CL:AIRE technical bulletin

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CL:AIRE technical bulletins describe specific techniques, practices and methodologies currently being employed on sites in the UK. This bulletin provides guidance on assessing ground gas monitoring data to ensure that sufficient data has been collected to cover critical variations in barometric pressure.

Ground Gas Monitoring and 'Worst-Case' Conditions

1. INTRODUCTION

This Technical Bulletin provides guidance on the critical barometric pressure conditions that influence gas monitoring results and provides a clear framework to allow risk assessors to determine when they have sufficient gas monitoring data to evaluate and manage ground gas risk with confidence.

Current guidance on ground gas monitoring suggests that it should be carried out over a sufficient period to allow prediction of worst-case conditions (BS8576: 2013). BS8576 also states that gas monitoring does not necessarily need to be carried out at worst-case conditions or at low or falling barometric pressure, although gas emission rates from the ground are likely to be at their highest when there are sharp falls in barometric pressure. BS8576 also states that gas monitoring should be continued until it is unlikely that any additional data will change the outcome of the risk assessment or mitigation design.

Not all sites will require gas monitoring or consideration of barometric pressure. If the conceptual site model and other data (e.g. desk study evidence and/or total organic carbon (TOC) content of a known thicknesses of Made Ground) shows very low gas risk the guidance in BS8576 suggests that gas monitoring may not be required.

This bulletin provides a simple method of assessing when data has been collected over a sufficient number of relevant barometric pressure variations. When combined with online real time access to the data it provides a powerful tool for ensuring sufficient gas data has been collected to cover critical variations in barometric pressure. It is important to consider whether barometric pressure is the only, or even the most important, driver for gas emissions on a site. On some sites there will be other factors that are more significant, for example rapid changes in groundwater levels or changes in groundwater chemistry.

2. BAROMETRIC PRESSURE VARIATIONS

Currently it is common practice in the UK to specify that gas monitoring covers a period of barometric pressure less than 1000mb and with periods of falling barometric pressure. This has been included in several earlier guidance documents (e.g. CIRIA Report C665 – CIRIA, 2007). However, in other parts of the world, it is not practical to restrict monitoring to times when barometric pressure is less than 1000mb.

For example, in Western Australia there may only be a couple of short cycles of falling trends that dip very slightly below 1000mb (996mb to 999mb at the bottom) during June and July. Even during some quite extreme rainfall during 2010 the pressure only dropped to 1010mb after a gradual drop from 1018mb during the 4 days before.

The British Coal Technical Department (1990) defined barometric pressure drops as follows:

- Gradual fall – <4mb over 3 hours;
- Gradual fall – <4mb over 3 hours;
- Sharp fall – 4mb to 8mb over 3 hours; and
- Very sharp fall - >8mb over 3 hours.

Some consultants in Victoria, Australia also require one or two results from a set to be obtained when the rate of atmospheric pressure fall prior to the monitoring is greater than or equal to 4mb in 3 hours.

BS8576 recommends that gas monitoring data is continuously assessed as it is received. This will allow monitoring to continue only to the point where sufficient data for the risk assessment has been collected, thereby minimising monitoring periods or reducing the risk of ending monitoring without sufficient data. Continuous assessment is readily done when gas data is uploaded to a web portal as the results are taken. The assessment process can also be automated to some extent with warnings given when certain criteria or limits are exceeded.

Barometric pressure is rarely constant for any significant time and changes in response to:

- Thermal and gravitational effects (diurnal changes); and
- Regional weather patterns.

Massmann and Farrier (1992) suggest that gravitational effects result in two peaks of barometric pressure each day, some 12 hours apart. However, the difference in pressure is minimal above 60° latitude. In northern latitudes the effects of the daily heating and cooling cycle are more important with maximum fluctuations usually up to 3mb. Weather patterns have a much more significant influence on barometric pressure variations and can cause changes in the order of 20mb to 30mb.

Changes in barometric pressure result in vertical pressure gradients developing in the soil pore atmosphere with either soil gas flowing out of the ground or fresh air flowing into the ground. This occurs because of compaction or expansion of the gas phase in the soil (Davis *et al.*, 2004). The effects decrease with depth below the ground surface. The direct effect of pressure changes on advective flow of soil gas from the ground is relatively small (Auer *et al.*, 1996), whilst others have suggested that expansion of gas is limited.

Whether flow is caused by pressure gradients or gas expansion the magnitude of the flow through the ground is dependent on several factors including the soil permeability to gas, pore size distribution and tortuosity. Flow due to barometric changes is only significant in fractured or highly permeable media. In low permeability soils there may be minimal flow over a shallow depth. This results in a lag between the variation in pressure in the soil atmosphere and variation in barometric pressure. The degree of saturation will also influence the flow, with saturated soils (and hence low gas permeability) showing minimal influence of barometric pressure changes on soil gas flow.

Another factor that reduces the effect of barometric pressure changes is the thickness of the vadose zone. The effect is reduced by a thinner vadose zone because there is less gas volume for expansion. A change in barometric pressure of 4% to 5% would give a volume change to the soil pore air of 4% to 5%. Theoretically this would amount to 40 - 50mm expansion over a 1m deep soil profile and 200 - 250mm over a 5m soil profile (Davis *et al.*, 2004).

The change in surface emission rates in response to barometric pressure variations is usually quite small where gas flow is through the soil matrix and is limited by the permeability of the soil and the depth of the gas source. For example, with a 3m deep source at 20% methane concentration analysis shows that for any appreciable surface emissions to occur the pressure difference in the soil must be maintained at greater than 1mb and the permeability of the soil must be greater than about 1 x 10^{-5}m/s (Figure 1).

Where soil has a greater permeability the soil atmosphere equalises quickly with any change in barometric pressure and any pressure differential is short lived.

Experience in the UK suggests that many soils, including Made Ground, have bulk permeability values lower than 1 x 10^{-5}m/s.

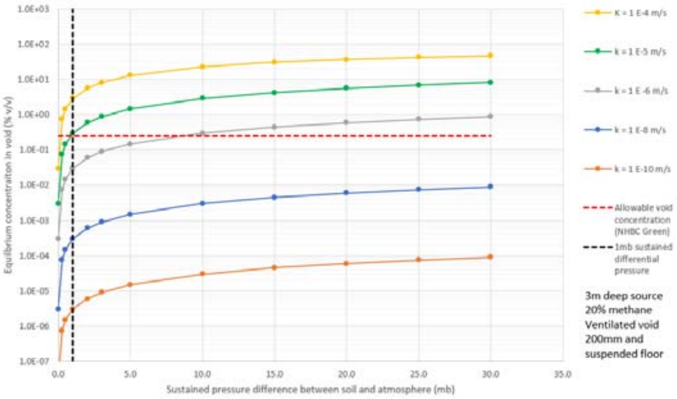

Figure 1. Gas concentration in underfloor void against pressure difference for various soil permeability values.

Typically sustained differences between soil air pressure at shallow depths and atmospheric pressure is rarely more than 1 or 2mb, unless there are specific gas sources such as within a domestic landfill that are generating large volumes of gas or there is a permeable layer that is confined by a significant thickness of impermeable soil.

In sites where the source is not generating large volumes of gas, the main transport mechanism is diffusion through soil. In this case the variation in methane concentration in a monitoring well that may be observed as barometric pressure changes is normally due to air ingress during high pressure diluting gas in the ground rather than increased surface emissions during low pressure. Where there are open pathways such as in fractured rock or mine workings barometric pressure changes may result in higher air or gas flows.

If there is a large gas pressure in the ground and variations in barometric pressure are small in comparison, there will be no significant effect on surface emissions. Hemp (1994) found that gas emissions from a coal seam at a gas pressure of 1.6MPa were not influenced by changes in barometric pressure. This may also apply to monitoring wells in actively gassing landfill sites with high gas pressure (Heroux *et al.*, 2010). They also found that the temperature and moisture content of the capping layer had a significant (and seasonal influence).

3. WORST-CASE BAROMETRIC PRESSURE CONDITIONS

Towler and Young (1993) suggested that for methane to reach 5% v/v in air inside a building a pressure difference of 4mb to 10mb was required to be generated between the soil atmosphere and the inside of the building. This is consistent with the analysis in Figure 1. They did not explain the basis of this assessment and whether it accounts for soil permeability. Boltze and de Freitas (1996) undertook a study into the changes in barometric pressure associated with dangerous ground gas emissions. They looked at the barometric pressure data for a period in London and concluded that the magnitude of the pressure drop was not the most important factor, and that the maximum velocity of gas exchange from the ground to air corresponds to the maximum slope of the graph of barometric pressure against time. They developed the "explosion risk threshold" concept. This considers the absolute value of the pressure drop and the time over which it occurs.

Boltze and de Freitas identified various zones of barometric pressure changes and concluded that the highest risk of gas emissions occurred in Zone 4 (See Figure 2). This is the area of the graph where very large pressure changes occur over a short period of time and potentially represents a risk of increased gas emissions from certain sites. The "danger threshold" was considered to be the boundary between Zone 4 and the zone of normal barometric pressure drops (defined as Zone 2 in Figure 2). Although it was stated to be an arbitrary boundary that would move depending on factors such as soil permeability it is a useful starting point to define whether gas monitoring data has covered a sufficient period of barometric pressure variations.

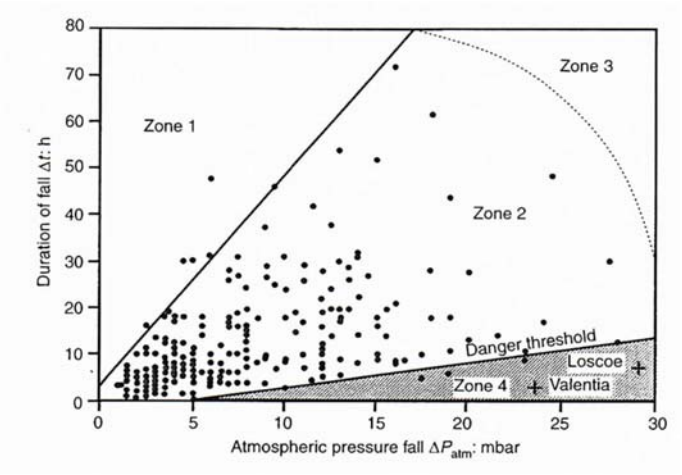

Figure 2. Provisional definition of danger threshold for methane explosions (After Boltze and de Freitas ,1996).

Notes:

Zone 1 - small variations in pressure over relatively long periods of time – the gradient of the time-pressure curve from the microbarograph is almost horizontal

Zone 2 - represents most of the values recorded (in London between March 1992 and February 1994) and is considered the normal range of pressure changes.

Zone 3 - large changes in pressure over long periods of time. These conditions did not occur during the period of recording.

Zone 4 - very large pressure changes in very short periods of time

If gas monitoring is completed over a period when a fall in barometric pressure is within Zone 4 then clearly worst-case conditions are likely to have been monitored (with respect to barometric pressure). Note that other factors may need to be considered (e.g. seasonal variation due to waterlogging of the ground).

Massmann and Farrier (1992) also concluded that vertical flow velocities in response to barometric pressure variations reached a maximum at times corresponding to the maximum slope of the barometric pressure curve. The fluctuations also cause fresh air intrusion into the ground resulting in lower gas concentrations in monitoring wells. This is often the cause of variations in concentrations in wells where gas flows are very small, rather than gas flow increasing at times of falling pressure.

Xu *et al.* (2014) found that a minimum period of continuous monitoring of 10 days was required to capture 90% of the total variance in methane surface emissions from a domestic landfill site Nebraska, USA (again with respect to barometric pressure variations). However this criterion should not be applied to all sites without considering the likely risks posed by gas emissions.

4. DATA ASSESSMENT OF COMPLETE CONTINUOUS MONITORING

Using the danger threshold concept described by Boltze and de Freitas above, the barometric pressure drops that occur during gas monitoring can be further assessed and examined. This has been completed for three example sites. Full details are provided in Appendix A. A further consideration is the British Coal lower limit for a "sharp" fall in pressure (a 4mb drop over 3 hours).

The magnitude and duration of the pressure drops that occurred over various periods of time from 1 hour to 48 hours at each site have been plotted on graphs, along with the different zones. An example is provided in Figure 3.

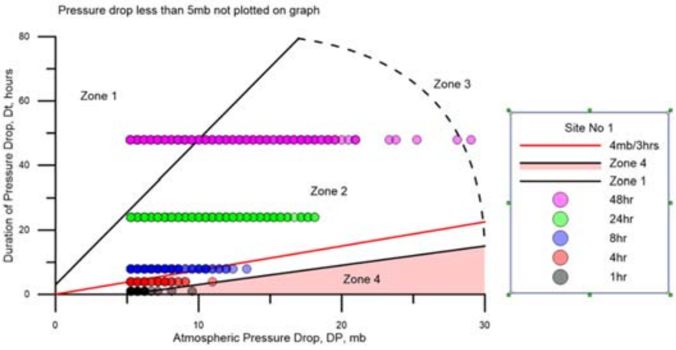

Figure 3. Example graph of barometric pressure drop vs duration.

The response of the gas concentrations and flow rates (and therefore gas screening value) during the pressure drops that fall either within Zone 4 or below the red line on Figure 3 has been assessed. The analysis shows that it is the rate of fall in barometric pressure that is critical and the absolute value of pressure has little or no influence on the gas monitoring results. This indicates that contrary to common perception it may be better to ensure monitoring is undertaken when the rate of pressure drop is at points below the red line in Figure 3 (i.e. greater than 4mb pressure drop in 3 hours), but the absolute pressure range is above 1000mb, rather than having lots of results with a lower rate of drop but in a range less than 1000mb.

The analysis also shows that pressure drops close to the boundary of Zone 3 can influence the peak GSVs and therefore it is another consideration when assessing whether sufficient data has been collected. Zone 4 could be extended to cover larger pressure drops at longer durations as shown in Figure 4.

5. NEW WORST-CASE ZONE AND OTHER CONSIDERATIONS

Based on the sites that have been reviewed a worst-case zone for atmospheric pressure drops can be defined as shown in Figure 4. The red shaded area combines the Zone 4 defined by Boltze and de Freitas (1996) with an area at pressure drops greater than 20mb that corresponds to a rate of 1mb between 1.15 hours and 1.7 hours over a period of 24 hours or greater. This is called the "worst-case zone" (modified Zone 4).

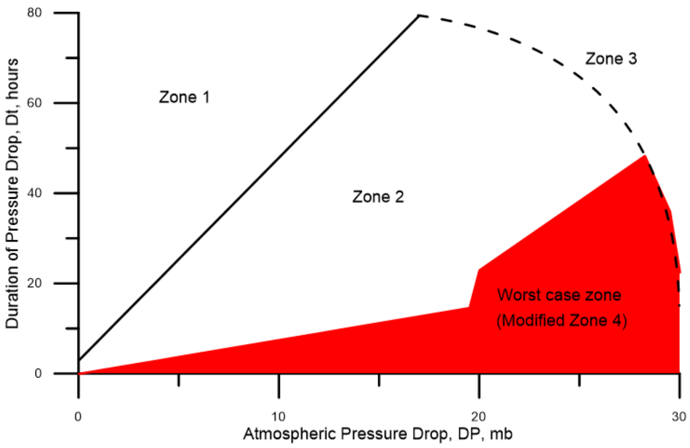

Figure 4. Worst-case zone for gas monitoring.

A small percentage of the data collected at Site No 1 would fall in the newly proposed extended part of Zone 4. It would make no difference to the assessment at Site No 2 in terms of checking whether 'worst-case' conditions have been met as much of the 24 hour and 48 hour data for Site No 2 plots outside the extended worst case zone. However, Site No 2 collected gas monitoring data over short and sharp pressure drops, which do fall within Zone 4. Much more of the collected data at Site No 3 would fall within or near the newly proposed Zone 4. Thus the extended zone 4 covers both short sharp drops in pressure along with greater pressure drops over longer periods.

The limits of Zone 4 may change depending on the global location and typical local rates of pressure variation.

Another aspect to bear in mind when considering the absolute pressure of 1000mb is that field readings (either with handheld or continuous analysers) are subject to both barometric variations and elevation (there is a decrease in pressure of approximately 1mb per 10m gained above sea level). This is another reason why the use of an arbitrary limit such as 1000mb is not appropriate.

6. CONCLUSIONS

Not all sites will require gas monitoring or consideration of barometric pressure. Flow resulting from barometric pressure changes is only significant where there is a large enough reservoir of gas and an open or highly permeable pathway. Where the conceptual site model indicates that barometric pressure may be a risk driver the most significant influence on ground gas monitoring results is the rate of barometric pressure drop rather than pressure being below any absolute value. Monitoring should cover several periods when the change in barometric pressure is within the worst-case zone shown in Figure 4. The evidence indicates that a requirement to monitor below an arbitrary value of barometric pressure such as 1000mb is not relevant (and is not practical in some parts of the world).

Where barometric pressure is the only driver for gas concentration and flow a relatively short period of monitoring may be appropriate to cover 3 or 4 critical pressure drops. It is important to consider whether barometric pressure is the only, or even the most important, driver for gas emissions on a site. On some sites there will be other factors that are more significant, for example rapid changes in groundwater levels or changes in groundwater chemistry. Longer periods may be appropriate where other factors are likely to be key drivers and where the results could change the outcome of any risk assessment.

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Appendix A

Site No 1

The monitoring well in this case was installed to a depth of 10m with the majority of the response zone in Alluvium comprising sandy CLAY with peat inclusions (the top 1m was in Made Ground comprising sandy gravelly CLAY with fragments of concrete, brick, gravel and charcoal pockets). The pressure drops and durations are shown in Figure A1.

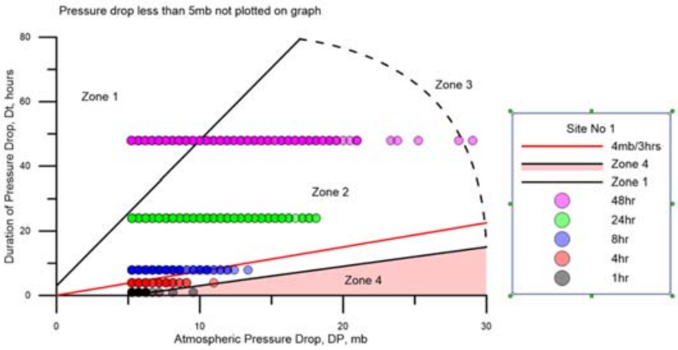

Figure A1. Site No 1 – barometric pressure drop vs duration

As would be expected, for site No 1 the short duration pressure drops greater than 5mb (8 hours or less) tend to give rates of change that are in or close to the danger zone, i.e. the worst-case scenario. Several of the peaks in methane concentration occurred after a pressure drop that was either below the red line or in the danger zone (Figure A2). However, there is a lag between the pressure drop and methane peak and that varies between events. There is also a larger scale variation in methane that is not related to barometric pressure. The reason for this on this site is not absolutely clear, but rainfall and air temperature appear to be having some effect.

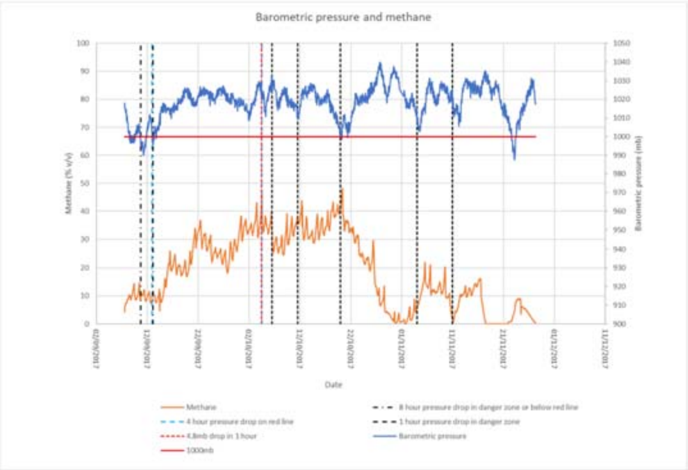

Figure A2. Site No 1 Barometric pressure

For Site No 1 most of the critical pressure falls did not occur at the lowest barometric pressure (Figure A2). For the one-hour duration only one of the results that were well into the danger zone occurred over a range less than 1000mb. A few 4 hour drops that were in or close to the danger zone occurred below 1000mb. Although there were many more points below 1000mb for the 8 hour duration, most of the pressure drops that were in the danger zone were over a range above 1000mb.

This suggests that it is not critical to obtain results at 1000mb or less although clearly on this site, over this period, six of the pressure drops did result in barometric pressure less than 1000mb.

The graph for GSV (for methane – Figure A3) shows that some of the peak values are preceded by critical pressure drops (e.g. 22/10/2017). However not all peaks are (e.g. those recorded before 2/10/2017) and there is varying lag between the drop in pressure and the peak GSV. The peaks that do occur are short lived (less than 3 hours) and they only just exceed the limiting value for characteristic situation CS1 (0.07 l/hr). In addition, sharp falls in pressure are not always associated with peak GSVs, e.g. the period between 21/11/17 and 01/12/17; and 01/11/17 and 11/11/17. They would therefore not pose any significant risk of gas ingress to a building if for example there was a ventilated void below the floor slab designed in accordance with CIRIA C665 or BS8485: 2015. Gas concentrations in the void may rise slightly for a short period but excessive gas ingress into the living space would not occur.

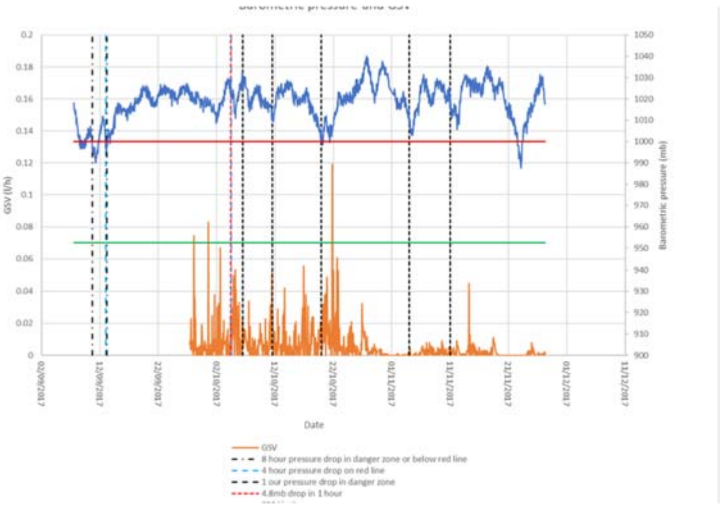

Figure A3. Site No 1 GSV

Site No 2

On this site the wells were installed in Made Ground comprising medium grained, pale grey with brown mottling, dense, moist clayey sand. It also contained a small proportion of dead grass. The response zone of the standpipe was between 1.4m and 2.9m depth.

For site No 2 only a few 1 hour duration pressure drops fall within the danger zone (Figure A4). Several 4 hour and 8 hour pressure drops fall within the region between the red line and the danger zone. Again, several peaks in the methane concentration occur just after the relevant pressure drops (Figure A5).

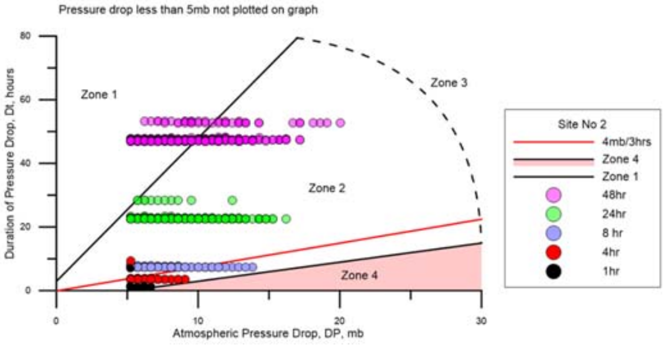

Figure A4. Site No 2 barometric pressure drop vs duration

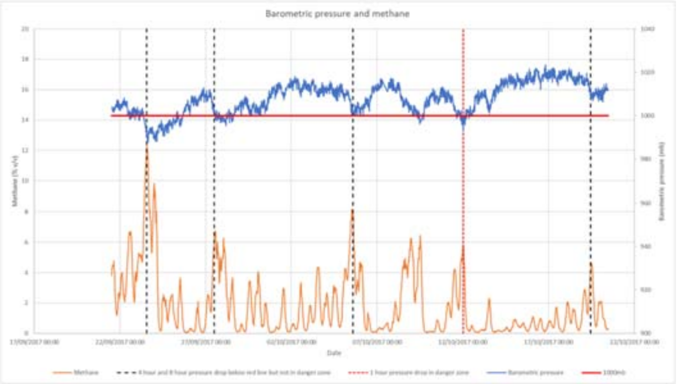

Figure A5. Site No 2 Barometric pressure

For Site No 2 most of highest peaks in GSV are preceded by critical pressure drops (Figure A6). Again, the peaks that do occur are short lived and, in any event, all are less than 0.07l/h (limit for CS1).

Figure A6. Site No 2 GSV

Site No 3

The well in this case had a response zone between 1m and 2.4m. It spans Made Ground comprising a layer of sandy gravelly clay with fragments of brick, concrete and ash which overlies black very moist landfill waste (rubber, timber, glass, etc). The landfill waste was placed in the mid-1980s and thus is still generating gas.

During monitoring at Site No 3 barometric pressure was below 1000mb for a large proportion of the time. The rate of pressure drop was never in the danger zone and rarely at or below the red line (Figure A7). This indicates that contrary to common perception it may be better to ensure monitoring is undertaken when the rate of pressure drop is at points below the red line in Figure A8 (i.e. greater than 4mb pressure drop in 3 hours), but the absolute pressure range is above 1000mb, rather than having lots of results with a lower rate of drop but in a range less than 1000mb. On this site methane is consistently above 65% (Figure A8) which is the typical methane content at the point of gas generation in a domestic landfill. The worst-case has clearly been identified (a rise to say 90% would not make any practical difference to a risk assessment and normally indicates that carbon dioxide is being lost into groundwater). Interestingly there is air intrusion and dilution of methane in the ground at rising barometric pressure of 4mb over 8 hours and 12 hours.

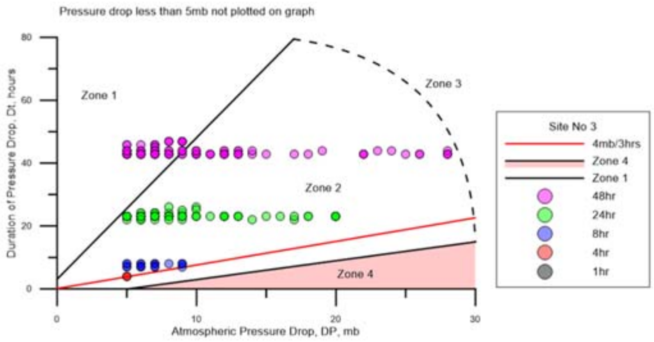

Figure A7. Site No 3 barometric pressure drop vs duration

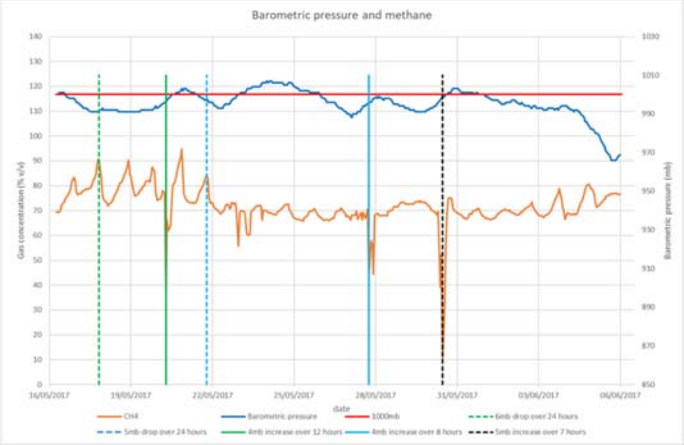

Figure A8. Site No 3 Barometric pressure

The highest peak in GSV occurred at a drop of 20mb over 23 hours or 28mb over 48 hours (Figure A9), both occurring between 03/06/17 and 06/06/17, i.e. close to the boundary of Zone 3 identified by Boltze and de Freitas (1996). Zone 3 is the practical limit for consideration of the influence of pressure drop and time. However, the data that is close to that boundary clearly has an influence on peak GSVs and therefore it is another consideration when assessing whether sufficient data has been collected. Zone 4 could be extended to cover larger pressure drops at longer durations.

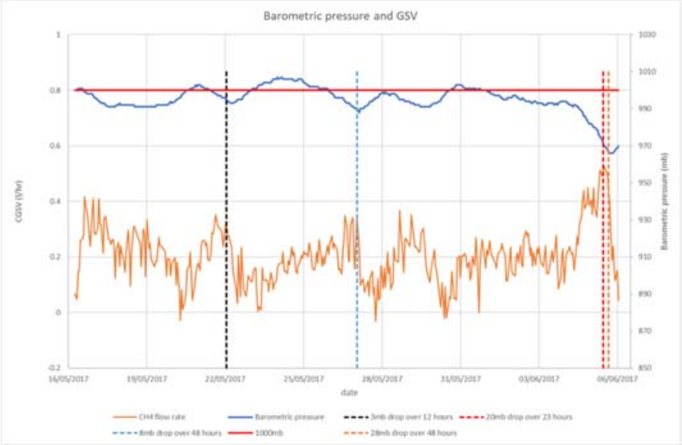

Figure A9. Site No 3 GSV