Supporting online Appendices

Appendix A

The following assumptions have been made when deriving the limiting Gas Screening Values (GSV) for the different gas regimes:

- Ventilation in the building is equivalent to 0.5 air changes per hour (Jefferis and Martin, 2009)
- Ceiling height in the building is assumed to be for small ground floor room 2.4m high, consistent with the CLEA Briefing Note (Environment Agency, 2005)
- Gas in the ground is assumed to be an infinite “cloud” at 100%v/v for each gas of concern
- The ground gas is assumed to be located 1m below the entire footprint of the ground floor. In most cases this is a reasonable assumption (where made ground is covered by a layer of clean soil, peat layers within Alluvium covered by soil with low organic content). Most ground gas investigations only measure the gas within the soil at depths greater than 1m (the response zone starts at 1m) and the soil air above 1m is normally of similar composition to fresh air because of air ingress, which is a consequence of barometric pumping and diffusion into the ground.

The proposed gas hazard values inside a building for various gas regimes are based on the values in Table A1. The indoor gas hazard values (GHV) that are used to define Gas Regime A are considered to be applicable for residential, commercial and industrial building types.

Table A1 - proposed indoor gas hazard values to derive gas regimes

<table>
<thead>
<tr>
<th>Gas</th>
<th>Gas Regime A</th>
<th>Gas Regime B</th>
<th>Gas Regime C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>100ppm (0.01%)</td>
<td>500ppm (0.05%)</td>
<td>5,000ppm (0.5%)</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.04%</td>
<td>0.5%</td>
<td>N/A</td>
</tr>
<tr>
<td>Oxygen depletion</td>
<td>20.5% (oxygen)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Notes:
1. The level of risk is assumed to be low and may be referred to as a category 4 case in accordance with the Department for Environment Food and Rural Affairs (Defra).
2. The level of risk is assumed to be low and may be referred to as a category 3 case in accordance with the Department for Environment Food and Rural Affairs (Defra).

For methane Gas Regime A, the value gives a factor of safety of 500 on the Lower Explosive Limit (LEL) of methane. 100ppm is often recorded inside buildings due to other sources such as household chemicals (eg cleaning fluids). The authors have recorded such levels inside many buildings of various types that have been present, without incident, for up to 30 years or more. Therefore, this is
taken as a background level below which the risk of explosion is minimal. This value has also been accepted by Regulators to assess risk on “Part IIA sites” in the UK. The normal atmospheric concentration of carbon dioxide is proposed for Gas Regime A, while the proposed indoor gas hazard value for oxygen is 20.5% based on fresh air containing 20.9% and adverse effects beginning from 19.5% and lower.

For Gas Regime B, the proposed indoor GHV for methane is 0.05% which gives a factor of safety of 100 on the methane LEL. For carbon dioxide the proposed value is 0.5%, which is the long term (8 hour) occupational exposure limit in the UK.

There are no upper limits to Gas Regime B for oxygen depletion because for this regime a gas membrane is required in all buildings. If flows exceed the GSV for Gas Regime A for oxygen deficient air then a site specific assessment will be necessary, with a particular focus on the influence of open pathways such as mine entries or old wells on gas flows.

For Gas Regime C the indoor GHV for methane is 0.5% which is a commonly used value at which the alarm for gas detection systems are set to (Wilson et al, 2008) and gives a factor of safety of 10 on the LEL. There is no upper limit for carbon dioxide. If flows exceed the GSV for Gas Regime B for carbon dioxide then a site specific assessment will be necessary, with a particular focus again on the influence of open pathways on gas flows.

A summary of the results for methane being driven into a building (without a floor slab) is provided in figure A1. These values are appropriate for considering a negligible to very low risk gas regime (defined as Gas Regime AM for methane and AC for carbon dioxide), where there is minimal risk from ground gas. Figure A1 gives an indication of the equilibrium concentration of methane in a building against sustained gas pressure. As the permeability of the soil reduces a greater pressure gradient is required to achieve a given internal gas concentration.

Figure A1 - Equilibrium methane concentration inside a building with no floor slab
Critical Differential Pressures and Radial Borehole Flow Rates

From the graphs in figure 5 the driving pressure above which the GHV is exceeded can be determined. The values for methane are summarised in Table A2.

**Table A2 - Limiting values of gas pressure for vertical gas flow into building - methane**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>1.00E-04</th>
<th>1.00E-05</th>
<th>1.00E-06</th>
<th>1.00E-07</th>
<th>1.00E-08</th>
<th>1.00E-09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of gas source</td>
<td>m</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Critical sustained pressure driving flow into building – without floor slab</td>
<td>mb (Pa)</td>
<td>0.00035</td>
<td>0.0035</td>
<td>0.035</td>
<td>0.35</td>
<td>3.5</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.035)</td>
<td>(0.35)</td>
<td>(3.5)</td>
<td>(35)</td>
<td>(350)</td>
<td>(&gt;5)</td>
</tr>
<tr>
<td>Critical sustained pressure gradient</td>
<td>-</td>
<td>0.0048</td>
<td>0.048</td>
<td>0.48</td>
<td>4.8</td>
<td>48</td>
<td>&gt;694</td>
</tr>
</tbody>
</table>

For comparison the same analysis has been completed using 30% methane, 1.5m source depth, internal allowable concentration of 1.25% and a hydraulic conductivity of $1 \times 10^{-5}$ m/s (critical parameters from ASTM 2016) along with 1 air change per hour in the building and a height of 2.8m. The results give a critical gas pressure of 500Pa which is the limiting value in the ASTM guidance.

The flow towards a gas borehole can then be estimated if the gas borehole radius of influence is determined for a given critical sustained pressure that could result in gas concentrations exceeding the proposed GHVs (see table A3), as per the theory given in equation 2.

The calculation assumes that the horizontal permeability of the ground is ten times greater than the vertical permeability (a reasonable assumption even in uncontrolled fill materials) and the gas flow is towards a fully penetrating circular 50mm diameter gas borehole.

The results for methane (assuming that there is no floor slab or underfloor void) are provided in table A3. This shows the borehole flow rates that must be exceeded for gas regime $A_M$ to be exceeded. The calculated flow rates into a gas borehole can be used as the limiting GSV for methane for gas regime $A_M$ for different values of soil permeability.

A similar approach can be taken to provide limiting GSV values for Gas Regime $A_C$ for carbon dioxide and $A_O$ for oxygen depleted air.

**Table A3 - Limiting radial flow rate towards a 50mm diameter monitoring well for methane**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Vertical permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal permeability (10x vertical permeability) m/s</td>
<td></td>
<td>1.00E-04 1.00E-05 1.00E-06 1.00E-07 1.00E-08 1.00E-09</td>
</tr>
<tr>
<td>Intrinsic permeability (horizontal) m²</td>
<td></td>
<td>1.02E-10 1.02E-11 1.02E-12 1.02E-13 1.02E-14 1.02E-15</td>
</tr>
<tr>
<td>Length of response zone m</td>
<td></td>
<td>1 1 1 1 1 1</td>
</tr>
</tbody>
</table>
Critical sustained pressure from flow analysis into building | Pa | 0.035 | 0.35 | 3.5 | 35 | 350 | >5,000
---|---|---|---|---|---|---|---
Absolute viscosity of methane | Pa.s | 1.09E-05 | 1.09E-05 | 1.09E-05 | 1.09E-05 | 1.09E-05 | 1.09E-05
Radius of gas borehole | m | 0.025 | 0.025 | 0.025 | 0.025 | 0.025 | 0.025
Radius of influence (depends on permeability and period of pumping) | m | 27.39 | 8.68 | 2.76 | 0.89 | 0.30 | 0.05
Flow rate into gas borehole | l/h | 1.06 | 1.27 | 1.57 | 2.07 | 2.99 | 14.45

To define the limiting concentrations for Gas Regimes B and C for the various gases a similar analysis to that above has been completed using the adopted GHVs provided in table A1. Modern buildings in the UK will typically have either a solid concrete floor slab that is cast on the ground or a precast slab that has an underfloor floor void below. This construction provides and inherent level of resistance to gas flow from the ground (Card et al, 2012) and is supported by an empirical database presented by the US EPA where 95th percentile and 50th percentile attenuation factors (α = indoor air concentration/sub-slab soil gas concentration) were 0.03 (33 times) and 0.003 (333 times) (USEPA, 2015). Based on the preceding discussions it is reasonable to assume the floor slab construction will provide an attenuation factor of at least 100 between gas concentrations in the ground and the interior of a building.
Figure B1 - USDA soil classification with intrinsic permeability (USDA, 2003)
Appendix C
The process for developing a GSV for a site is summarised as follows:

- Borehole hazardous gas values are calculated for each borehole standpipe for each monitoring event
- The reliability of the measured gas flow rates and concentrations is assessed considering borehole construction (and geology)
- Decisions are made as to whether to use peak gas flow rates or steady state rates in each calculation (Note: British Standard BS 8485:2015+A1:2019 states that steady state values are to be normally used, as does BS8576: 2013)
- Decisions are made about how to deal with any temporal or spatial shortages in the data (note application of the screening values in Table 8 require continuous flow monitoring over a period that includes worst case atmospheric pressure as defined in CLAIRE TB17 (Wilson et al., 2018))
- Judgements are made about what GSV to use for design purposes taking all relevant information into account. This requires an assessment of the gas generation of the source, (e.g., consider TOC content) and the permeability of ground around the monitoring wells. Only data taken from wells installed in the unsaturated zone should be used.

Using the GSV the site is characterised as one of the four gas regimes in Table 1. Selecting an appropriate GSV from the collected site data should consider the current or potential future presence of open pathways or reservoirs for gas accumulation close to buildings (including stone columns, mine shafts, etc) and the key drivers for gas flow and concentration such as barometric pressure (refer to Wilson et al., 2018), groundwater changes and rainfall. BS8485:2015+A1:2019 also advises that to adopt the worst case GSV, an assessor should be confident that it is prudent and reasonable and does not result in unnecessarily conservative protection of the development. It is normally not realistic to do a worst case assessment based on the maximum concentration and maximum flow rate regardless of where each occurred and from what stratum.
### Appendix D

<table>
<thead>
<tr>
<th>BS4845: 2015 + A1: 2019</th>
<th>Risk and Reliability - 20 years on</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Methane</td>
</tr>
<tr>
<td>$k = 10^{19}$ m/s</td>
<td></td>
</tr>
<tr>
<td>CS3</td>
<td>Moderate hazard</td>
</tr>
<tr>
<td>16</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

**Figure D1 - Comparison of British Standard BS 8485:2015+A1:2019 characteristic situations and gas regimes from this paper (enlargement at low end of scale)**
## Appendix E

### Table E1 - Protection methods to give one level of protection

<table>
<thead>
<tr>
<th>Examples of protection methods that may provide 1 level of protection on its own if constructed and sealed correctly</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural Barriers</strong></td>
<td>Slabs should be designed by chartered structural or civil engineer. Minimum 150mm thick. Minimal service penetrations should be cast into the slab (see below for advice on minimal), joints, etc should be sealed.</td>
</tr>
</tbody>
</table>
| Suspended cast in situ reinforced concrete slab | Notes:  
- Cast insitu ground bearing slab: Note this may look like suspended cast insitu at first glance. If it is not supported on a foundation or edge beam it is not suspended and there will be a gap around the whole perimeter of the slab. May provide some resistance to gas ingress.  
- Precast concrete “block and beam” floor provides minimal resistance to gas ingress.  
- Some Precast concrete panels: Some panels require a screed over the top of them that seals the joints. This can give resistance to gas ingress as the panels normally have a ventilated void below. |
| Waffle raft slab | The justification for use of the slab as part of the gas protection system should be included in the Design Report for the gas protection system, as advised in British Standard BS8485:2015+A1:2019. The Design Report should be approved by a Charted Engineer experienced in the assessment and design of gas mitigation systems. |
| Reinforced concrete raft slab, including piled raft. Includes basement slabs and walls if constructed to provide a Type B structural waterproof barrier in accordance with BS8102: 2009. Advice on the design of gas protection for basements is provided in Ground Gas Information Sheet No 4 (Wilson et al, 2018) | |
| Membrane | The membrane should be:  
A. Sufficiently impervious to methane and carbon dioxide  
B. Capable after installation of providing a complete barrier to the entry of the relevant gas  
C. Sufficiently durable to remain serviceable for the anticipated life of the building and duration of gas emissions  
D. Sufficiently strong to withstand in service stresses (eg due to ground settlement if placed below a floor slab)  
E. Sufficiently strong to withstand the installation process and following construction activities until covered (eg penetration from steel fibres in fibre reinforced concrete, penetration of reinforcement ties, tearing due to working above it and dropping tools)  
F. Chemically resistant to degradation by other contaminants that may be present |
| Gas resistant membrane | |
G. For standalone gas membranes a methane gas transmission rate of <40ml/day/m²/atm (average) (tested in accordance with the manometric method in BS ISO 15105-1) is usually considered sufficient.

Installed by specialists or suitable trained workforce withy appropriate CQA.

Independent verification of installation and Integrity testing of joints and whole membrane installation where required in accordance with Ciria C735.

Puncture and impact resistance are particularly important properties for gas membranes. Thin membranes (less than 0.5mm thick when measured between any reinforcing scrim) are more prone to puncture than thicker membranes such as 1mm LDPE. Information about puncture resistance and corrosion of aluminium foil membranes is provided by Lucas and Wilson (2019).

Methane gas transmission rate – the acceptable value depends on floor slab or basement construction. Where membranes are used in conjunction with good quality insitu concrete construction which is far more resistant to gas ingress than block and beam floor construction for example A higher gas transmission may be suitable because less reliance is placed in the membrane to prevent gas ingress. The probability of gas flowing through a defect in the membrane and then through the defect in concrete should be assessed by the gas protection designer. A gas transmission rate of 40ml/m²/d/atm is a baseline value suggested in British Standard BS 8485:2015+A1:2019 but values greater than this may be acceptable if justified by the designer. The justification for the choice of membrane and the appropriate specification requirements should be included in the Design Report for the gas protection system, as advised in British Standard BS 8485:2015+A1:2019. The design report should be approved by a charted engineer experienced in the assessment and design of gas mitigation systems.

<table>
<thead>
<tr>
<th>Venting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ventilated void – standard venting requirements for NHBC</strong></td>
</tr>
<tr>
<td>Minimum height and vent requirement from NHBC Standards</td>
</tr>
<tr>
<td><strong>Bespoke venting system using void formers or other systems (gravel, pipes, etc).</strong></td>
</tr>
<tr>
<td>Design by chartered engineer or other chartered professional using analysis of advective or diffusive flow from the ground based on the properties of the ground and gas. As described above the use of the Pecksen correlation between surface emission rate and borehole flow rates is likely to be highly conservative and result in overly expensive venting systems. See Ground Gas Handbook (Wilson et al, 2008) for design advice</td>
</tr>
<tr>
<td><strong>Note</strong> Type 1 sub-base or hardcore will provide minimal venting but may provide a gas release pathway to the surface. Passive venting is preferred, although in some circumstances active can be used.</td>
</tr>
</tbody>
</table>
The justification for the choice of membrane and the appropriate specification requirements should be included in the design report for the gas protection system, as advised in British Standard BS 8485:2015+A1:2019. The design report should be approved by a charted engineer experienced in the assessment and design of gas mitigation systems.

Passive venting systems are preferred in all types of buildings if at all possible. If active fans are used, then long term maintenance is required and experience has shown that this is difficult to guarantee. Some active systems work by pumping air below floor slabs or into drained cavities of basements (known as sub-slab pressurisation in the US). These systems are often claimed to act as a barrier and vent layer together. The principle of gas protection design is that where two or more layers of protection are provided that each provides protection on its own. Therefore, a single method can act in two different ways. It is also possible that the positive pressure will drive gas into the building if there are pathways such as cracks in a slab. Therefore, the slab above must either be well sealed (or where used to vent a cavity drain in a basement the drain must be well sealed). Sub-slab pressurisation systems do not remove the need for a membrane where one is required.

References


