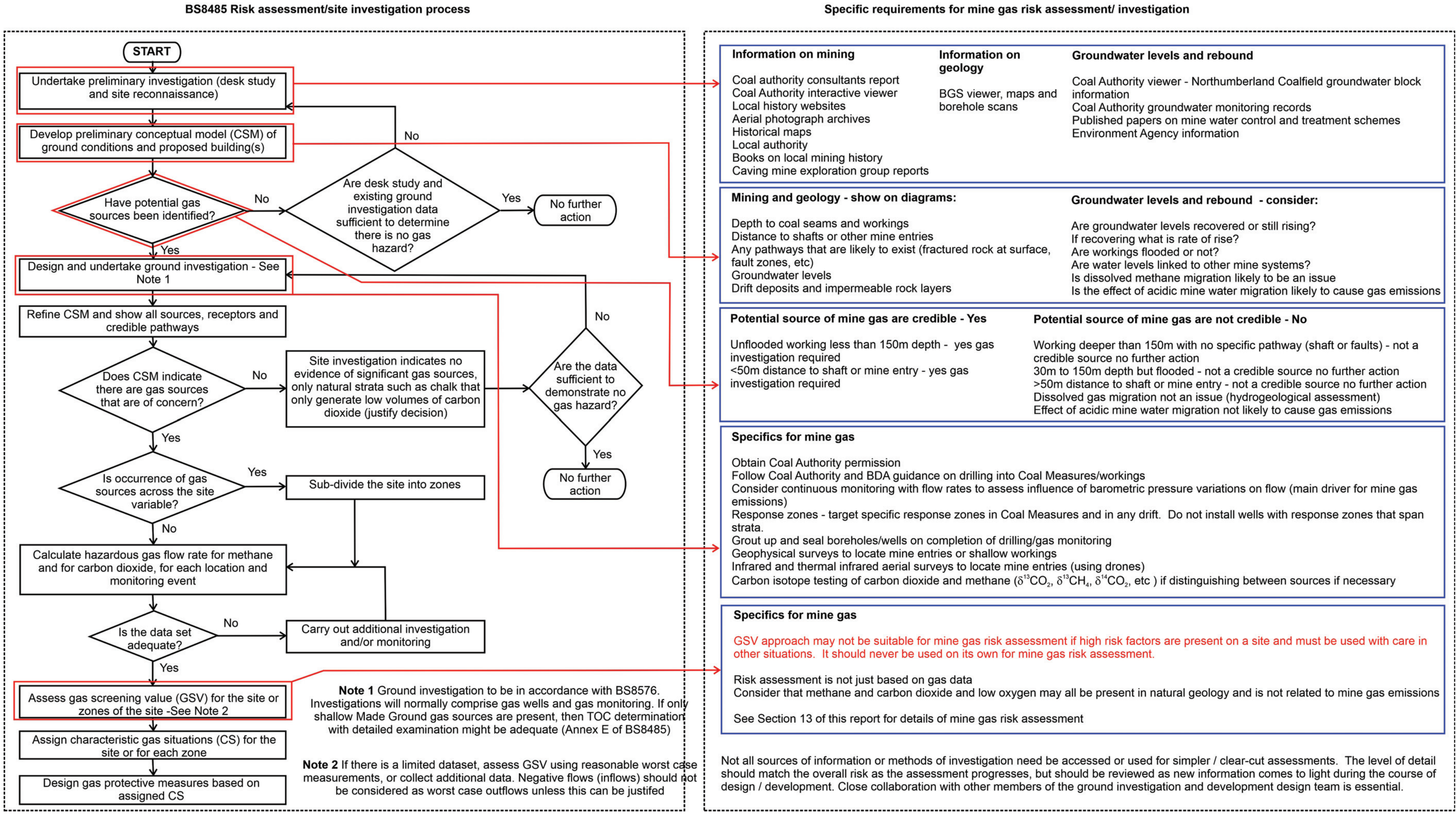


Figure 12.1: Flow chart for gas risk assessment with specific considerations for mine gas assessment. The left hand side has been adapted from BS 8485 and the right hand side shows how the specific considerations for mine gas assessment described in this document follow the generic flow chart from BS 8485 – page 27.

NOTE 1
PRELIMINARY INFORMATION REQUIREMENTS

Before proceeding further with the decision process the following should be in place:

1. Sufficient information to develop an initial schematic CSM. This should be a site specific visual CSM (i.e. geological cross section showing development proposals including foundations, mine entries and workings with relevant seam levels). Examples of visual CSMs are provided in Appendix 4 (Case studies).

2. Comprehensive desk study information collected from sources including Coal Authority Consultants Report and other data.

3. Data has been checked and is sufficiently robust to allow the preliminary mine gas risk assessment and design of any site investigation if required.

NOTE 2
DECISION PROCESS

The decision process is started with a desk-based study. The process is followed and at any point if site investigation data is required to confirm any specific factor then a suitable investigation should be designed, the data collected and then the decision process restarted.

For example, where workings are considered permanently flooded at shallow depth, groundwater level monitoring may be required to confirm likely variations will not cause levels to drop below the level of the workings. Likewise, site investigation may be required to confirm the thickness and nature of any low permeability layer to determine if it can be relied on as a barrier to potential gas migration.

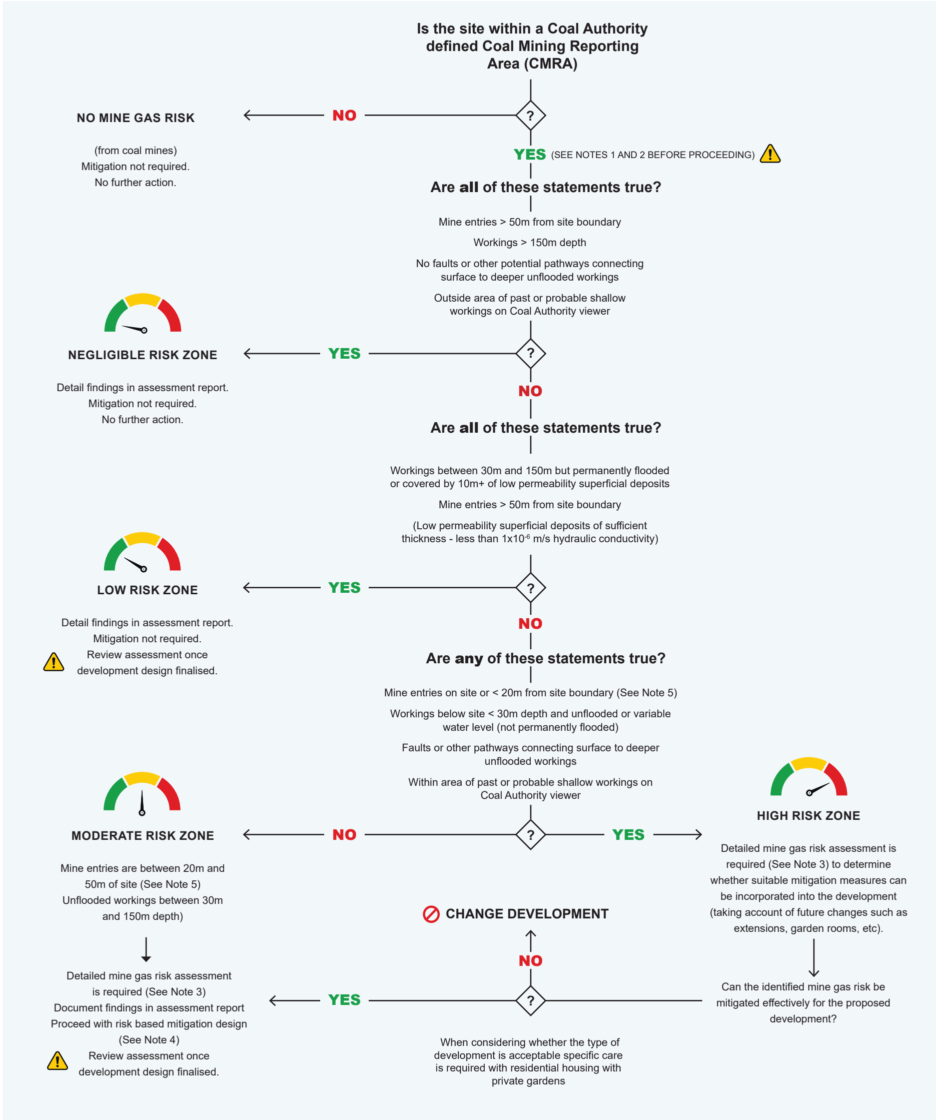
NOTE 3
DETAILED MINE GAS RISK ASSESSMENT

Detailed mine gas risk assessment will require suitable site investigation and use of a multiple lines of evidence approach to risk assessment.

Consider - depth and permeability of drift deposits and if >5m to rock head from underside of foundations and drainage trenches (including any deep soak away or attenuation tanks).

Model and assess gas migration rates through the ground using approaches in the Ground Gas Handbook.

Assess whether shafts or other pathways are connected to unflooded deep or shallow workings Assess risk of gas migration from shaft or adit (consider filling, capping type, any venting and geology and relationships between flow rates and mmeteorological conditions) - see next column.



NOTE 3 (CONTINUED)

Detailed assessment of gas monitoring data looking for correlations of flow rates with barometric pressure, temperature, groundwater levels and whether elevated flows are likely to be associated with mine gas emissions, consideration of gas ratios and other potential sources of gas.

Assess volume of potential gas reservoir that could accumulate in workings.

Assess impact on the gas risk of any grouting works to shallow mine workings. Consider relevant uncertainties from Table 14.1.

Consider credible future changes that could impact on mine gas risk (water level changes or grouting in connected workings).

Consider risk to external areas (gardens, landscaped areas) e.g. sheds. The rate of gas emissions from open fractures or shafts can overcome the ventilation in these types of buildings.

Consider floor construction and resistance to gas ingress.

NOTE 4
DESIGN OF GAS PROTECTION SYSTEM

Design gas protection measures (see CIRIA Site Guide for Hazardous Ground Gases for guidance on procurement and competence). The points system in BS 8485 should not be used, site specific detailed risk-based design is required.

Specify requirements for floor slab construction (with respect to gas protection).

Specify appropriate gas membrane.

Design venting layer if required based on estimated gas expansion and flow rate from mine workings during fall in barometric pressure (see CL:AIRE TB17 for critical events).

Consider implications of residual uncertainty on mitigation design.

⚠ Review design once all other elements of the development design are finalised.

◇? Decision points

NOTE 5
ADITS

Adits require specific consideration of their direction in relation to the development. In cases where the adit entry is close to the development (between 20m and 50m or less than 20m) but it dips in the opposite direction, it might not be considered a pathway for mine gas emissions and may be considered low risk.

Figure 13.1: Decision support tool for mine gas risk assessment – page 35.

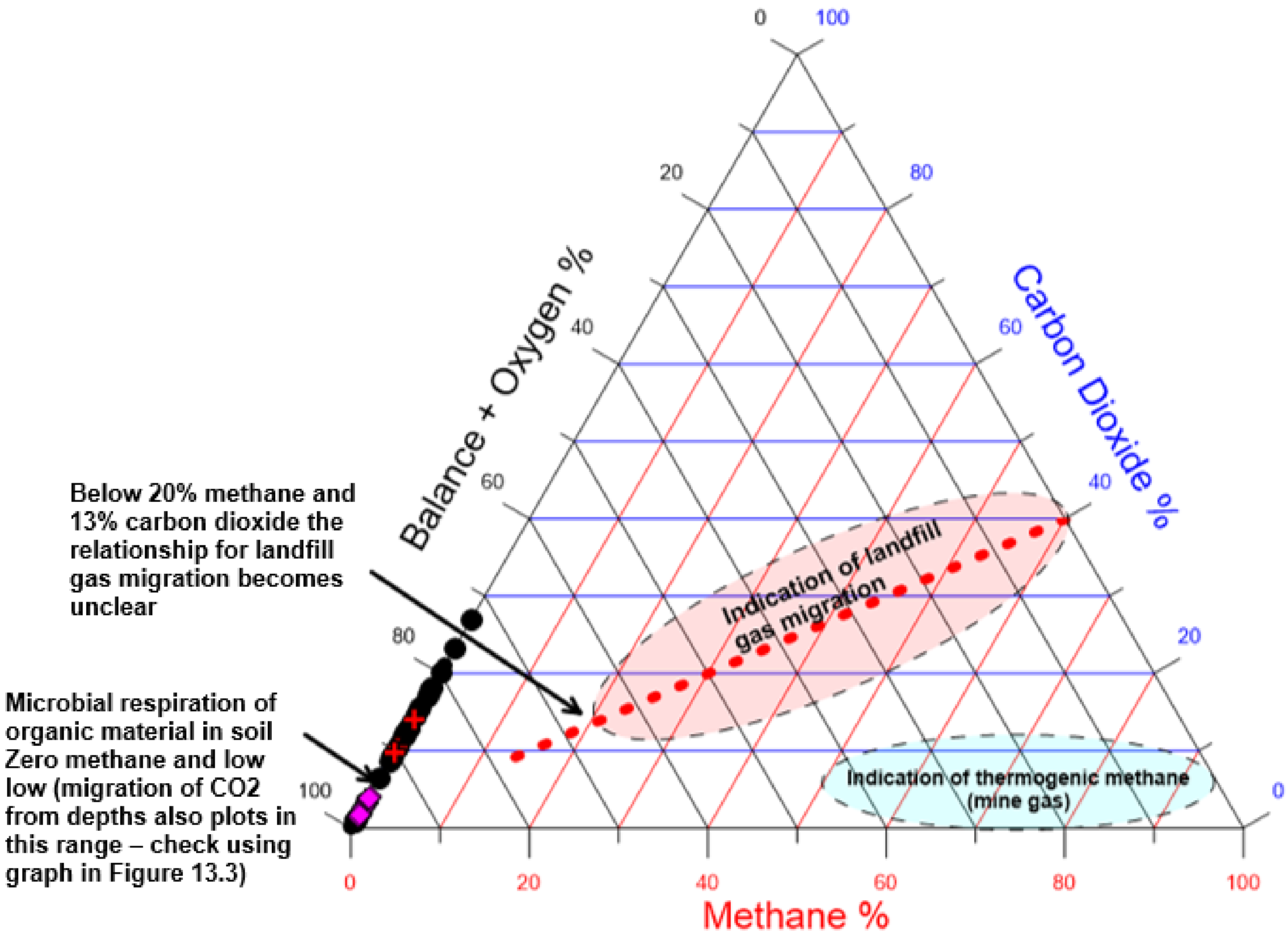


Figure 13.2: Ternary plot showing aerobic soil respiration, thermogenic methane and landfill gas migration zone (after Wilson et al., 2018) – page 39.

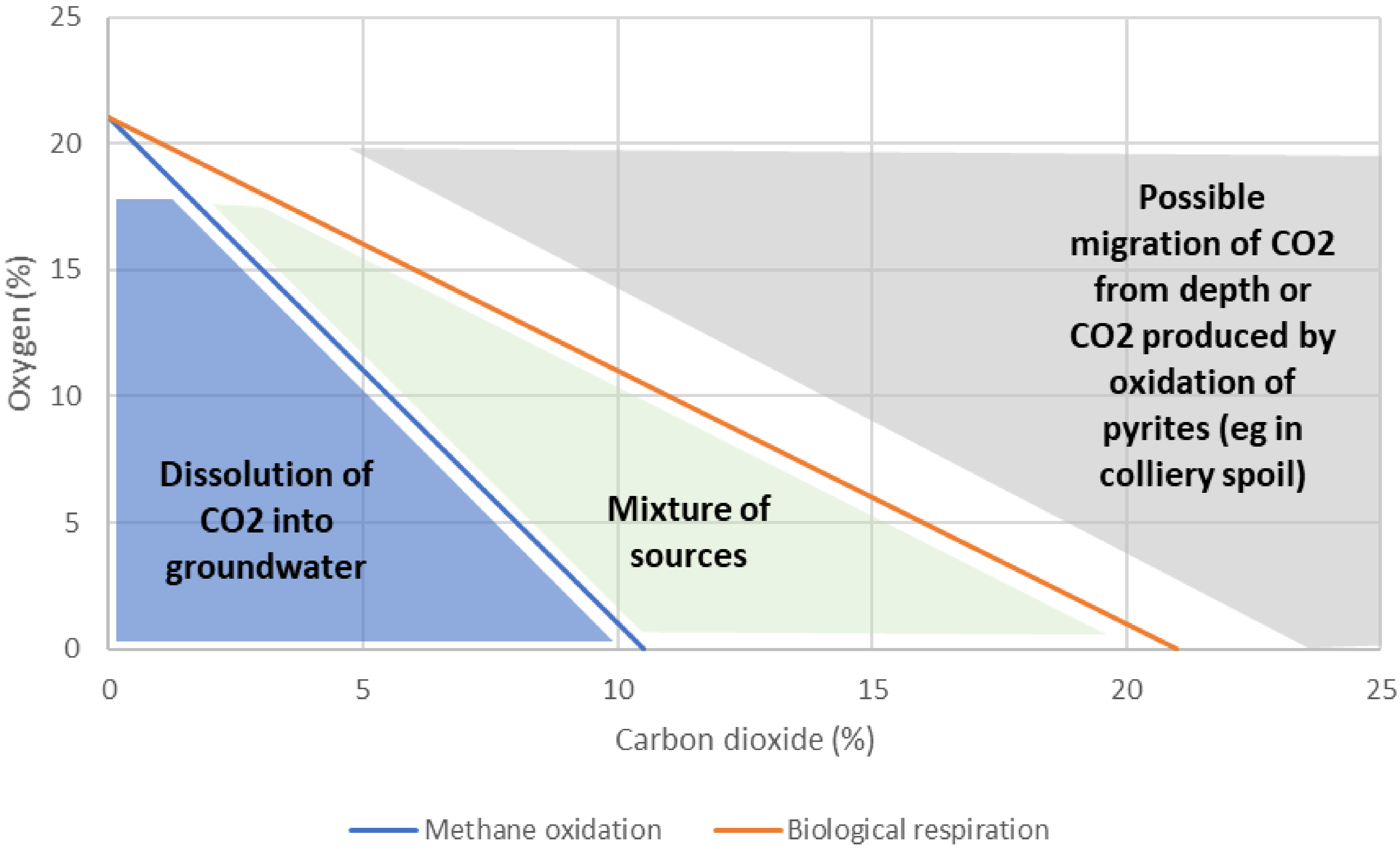


Figure 13.3: Stoichiometric assessment of carbon dioxide and oxygen - page 39.

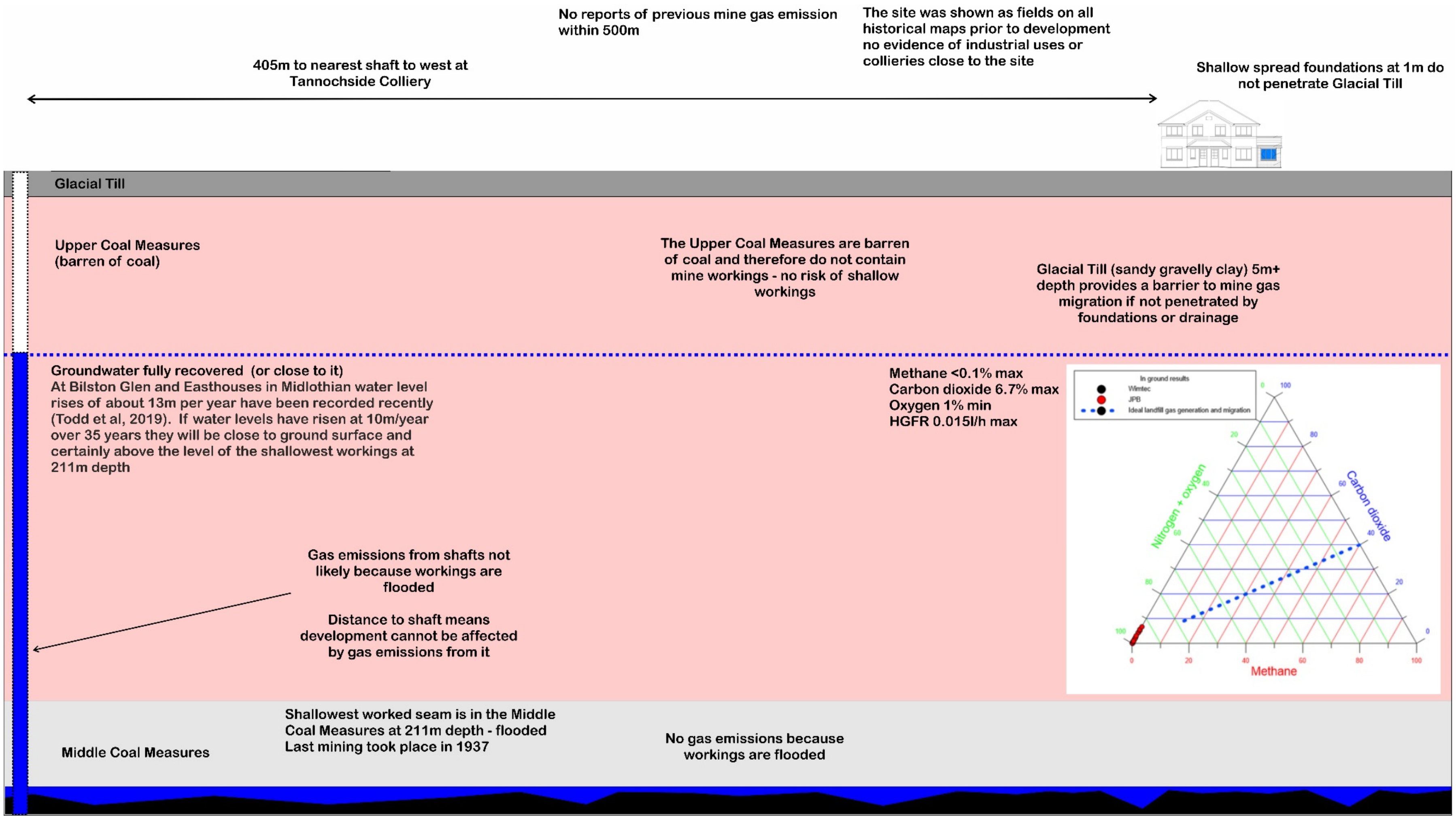


Figure A4.1: CSM for a site with deep flooded workings and no nearby shafts – page 61.

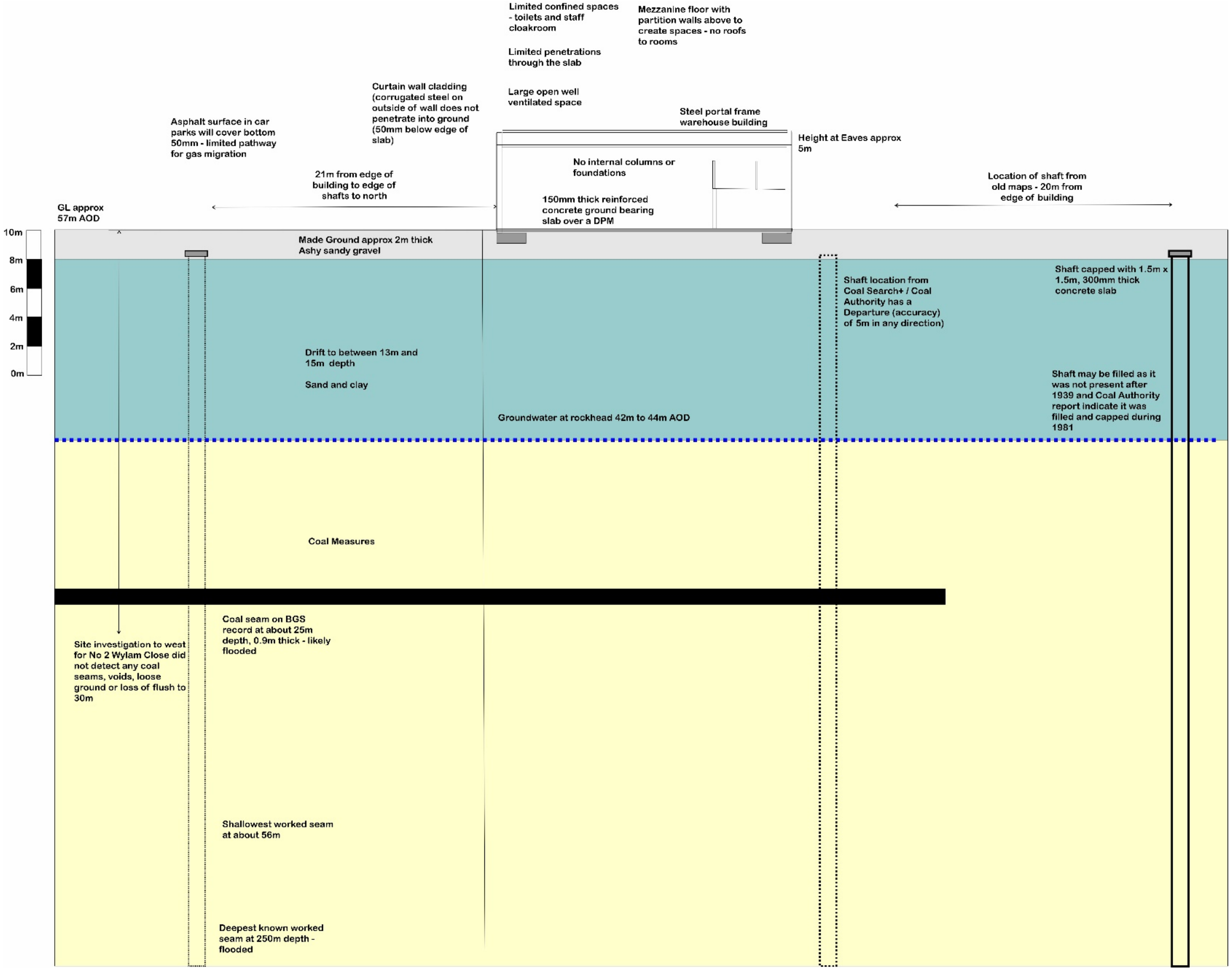


Figure A4.2: CSM for existing building within former colliery – page 62.

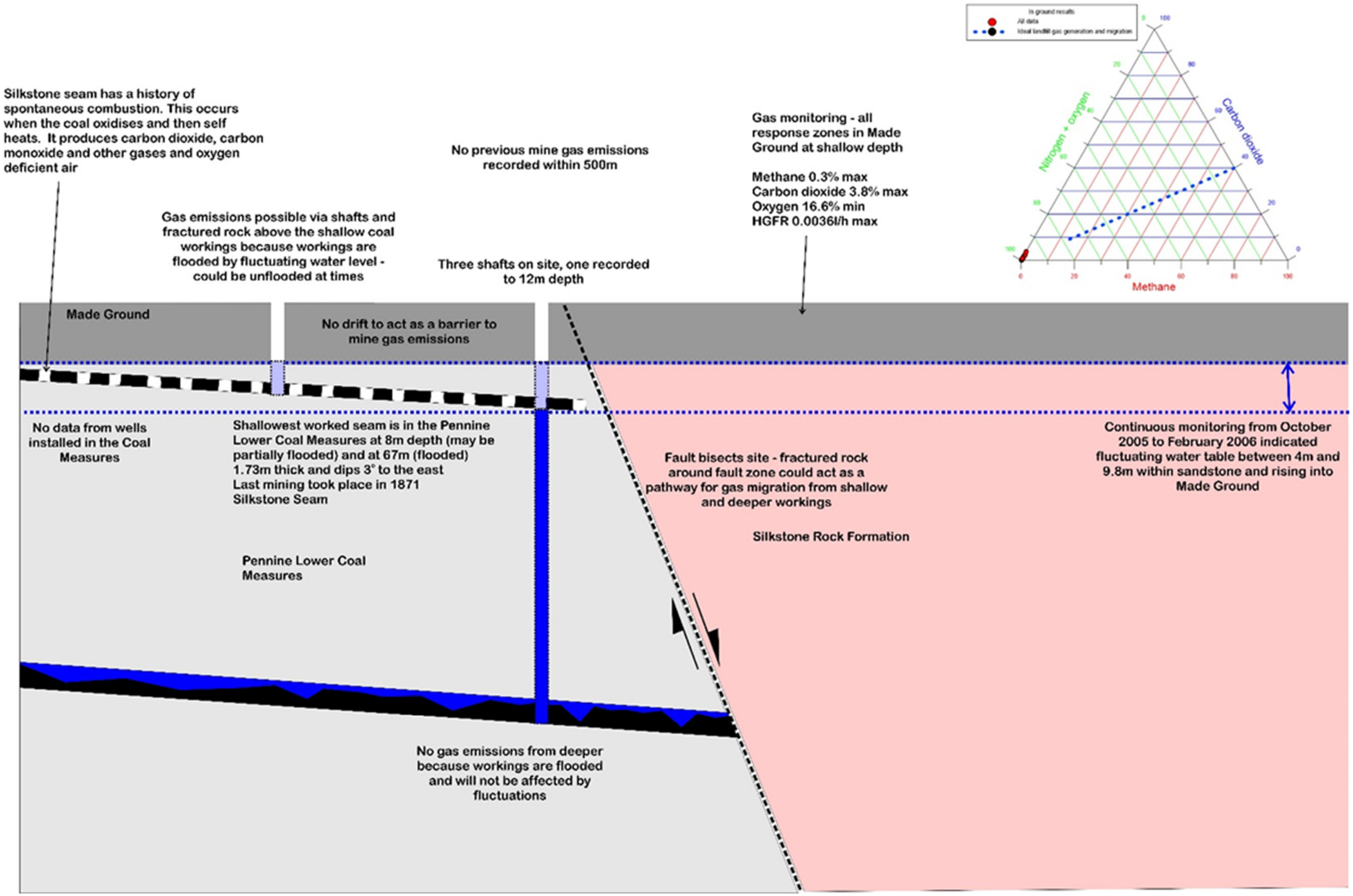


Figure A4.3: CSM for a site with shallow mine workings and shafts – page 64.

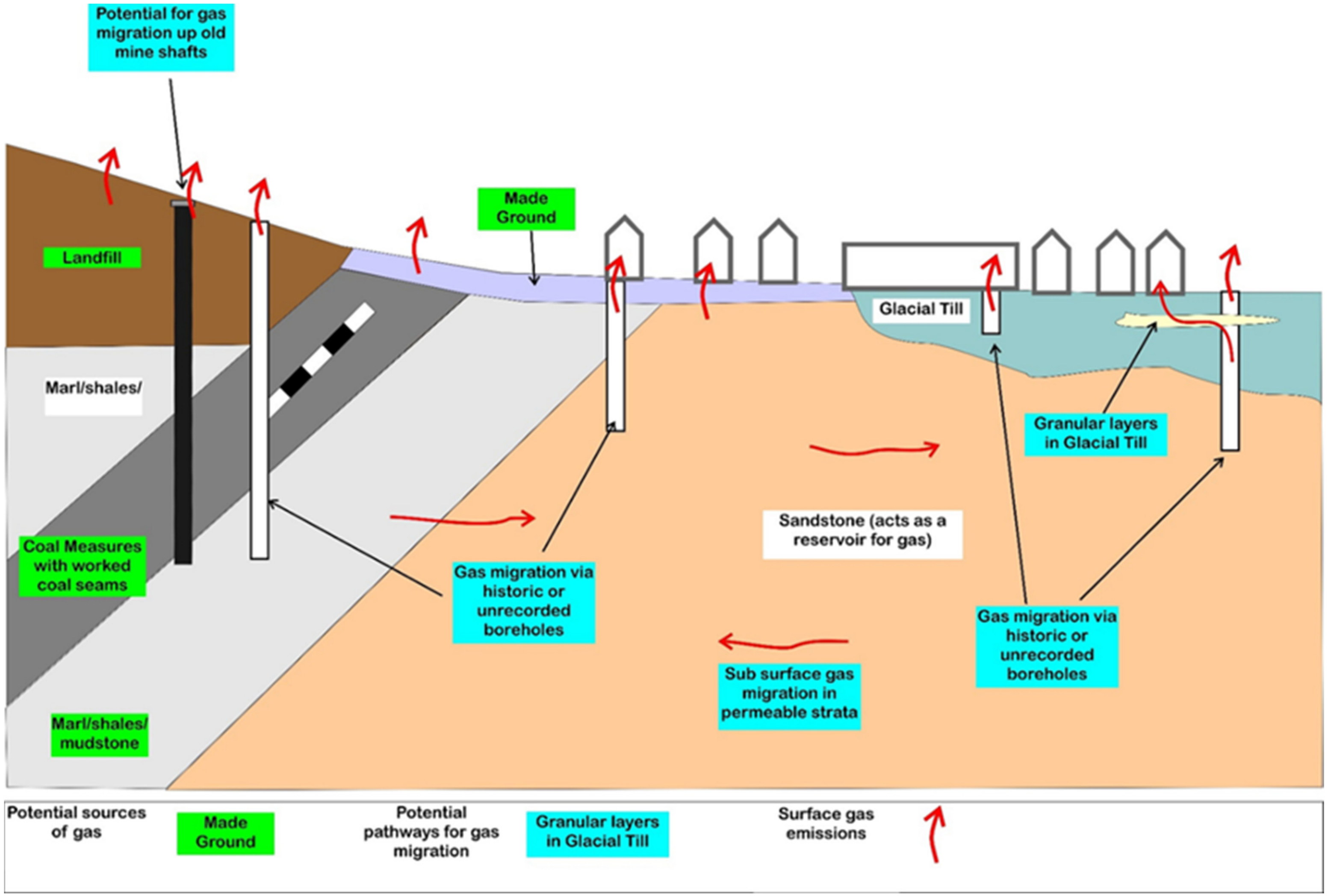


Figure A4.4: CSM for a site with old site investigation boreholes – page 66.

CL:AIRE
Chiltern House, Haddenham Business Centre,
Thame Road, Haddenham, Buckinghamshire, HP17 8BY
Telephone: +44 (0)1844 292281
Email: enquiries@claire.co.uk
Website: www.claire.co.uk

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