Perimeter soil gas emissions criteria and associated management

Industry Guidance

C&P Environmental Ltd

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1. Executive Summary

In completing this ICOP, the industry has attempted to set out, with the help of the regulator, best practice for future perimeter well monitoring and analysis. Appropriate proven frameworks for the best practice of subsequent actions/management are presented in the event that further investigation of soil gas concentrations is required.

In building on three decades of monitoring of sites (both operational and now closed), it is recognised that the requirement for perimeter monitoring of soil gas concentrations will continue as a key means of assessing the performance of gas management from a landfill. In ensuring standards are clear and accessible to the wider industry, primary assessment of monitoring data will continue to be made on a "concentration" of gas basis as opposed to a more complex "risk assessment" or "flux" basis.

The ICOP presents "best available" approaches to establishing background methane and carbon dioxide concentrations at sites ahead of, and even following, the placement of waste in any engineered cell. Statistical techniques are proposed to define background limits for stable and unstable data sets, with background concentrations being set on a well by well (or zonal) basis rather than a site wide basis. The key recognition for the need to balance statistical analysis with appropriate professional judgement of the meaning of the data is also identified.

However, in a change from the previous approaches taken by WMP27 and LFTGN03, it is now recognised that carbon dioxide is a poor choice of gas to regulate emissions from landfills because there are alternative sources in the sub-surface environment. This is reflected in this ICOP through the position that no compliance (formerly trigger) limits should be set for carbon dioxide in the future emissions performance assessment of a site. It has however been agreed that carbon dioxide data should continue to be collected and assessed against a lower action (formerly control) level because this activity informs the conceptual model and initiates investigatory action by the Operator.

Exceedance of either an action level or a higher compliance concentration will invoke one or more response actions from proposed response frameworks. It is envisaged that these frameworks will be incorporated into Operator's Gas Management Plans to establish not only the appropriate actions but also target timescales for completion of further works. The frameworks for such works and timescales have been proposed based on risks beyond the installation boundary and typically address both external and also in-waste assessments and actions to assess data against the conceptual model for the site.

Adherence to the ICOP enables an Operator not only to manage installations on sound emissions criteria but also to demonstrate good management systems and operating procedures/techniques as required under the Environmental Permitting Regulations.

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This report is intended to be a living document that will develop with time. Comments received at perimeter@candpenvironmental.co.uk will be assessed periodically by the steering committee that developed the document. Additional case studies and practical examples of perimeter emission criteria development will be especially welcome.

DISCLAIMER

No guidance can accommodate the circumstances of every specific site and every possible conceptual model. This guidance has been written to be applicable to most, but not all, sites. Sites with exceptional conceptual models will need to develop their own bespoke management and regulatory thresholds.

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1. Introduction

Many landfill sites in the UK have been developed before the requirement to establish background concentrations of methane and carbon dioxide was introduced. Subsequently, when compliance limits were set in Environmental Permitting (EP) permits they were often based on no site specific background data. The compliance levels were not based on any quantitative assessment of risk to site-specific potential receptors. Both industry and the Environment Agency/SEPA have recognised that a robust, scientific method of quantifying background levels of gas in surrounding land and setting compliance limits is required to allow pragmatic regulation.

Also, when compliance limits are exceeded on landfill boundaries, a sequential, risk based approach to managing the exceedance is required, which will address the necessary “appropriate measures” required to manage the incident in a timely and coherent manner. Historically the site has been ‘scored’ from a regulatory perspective before any assessment of the sub-surface gas has been carried out. When the subsurface environment is not stable, developing a reasonable scoring regime also becomes important.

When a compliance limit is exceeded, the first question is typically ‘prove that the exceedance is not the result of a poor gas control system or inadequate containment engineering’. A robust method of assessing whether a gas control system is operating properly is also required. To address this, the reader is referred to the assessment of gas management systems in the revised LFTGN03 Guidance note, the Industry Code of Practice developed for assessing gas management systems, and the Environment Agency’s technical review process.

1.1 Objectives

The primary objective of this report is the publishing of a document, developed by industry with consensus from the Environment Agency/SEPA, which provides guidance on determining appropriate management levels, compliance limits, and action protocols for dealing with perimeter monitoring wells around landfill sites. NOTE – this framework cannot deal with every contingency at every site.

1.2 Report structure

The report structure is set out below:

1 Introduction
2 Current regulation
3. Methodologies for setting compliance limits
4 Gas migration
5 Initial activity associated with suspected gas migration
6 Preliminary management of gas migration
7 Detailed investigation of gas migration
8 Mitigation options
9 Verification
10 Conclusions

2. Current Regulation

EP permit conditions have to date set compliance limits for perimeter wells with a small, uniform or arbitrary increase in methane and carbon dioxide concentrations above what is perceived to be background soil gas concentrations at the site regardless of the risk presented by ground gas concentrations at specific well locations. There are also uncertainties in how data should be interpreted, reported, and regulated.

An historical assumption was that as soon as any waste was placed, the gas in perimeter monitoring wells was no longer 'background' gas. With regard to critical gas production (CGP - the point at which methanogenic conditions are achieved), current consensus is that this occurs 6-9 months after waste has been placed in a landfill. Even after the point of critical gas production in the first or early cells, most landfill cells are sequentially developed next to undeveloped ground and monitoring wells, particularly those distant from waste mass, are most likely to be measuring 'background' concentrations long after waste has been placed at the site. Obviously any rise in gas concentrations following placement of waste in adjacent or non adjacent wells would still need to be adequately monitored and ultimately explained. Another confounding factor is that this 'background' may be changed by the placement of the liner rather than placement of the waste if there is an alternative gas source in the subsurface and until recently, this was poorly understood.

In addition, there is confusion within in the industry over terminology. To clarify this, the following terminology should be used:

- Action Levels: These are set at a level at which the operator should take action to remain compliant and form an early warning and/or may instigate additional monitoring or emergency procedures. An exceedance may mean an interruption to the gas management system, but the Environment Agency/SEPA does not need to be informed. Action levels are not set in the EP permit but should be in the gas management plan or operator's management procedures. Action levels should be concentrations between background and the Compliance limits.

- Compliance limits. These are set by the Environment Agency in the EP permit and are designed to show the gas control system and the liner, are performing properly. Typically, they have been set at (as referenced in LFTGN03 Table 6.2):
    - Methane 1% above agreed background concentrations, and
    - Carbon dioxide 1.5% above agreed background concentrations

  Compliance limits are a regulatory requirement. If the results of monitoring are at or above the agreed compliance limits, the Environment Agency/SEPA must be informed immediately and remedial action implemented within an agreed, defined, timescale because the site is deemed not to be in compliance.

2.1 Action Limits

The monitoring of external boreholes is essential to demonstrate the efficiency of gas management systems within landfill sites, and to detect any gas migrating from the site. Action/assessment/remediation is initiated when concentrations are above background and the first signs of a possible 'event' emerge. The Environment Agency/SEPA does not yet need to be informed because only a management limit has been exceeded in contrast to a compliance limits breach. In scenarios where other sources of gas generation are present, then location specific background concentrations are more appropriate than a site wide limit.

There are many problems facing operators trying to assess whether the off-site gas concentrations above background are from the landfill or elsewhere. This section focuses on the factors present in the sub-surface environment that make setting management concentrations difficult. Many of the problems are also applicable to problems of applying the compliance limits discussed in Section 2.2.

Setting background concentrations. The common problems associated with the setting of background concentrations include:

1. At sites where permitting requirements came after the landfill was operating there are often no pre-disposal data. This is a particular problem at sites with old cells nearby built on the 'dilute and disperse' principle. Elevated background concentrations may be due to the neighbouring 'old' cells, but this is difficult to prove.
2. Depending on the adjacent land-use, hydrogeology and geology to a landfill, one area of the landfill may have different background concentrations compared to another. In this situation setting site wide background concentrations may have limited applicability, subject to the risks posed by the site and the local environment and may be inappropriate.
3. If data are collected, there are no agreed statistical methods for removing or discounting outlier data that may be associated with increased uncertainty of measurement. This is partly because the data distribution is rarely a perfect 'normal' distribution. Assessment of the data can usually determine whether statistical methods provide a reasonable approach. A suggested method for setting background levels for datasets that are judged to be close to a normal distribution is explained in section 3.1.2.
4. There is an active ground gas cycle with pressure and moisture changes on a daily basis and seasonal changes on a quarterly basis. At least one year of intensive monitoring is required before this can be understood at a particular site, with the ideal background data gathering period being as long as is possible.
5. The presence of strata such as the Coal Measures near the site can make setting background concentrations problematic. Coal Measures strata produce methane and carbon dioxide. The mechanisms for release of methane and carbon dioxide from these strata are poorly understood, with perhaps their own 'coal gas' cycle. However, when mines gases appear in landfill monitoring wells the increase in concentrations are often short lived and may or may not be linked to external influences such as the weather. For example, there may be no mines gas detected for many years and then it appears – in this instance it would need to be proven to be mines gas by radiometric analysis. Setting viable background concentrations in these circumstances is difficult.

6. At sites with adjacent, poorly engineered dilute and disperse sites leachate seeping into the subsurface (as it was intended to do) can de-gas methane and carbon dioxide. There is a time lag between leachate generation and de-gassing that can mean apparent increases in gas concentrations outside the permitted site appear unrelated to any meteorological event.
7. Monitoring infrastructure. Reliable observations depend on the appropriate location, proper construction, and maintenance of monitoring wells.
8. Data collection. There are a number of methods of recording methane and carbon dioxide concentrations. Most measurements are taken with a field meter, but some people record the initial concentration in the well, some the highest concentration in a 30 second monitoring window, while others record the stabilised reading if possible (gas concentrations in some wells do not stabilise, but gradually drift lower). In addition, the interval between calibration and/or verification of field meters differs widely among practitioners. All monitoring methods have their own advantages and disadvantages, but there is no common standard. This means that validation of third party data (quality) is difficult and using it for interpretation can be flawed unless the uncertainties are constrained.
9. There are many potential off-site sources of carbon dioxide in any landfill – natural respiration in fertile topsoil, degassing from limestone and chalk geology, local coal and shale seams etc. For this reason, setting background carbon dioxide concentrations is particularly difficult.

Further detail on the best practice in quantifying background soil gas concentrations is presented in Section 3.1.2 of this ICoP.

2.2 Compliance limits

The current guidance applicable to this issue is Landfill Technical Guidance Note 3 (LFTGN03). At the time of finalisation of this ICOP, it is understood that the revised LFTGN03 will propose the historical method of setting perimeter monitoring thresholds should any operator/permit holder not wish to follow the principles of this ICOP. In 2010 the Environment Agency has made it clear that they view these criteria as an emission limit, and exceedance of this limit represents a failure to control landfill gas within the site, either through a failure in containment or management of landfill gas extraction systems. The compliance limit therefore does not take account of the risks associated with the gas concentration in the sub-surface. Risk based regulation will be applied in assessing the magnitude of the non-compliance. A methodology for assessing risk is provided in Section 3.1.7.

In addition to factors in the sub-surface environment discussed above, specific problems relating to regulation include:

1. It is often assumed that gas migration and subsequent rapid oxidation of methane to carbon dioxide is the cause of elevated carbon dioxide concentrations, when there may be other sources.
2. The CCS scoring mechanism currently used by the Environment Agency/SEPA moves to strict liability without necessarily considering proactive technical investigation and management. For example, regulatory emphasis can be placed on a single exceedance of a limit rather than an assessment of the wider temporal and spatial dataset.

3. Regulation has been and should be more in future on a well by well or zonal basis where there is evidence of variable background conditions across the site.
4. Reported measurements do not take into account sampling and measurement errors even though they are acknowledged by the Soils Test Association to be up to ±30%, depending on the magnitude of the concentrations i.e., errors can be large at small concentrations.
5. At sites next to old 'dilute and disperse' landfills with no containment engineering, Compliance limits 1% above methane background concentration may not be possible to achieve consistently because of the changes in gas generation and barometric pumping effects within adjacent old cells. In this scenario there may be little logical justification for setting compliance limits on shared boundaries.

2.3 Summary of Current Criteria

Established Two Tier Criteria

Level	Definition/Meaning
Action Level	Point of Intervention / Assessment / Action
Compliance Limit	Point of Regulation* Formal Notification to EA*

In order to not exceed a compliance limit, a credible gap is required between the action level and compliance limit. Other terminology that needs to be understood:

- Schedule Notification. This is a reporting sheet found within EP permits that outlines the data required to be reported within 24 hours of a measurement exceeding a compliance limit as defined in the Permit by the operator. Note, this may be referred to as a Schedule 1, Schedule 5 or a Schedule 6 notification depending on which version EP permit was issued.

- CCS Score. Compliance Classification Scheme (CCS) scores are applied where Environment Agency/SEPA staff have identified non-compliance with conditions of an environmental permit. They are scored and recorded on the Compliance Assessment Report (CAR) Forms, normally following a Schedule Notification.

Two limits are still believed to be required. Refinement of these levels is discussed in the following section.

3. Methodologies for setting assessment levels

There is a diverse array of international approaches to monitoring soil gas concentrations adjacent to landfills. Some approaches monitor the soil gas concentrations along the pathway either at the landfill, or close to the receptor (standards for methane in soil next to buildings close to the landfill). The most common approach appears to be receptor point monitoring with limits set for methane concentrations in buildings. International approaches to perimeter gas regulation are included in Appendix 2.

The Environmental Permitting Regulations cite the Landfill Directive (LFD) and these only refer to the use of trigger and control levels in relation to groundwater protection (Annex III [4]). The relevant parts of the Landfill Directive to gas migration are:

- Article I, which states that the overall objective of the directive is to '….*reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air…..as well as any resulting risk to human health*'.
- Article 12, control and monitoring procedures, which states '…*in the operational phase shall meet at least the following requirements*':
    - *(a) 'the operator of a landfill shall carry out…a control and monitoring programme as specified in Annex III.*
    - *(b) the operator shall notify the competent authority of any significant adverse environmental effects revealed by the control and monitoring procedures and follow the decision of the competent authority on the nature and timing of the corrective measures to be taken'.*
- Annex I of the Landfill Directive requires that; *'4.1 Appropriate measures shall be taken in order to control the accumulation and migration of landfill gas (Annex III).'*
- Annex III Section 1 of the Landfill Directive requires that minimum monitoring procedures are in place to check '…..*that the environmental protection systems are functioning fully as intended*'. In Section 3 of Annex III it states that gas monitoring '*must be representative for each section of the landfill'* and that '*potential gas emissions are monitored for at specified frequencies'*.

In summary, it is the overriding requirements of Article 1 and Article 12 that need to be followed in respect of gas monitoring. These do not require the Environment Agency/SEPA to set compliance limits in the permit.

In practice however, the Environment Agency/SEPA needs to regulate sub surface gas emissions and the operator needs to have monitoring procedures in place for health & safety reasons, environmental protection and to demonstrate compliance with Articles 1 and 12 of the Landfill Directive.

At present the aims of both the Environment Agency/SEPA and the operator are being met by regulating carbon dioxide and methane concentrations in the ground next to the site boundary.

While carbon dioxide monitoring is very useful in terms of understanding the sub-surface conceptual model, landfill emission based carbon dioxide regulation is difficult to administer and empirically justify because there are many other natural sources of carbon dioxide that can cause interference and confusion. If there are confined spaces or basements next to the landfill, then carbon dioxide is a reasonable parameter to regulate because there is a high risk receptor in close proximity. However, in all other circumstances, sound regulation can be achieved by enforcement of a site specific gas management plan and the CCS scoring mechanism, notably through assessment of "General Management" and "Incident Management" activities required within EP permits.

For both carbon dioxide and methane concentrations, it is noted that soil gas concentrations differ from comparable groundwater trigger hydrogeology as groundwater flow is relatively predictable, with clear up and down gradient boundaries at most sites. This can be contrasted with the changes in soil gas concentrations both temporally and spatially around sites where driving pressure gradients may change over very short periods of time, making forward planning and assessment difficult.

A new approach is required that allows gas management to be efficient and proportional to the site specific circumstances.

3.1 Proposed UK methodology

Source control of the gas in the waste is typically the most cost-effective means of preventing gas migration. Consequently, monitoring and control of methane and carbon dioxide within the landfill or at the landfill boundary is considered the most reasonable first step in landfill gas control around a municipal solid waste landfill.

The proposed methodology has to be workable at three types of site:

(a) No background concentrations of methane in perimeter wells.
(b) Elevated methane concentrations in perimeter wells due to other proven off-site sources.
(c) Elevated methane concentrations in perimeter wells from on-site .

While the gas management plan and the CCS scoring must also consider the conceptual model and sensitivity of neighbouring potential receptors, the compliance limits should be dictated solely by controlling the potential landfill emission.

Landfill operators need to know if the elevated perimeter well reading is gas migration. The Environment Agency/SEPA want to know if the elevated perimeter well reading is an emission and more importantly whether it is safe. Re-iterating the two limits that are still believed to be required:

1) A lower **action limit** set at a point when **management** reactions are required because exceedance may mean an operational loss of gas control. However, at this stage when the data have not been confirmed or investigated, trend data are not available, and there is no risk, the Environment Agency/SEPA does not need to be informed. A predefined action plan is instigated; and,
2) A higher compliance limit linked to an increased **emission** because the site is not in **compliance**. At this point the Environment Agency/SEPA is informed and the level of effort in the predefined action plan is increased.

It is proposed that **carbon dioxide is not used** for regulating the sub-surface strata outside a landfill. However, carbon dioxide data should continue to be collected and assessed against an action level because it informs the conceptual model and processes such as potential methane oxidation. The Environment Agency/SEPA can still regulate carbon dioxide through the gas management plan if, for example, operator management systems did not react when carbon dioxide concentrations exceeded an action level. This will especially be the case where there is a high sensitivity site specific receptor in the area such as an underground confined space. Also, any long term changing trends in carbon dioxide above the Action Level should be identified to the Environment Agency/ SEPA as part of the routine submission of monitoring data. Methane is almost always the risk driver of concern and is the best indicator of a landfill emission. However, in the event of carbon dioxide Action Levels being exceeded, although this would not be scored by the regulator, the risk associated with the increased concentration in external boreholes will still need to be assessed as part of the operator's management plan (see 3.1.7).

In order to set site specific limits, the context for the site needs first to be properly understood. This requires an adequate conceptual model to be developed. Until source term management and gas provenance work has been done, it will not be possible to apply this proposed UK methodology.

3.1.1 Determining the conceptual model

The conceptual model should be a simplified representation or expected working description of the landfill and its geo-environmental context, based on a qualitative assessment of desk study and field based data. Key components requiring identification are source, pathway, and receptor elements within the gas management model (Landfill Gas Risk Assessment), including a description of possible alternative sources of naturally occurring gases that may be present within the shallow soils around the site.

The location of a landfill must take into consideration requirements relating to:

- the distances from the boundary of the site to residential and recreational areas,
- waterways, water bodies and other agricultural or urban sites;
- the existence of groundwater, coastal water or nature protection zones in the area;
- the geological or hydrogeological conditions in the area **and especially the permeability of potential gas migration pathways**;
- the risk of flooding, subsidence, landslides or avalanches on the site; and
- the protection of the natural or cultural heritage in the area.

It is noted that while modern landfill sites are designed with containment engineering techniques around the waste mass and employ gas management systems, a small degree of leakage of gas may occur through the lining system. This reflects the properties of the lining systems, diffusion from areas of high concentration to low concentration, and the potential for some post installation defects to exist. It is noted that a similar approach is adopted in respect of hydrogeological risk assessments carried out for landfill where these factors are incorporated into the Environment Agency/SEPA approved LandSim risk assessment software.

Both diffusion and advective gas movements through such engineered systems can be expected to a small degree, although this should be mainly restricted to the unsaturated zone. An understanding of the composition and variability of natural soil gas concentrations under and around the installation should also be considered at this stage, both spatially and temporally.

The conceptual model should identify any underground confined spaces off-site. In this instance carbon dioxide may need to be included in the site specific gas risk assessment. In almost all cases, methane will be the main risk driver in a site specific conceptual model.

This guidance applies to new sites with modern engineering. It is unlikely to be suitable for dilute and disperse old sites that were designed to leak or sites with an anomalous conceptual model (high background mines gas etc). Also, its' successful application on a new site with a contiguous boundary with a dilute and disperse site is also unlikely. On such boundaries, assessing gas migration from the new site onto the old site is not likely to be achieved using compliance limits, however action levels should be set within the operator's gas management plan to identify any failures in landfill gas control.

3.1.2 Determining background levels

Determining action levels or compliance limits first requires an understanding of background or baseline conditions since trying to 'manage' background soil gas concentrations is illogical. In the context of a permit, background conditions are the data measurements within the defined monitoring network prior to a gas migration event. However, the process is based on the limited presumption that what has been observed to date in the monitoring network will be truly representative of every future baseline concentration observed in the monitoring well without any gas migration from the landfill. Background data will include:

- Data obtained 12 months prior to any landfill operations commencing – it is essential that new cells have boreholes in place well before the liner or waste is placed.
- Data after the lining system has been placed but prior to placement of waste within specific cells in the landfill.
- Data obtained as early as practically possible prior to the onset of methanogenic conditions within specific cells in the landfill (these data should be cross referenced to on-site monitoring data to show when methanogenic conditions start); and
- Note that lining a landfill changes the background conditions because gas generated in the subsurface that has previously diffused to surface unimpeded now has to migrate around the impermeable lining. This may result in soil gas concentrations changing during or following lining construction which may not be related to any emission from the installation. Typically there is a four week period between the end of liner construction and waste deposit to allow the regulator to assess the CQA verification report for the lining works. A period of intensive background monitoring is recommended during and after liner

installation in order to understand such changes if there is evidence to suggest this is an issue at the site.

There has been some discussion regarding splitting a landfill site up into risk zones to accommodate for example, old landfills next to one boundary of the licensed landfill. The logical extension of this idea is to address each well on an individual basis. In completing an assessment of baseline and background concentrations in the soil gas environment, production of time-series plots of concentration against time is essential to identify temporal changes in concentration and should form a starting point for the assessment process because temporal changes may not be amenable to assessment via basic statistical analysis techniques alone. Where possible, conformity of axes (date ranges and concentration spans) is recommended to enable ease of visual assessment between successive plots.

1. **It is proposed that background concentrations will be set on a monitoring well by monitoring well basis.**

This has two advantages:

1. There does not have to be a discussion of where a zone boundary is and which wells to include or exclude in such a zone (although this may useful in developing a site specific conceptual model);
2. No complicated statistics are required to deal with multiple datasets that may not have equivalent data.

Note: there is still merit in looking both at location specific data and site/zone data to see how any one well fits the general response of many/other wells. This may be an acceptable alternative approach for setting reasonable background concentrations.

At complex sites this will still allow reasonable background levels to be set that account for the 'old landfill next door' or the other sources of methane. For many simple sites with no alternative sources of methane, the individual well criteria will be the same and become the 'de facto' site criteria.

Considerations when trying to establish a background dataset include:

- In situations where there are no data but a 'background' methane source other than the waste is suspected, then trace gas testing may be used to determine whether the methane is from a landfill or from another background source (See Section 7.1).
- If the variations in methane are rapid (both up and down) and it is suspected that the methane may be from geological strata, then isotope analysis may help at complex sites (see sections 7.6 and 7.7).
- Is the boundary of waste deposition accurate? At many older sites the perimeter well borehole logs show shallow buried waste. This background source will need to be accounted for, but strictly speaking the well is not fit-for-purpose and should be re-drilled further from the waste boundary.
- Trends/stability of background data. If the background data are already showing an upward methane trend, then applying statistics or trying to establish a baseline will not be possible. In this instance the cause of the upward trend

would obviously require explanation. Statistical analysis should only be undertaken on broadly stable data sets.

- Consideration should be given to whether old data or data obtained by third parties meets the required data quality objectives. Using old data of poor quality may skew a background dataset.
- Note: Where monitoring wells are identified to be monitoring background conditions with no source term present in the adjacent landfill cell (i.e. the point when critical gas production has not been established), then no Action or Compliance levels are required within these monitoring wells for regulatory compliance assessment. However, an operator may find it useful to propose internal assessment levels to assist the assessment of the data collection during the pre- critical gas production period.

Stable datasets

The overall objective for stable datasets with an approximately ‘normal’ distribution is to establish a statistically significant background concentration with sufficient flexibility to account for natural variability, and hence reduce unnecessary investigation or compliance works. The preferred methodology is to use the method outlined in Environment Agency R&D document P1-471, as referenced in LFTGN02. A typical dataset is provided in Appendix 3, where a discussion of whether it is a ‘normal’ dataset is also included.

The P1-471 outlier test is a screening tool with the general aim of 'cleaning up' data to estimate baseline statistics. The method standardises and ranks the data (n - mean / standard deviation) and compares the numerical maximum value (Tmax) to a Critical Value at P = 1%. If the Tmax is greater than the critical value, then the probability that a value as extreme as this could have arisen by chance from a normal population (of data) is less than 1 in 100. The P1-471 method is proposed for the following reasons:

- it is taken from Environment Agency Guidance;
- it gives a statistically sound, unbiased analysis and targeted identification of outlier values;
- the calculations can be carried out on a basic Excel© (or similar) spreadsheet without extended analysis using software add-ons and visual assessment thereof;
- the P1-471 outlier test gives an unbiased indication of migration events expressed as outlier values. This can also be applied to remove errors in data.

It is however noted that other approaches to statistical analysis may be applicable for data processing. Where probabilistic assessment is completed, it is noted that the 95th percentile concentration is lower than the value of Tmax and may be a conservative substitution for Tmax.

The information provided in the technical report P1-471 explains the concept and is described below in the context of a perimeter landfill gas dataset. A worked example is presented in Appendix 3A:

It is essential that any application of statistical techniques is underpinned by a sound understanding of the site’s conceptual model, expected or established data sets within the local environment and appropriate, balanced professional judgement of the significance and meaning of the data.

What is the Tmax?'

The Tmax value of any standardised and stable dataset is the numerically most extreme value of that dataset and, therefore, is the lowest value or the highest value present. When considering the application of the Tmax methodology to carbon dioxide or methane concentrations in off-site monitoring wells then the Tmax value will be the highest numerical value of the standardised dataset. The Tmax methodology can be used to determine whether this most extreme value is an 'outlier' of a normally distributed dataset and can therefore be discounted, or is part of a 'normal' dataset.

Standardising the dataset

Prior to considering the Tmax value, the dataset must be 'standardised'. This requires the 'mean' and the 'standard deviation' of the dataset to be calculated. Then:

- For each data value: subtract the 'mean' from the data value and then divide by the 'standard deviation'.
- Sort the values into increasing order.

Select the Tmax

For use in the ICOPS the highest value of this standardised dataset is the Tmax value.

Consider whether the value is an outlier

To assess whether the most extreme value of the standardised dataset is an outlier the Tmax must be compared with a table of 'critical values' of a normal distribution. The 'critical values' are determined for a specific confidence level (e.g. 99%) for each number of data values present in the dataset being considered. The Table of critical values in the Technical Report P1-471 provides the critical values at a 99% confidence level. To determine whether the value is an outlier then simply compare the Tmax value with the corresponding critical value (for the number of data values in the dataset).

If the Tmax value is higher than this critical value (on the assumption that the carbon dioxide readings are normally distributed) then it can be concluded that the data value is an outlier. That is, the probability that a value as extreme as this could have arisen by chance from a Normal population is less than 1 in 100.

Removal of outliers

If the Tmax is not greater than the critical value then the highest data point is not an outlier. Use this Tmax for setting background.
Or, if determined to be an outlier, then this data value should be removed from the dataset and the Tmax value becomes the second highest value of the standardised dataset. Use the second highest Tmax for setting background.
If multiple outliers are suspected then this methodology can be continued in order to confirm the Tmax value (after outliers removed). Use the highest Tmax value that is not an outlier for setting background.

Determination of the action and management response concentrations
Once all outliers have been removed, the Tmax value to be used for assessment of the background concentrations is the corresponding data value (percent methane or carbon dioxide) from the original dataset (not standardised) - i.e. the data value that when standardised became the Tmax value). This Tmax value is then used as the background concentration and can subsequently be used to determine the appropriate action levels or management response levels.

Once the Tmax methodology has been applied to the dataset, then background concentrations should be calculated on the following basis:

- **The proposed statistical technique for setting background concentrations is the Tmax concentration.**
- **The justification of an alternative statistical tools may be applicable on a site by site basis. For example, the 95th percentile may be applicable (see below).**

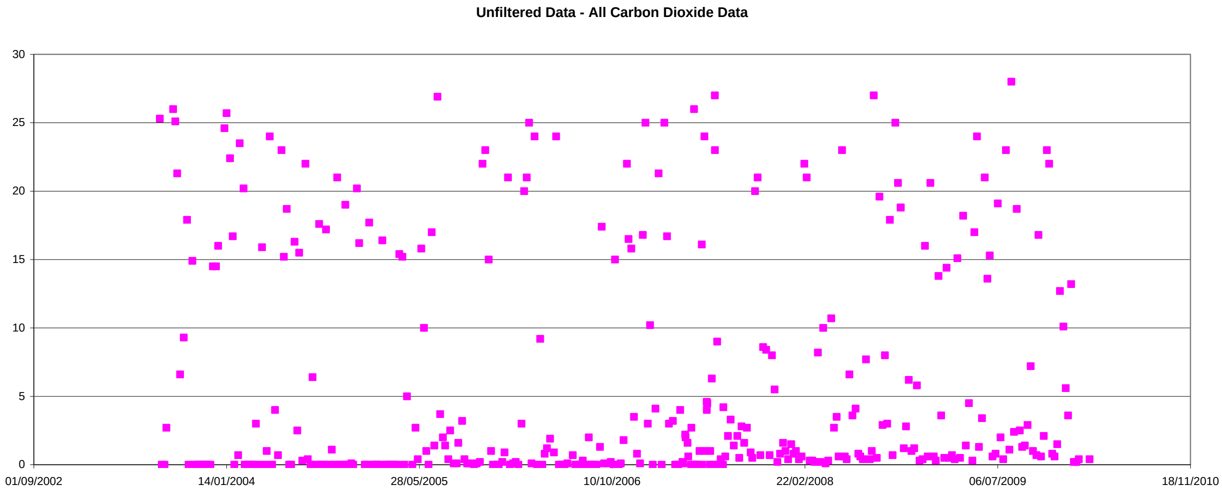
Percentile concentrations can be calculated using statistical analysis tools (such as 'Minitab') or =PERCENTILE (N1:N2,0.95) in Microsoft Excel© and may be assigned where a data set contains more than ~ 30 data points. The accuracy and reliability of the percentile calculation improves as the number of data points increases. An alternative methodology for removing outlier data using box plots is also provided in Appendix 3B.

NOTE: Recommended statistical methods make the assumption that the data is Normally distributed (after logging where appropriate). For outlier detection the assumption is particularly critical, because the method is concerned with the extreme tails of the distribution - which is precisely where the assumption is most likely to breakdown. For this reason, **outlier tests should be regarded as providing no more than a rough screen of the data, with an element of judgement applied in marginal cases**. Nevertheless, experience shows that outlier tests are extremely useful for flagging up gross outliers (such as those in error by a factor of 1000), and in general the routine use of such tests is highly recommended.

To help make this judgement in marginal cases a histogram plot or other methods may indicate that the one or a few elevated results from the data set are outliers.

Unstable datasets
Standard statistical techniques may be readily applied to broadly stable data sets. However, within the natural environment, fluctuations in soil gas concentrations may occur in short periods of time, where the data from a low range to a high range and then back again in an unpredictable manner. A discernible gap can be recognised between the high and low ranges, with the gap typically being greater than 10% v/v. Such data may exhibit a saw tooth pattern over time.

An example of such a data pattern is presented below:

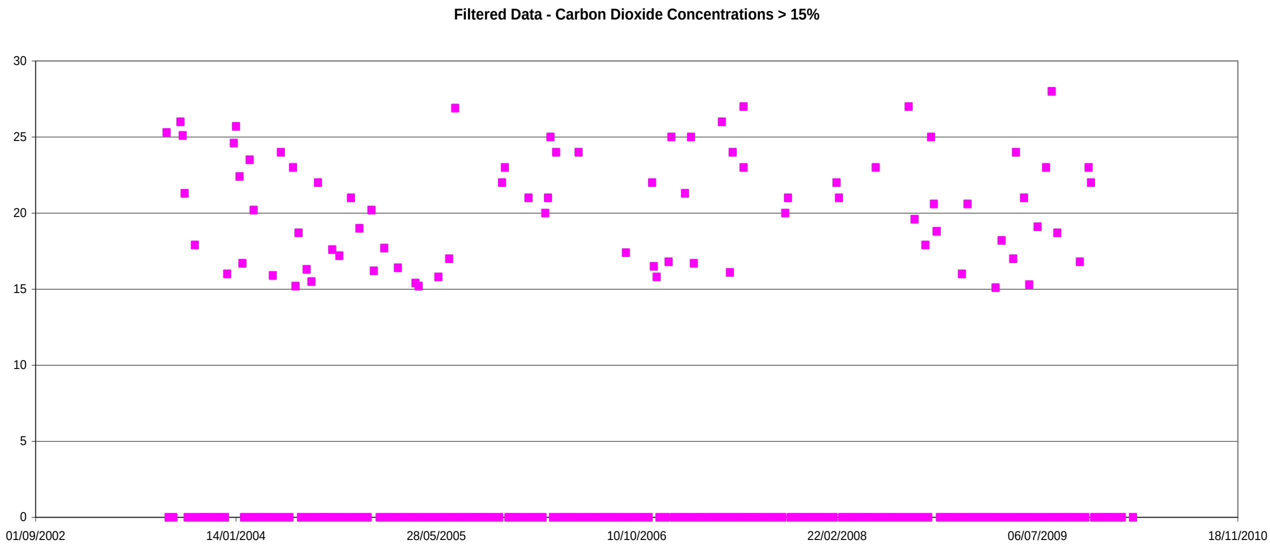


A percentile statistical analysis of all the data above is as follows:

N = 355; Mean: 6%; SD: 7%; 95%ile: 19%; Range: 0 – 29%.

While statistically true, 44 readings in the data set are above the calculated 95th percentile limit and the range between the 95th percentile limit and maximum data value is >10% v/v. Conventional statistical techniques are limited under such circumstances, where sufficient data exists to support the presence of saw toothed data. If the focus is on the higher data range, the data set can be filtered to remove the low end data from the subsequent analysis. Filters can be applied at any interval, but can be typically set at 2.5%, 5%, and 10%, allowing the subsequent analysis to focus only on data above the filter threshold. The use of such a filter enables more accurate quantification of the high end of the data set, which is the area of interest in the setting of any future compliance limits within the perimeter borehole network.

If the data set above is passed through a 15% filter, the data set is refined to appear as follows:



A percentile statistical analysis of the filtered data is now as follows:

N = 82; Mean: 21%; SD: 4%; 95%ile: 26%; Range: 15 – 29%.

Another alternative to using the unadulterated statistical tools is to produce time series plots of background data and review by eye to identify, evaluate, and remove possible outliers arising within the data sets, having consideration to both the data set in the monitoring well and an appreciation of the range of data observed elsewhere across the site. These methods ensure that the data sets are reflective of background conditions and that proposed action levels and compliance limits are not set artificially high by 'one off' spikes. Only when this process has been completed and all the outliers removed can the statistical appraisal commence. This method may be more appropriate than the applying statistical methods in isolation when mines gas events that are transient over a short period of time are common at the site concerned. The use of outlier data removal should be justified before being employed. Only following the removal of the outlier data points should a statistical assessment be performed to establish background concentrations.

An example dataset provided by the Environment Agency from a permitted landfill site is shown in Appendix 3. These data have been used to determine 95^{th} percentile background concentration in Appendix 3B.

The application of filtering and other statistical techniques that may enable an operator to better quantify the soil gas regime around any site can be used to assess unstable data sets. However, details and the extent of the data processing should be clearly documented to enable appropriate review by others.

In the event that a replacement borehole is drilled, the background data from this new well will not be available. The data from the old well could be used, or if the new borehole is in a line of perimeter boreholes, then the background data from the adjacent wells may be useable. However, if the data from the new borehole turn out to be statistically different to either of these choices, then a new dataset will be required before background or any other levels can be set.

Some datasets do not lend themselves to the use of statistics. One common example is a dataset that has mainly zero values with an occasional peak that immediately disappears. Statistically the occasional peaks will be outliers, so the background will be set at zero. When another blip then occurs it will initially be viewed as exceeding the action levels and compliance limits. In this instance the return to zero will show that the elevated reading was an isolated incident, but the CCS scoring mechanism will also need to reflect the fact that this was a natural 'blip' and not caused by gas migration.

3.1.3 Time series data and statistics

It is recognised that the spot measurement of soil gas concentrations and fluxes in the perimeter monitoring network of a site will reflect a 'snap-shot' of the soil gas environment, which is transient with time. It is therefore possible for data to lie above or below the normal range that has been established from historical monitoring at any well location on any one occasion. As such, it is possible for any single monitoring result to exceed an action level or compliance limit without there being an uncontrolled or unauthorised emission from the installation, particularly if the data set returns to the normal range during the following 'contingency' and routine monitoring events. Such exceedences are expected to become fewer with time as the increasing data set results in a better understanding of the system variability at the site with respect to soil gas concentrations.

This may be contrasted with a systems failure at the site which could be indicative of a loss of control of landfill gas at the site – where a number of consecutive exceedences of a compliance limit would be likely to be associated with loss of adequate gas management. However, it is likely that this would be accompanied by other key performance indicators that should be taken into account/assessment – such as the local performance and extent of gas control systems, capping/lining systems, key gas composition ratios and the potential for other gas sources.

- **The sampling frequency for routine perimeter well monitoring on operational sites is monthly (as per LFTGN03).**
- **Background data should be collected ideally 2 years prior to waste placement. 1 year of data is a minimum requirement to understand seasonal variations.**
- **A high intensity monitoring frequency is required in the period after a liner has been installed but before waste is placed to understand the change to the subsurface gas regime as a result of liner placement.**
- **24 - 30 background data points should be viewed as a minimum before statistics can be reliably applied to the dataset.**

3.1.4 Setting Action levels

Well-specific action levels relating to methane and carbon dioxide concentrations will be used to determine whether a landfill is performing as designed. They are levels that are intended to draw attention of site management to the development of adverse, or unexpected, trends in the monitoring data. While such trends could result from a failure of the site's engineering or management systems, early identification and assessment of such variations could simply reflect natural variation between actual conditions and those assumed within the conceptual model. The action level should be treated primarily as an early warning system to enable appropriate investigative or corrective measures to be implemented, particularly where there is potential for a compliance limit (see next section) to be breached.

The action level will not be included in the landfill EPR permit but it should be required as an integral part of a site's gas management plan. However, if the Environment Agency consider that the operator's gas management plan does not specify appropriate action levels, it may include action levels as part of the permit conditions. Methane concentrations below the action level indicate that the performance of the site's gas containment system and gas collection system is good with respect to sub-surface migration. An exceedance of an action level will mean to the operator that some gas might have been lost. The consequence of this will be an investigation into, but not limited to, the following factors:

(a) Is the reading from the perimeter well repeatable? Is there a reason why the readings may not be consistent with previous ones? Is there an increasing trend in perimeter well methane concentrations?

(b) Is the gas field balanced, with suction particularly being applied to wells closest to the perimeter well with the management limit exceedance?
(c) What is the weather? Has a low pressure front just come through? Has it been raining a lot in the past few days/weeks?
(d) Are the engines performing? Has the total gas flow from the field decreased recently?

The suggested reaction to a reading in excess of an action level is described in more detail in Section 5. The results of this investigation will govern the response, but an increased monitoring frequency for a defined period would be a sensible minimum response.

The action level should:

- allow for naturally occurring variation in methane concentrations from baseline conditions; and
- give sufficient time to take corrective or remedial action before regulatory risk levels are breached.

In reflecting natural variations in methane concentrations with time, it is proposed that the action level is set based on an assessment of the stability of the data set since recording began but with a strong focus on the data collected over a period of the most recent 24 data points/2 years data (assuming there is no unexplained long term increasing trend). Well specific action levels will be derived from basic soil gas concentration data using contemporary statistical techniques. It is noted that the selected period of analysis within a lengthy time series data set will affect the outcome of the statistical analysis that could be used to set a subsequent action level. At selected locations the action level can be based on high background methane concentrations due to the established presence of other sources of gas within the soil gas profile. Two scenarios for setting action levels are suggested:

A. Stable Sub-surface environments

- **For every well the action level will be the Tmax (background) methane concentration plus 0.5% (the justification of an alternative statistical tool may be applicable on a site by site basis). NOTE Background = Non-outlier Tmax concentration.**
- **For every well the action level will be 1% carbon dioxide above the Tmax carbon dioxide concentration if the Tmax carbon dioxide concentration is less than 5%.**
- **For every well the action level will be 2% carbon dioxide above the Tmax carbon dioxide concentration if the Tmax carbon dioxide concentration is between 5 - 10%.**
- **For every well the action level will be 3% carbon dioxide above the Tmax carbon dioxide concentration if the Tmax carbon dioxide concentration is between 10 - 20%.**
- **For every well the action level will be 4% carbon dioxide above the Tmax carbon dioxide concentration if the Tmax carbon dioxide concentration is > 20%.**
- **No action levels are proposed for Tmax carbon dioxide concentrations above 25%**

The stable dataset requires an offset or factor of safety because in a dataset of all zeroes, the Tmax will be zero and any exceedance will always exceed the action level.

B. Unstable Sub-surface environments

- **For every well the action level for methane or carbon dioxide will be the Tmax concentration. The justification of an alternative statistical tool may be applicable on a site by site basis.**

Unstable environments are suggested to occur when the range in concentrations values (between high and low data) is > 8% but this may be decided on a site by site basis. The use of any statistical technique in assessing unstable or widely fluctuating data must be carefully considered to ensure that realistic and defensible action levels are set. The use of statistical models does also make the assumption that what has been observed in the past will be what is seen in the future, which for fluctuating data sets or data sets with rising trends, may not be appropriate.

Perimeter soil gas emission criteria and management

This is summarised below and can be contrasted with a stable data set as follows:

Stable gas concentrations

Methane action level	**Carbon dioxide background**	**Carbon dioxide action level**
Tmax +0.5%	**Tmax** carbon dioxide concentrations in range 0 - 5%)	**Tmax** +1%
Tmax +0.5%	**Tmax** carbon dioxide concentrations in range 5 – 10%	**Tmax** +2%
Tmax +0.5%	**Tmax** carbon dioxide concentrations in range 10 – 20%	**Tmax** +3%
Tmax +0.5%	**Tmax** carbon dioxide concentrations in range 20 – 25%	**Tmax** +4%
Tmax +0.5%	**Tmax** carbon dioxide concentrations in range >25%	None

Unstable gas concentrations

Methane action level	**Carbon dioxide background**	**Carbon dioxide action level**
Tmax	Not applicable	Tmax

Note: The factor of safety for carbon dioxide needs to reflect the variability and stability of a particular dataset. For example, if carbon dioxide concentrations in perimeter wells are between 18 and 20%, then a 2.5% factor may be appropriate. However, if carbon dioxide concentrations vary naturally between 0 and 20%, then a 5% factor is more appropriate. If background carbon dioxide concentrations are routinely higher than 25%, then setting action levels is unlikely to be appropriate when trying to assess gas migration from landfills.

If background methane concentrations are routinely higher than 10% then setting action or compliance limits are unlikely to be appropriate to assessing migration from the adjacent landfill unless the elevated concentrations remain stable.

Action levels will identify changes in soil gas conditions that may be reflective of either/both: (a) changes within the normal range of background conditions; and (b) possible emissions of gas from the installation.

Exceedence of an action level will initiate further investigation/action as per the site's Contingency Action Plan for the Perimeter Gas Network. It is envisaged that because the initial exceedance will be a field meter reading, that the first action will always be to immediately re-monitor the well and review the data quality.

While action levels may not be formerly set in the Permit, breaches of such levels and the consequent actions taken to address them will be recorded such that if subsequently the compliance limit is breached, the Environment Agency/SEPA will have an audit trail on which to base their decision to CCS score the incident or not.

If the cause of the elevated methane is determined and rectified leading to a decrease in concentration, or the concentration declines of its own accord, then perimeter monitoring can return to the agreed frequency. If the methane concentration continues to rise, then it will soon exceed the compliance limit (see next section).

It is envisaged that action levels will be reviewed on a two yearly basis. If there has a been a slow increasing trend in methane or carbon dioxide concentrations during this period then action thresholds will not be able to be changed unless the rising trend has been definitely shown to be from an external source.

3.1.5 Setting Compliance Limits

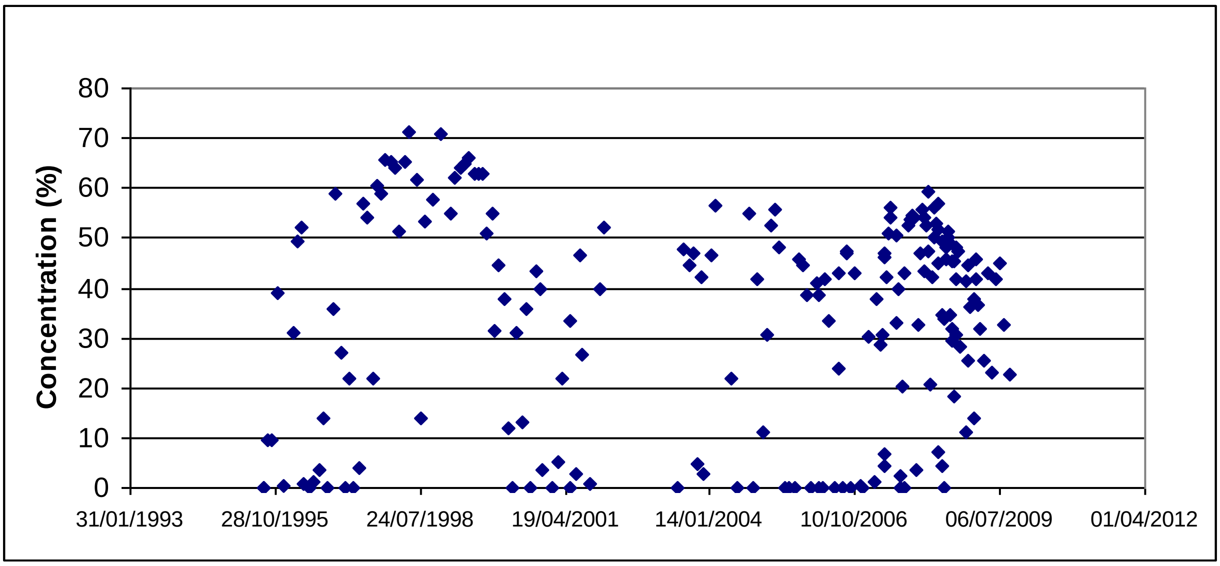
Existing limits are set in LFTGN03 and these can continue to be used if the operator prefers. However, the following limits are proposed as being more rational and flexible. The levels below are proposed for inclusion in the EPR Permit and their breach is to be taken as a potential indication that a compliance failure of gas control has occurred. These levels will be used for regulating sub- surface areas outside the landfill boundary. Above a compliance limit there will be a presumption that the elevated methane is from the landfill until proved otherwise. The presence of a defined compliance failure has potentially serious consequences and may lead to CCS scoring.

- **No compliance limits are suggested for scenarios where background methane concentrations are > 10%*.**
- **For every well under post-critical gas production conditions, the compliance limit will be 1% methane above the Tmax methane concentration (the justification of an alternative statistical tool may be applicable on a site by site basis).**

*10% methane is not normally seen as background concentrations except on shared boundaries with old landfills and in this case not setting a compliance limit is a reasonable approach. If >10% methane concentration was detected not on a shared boundary then the methane source would need to be identified before not setting an emission limit value could be considered. Further, the repeatable presence of any discernible (>1%) concentrations of methane during the background monitoring should give rise to further investigation and/or assessment of the possible causes of methane in the environment and its variability (spatially and temporally) so as not to give rise to false exceedances during subsequent monitoring of the site.

Unstable Datasets

An extreme example of a non stable data set with methane concentration fluctuations > 8%, is shown below:



Minimum	5th %ile	Average	Median	95th %ile	99th %ile	Maximum
0.0	0.0	33.2	39.4	63.0	66.3	71.1

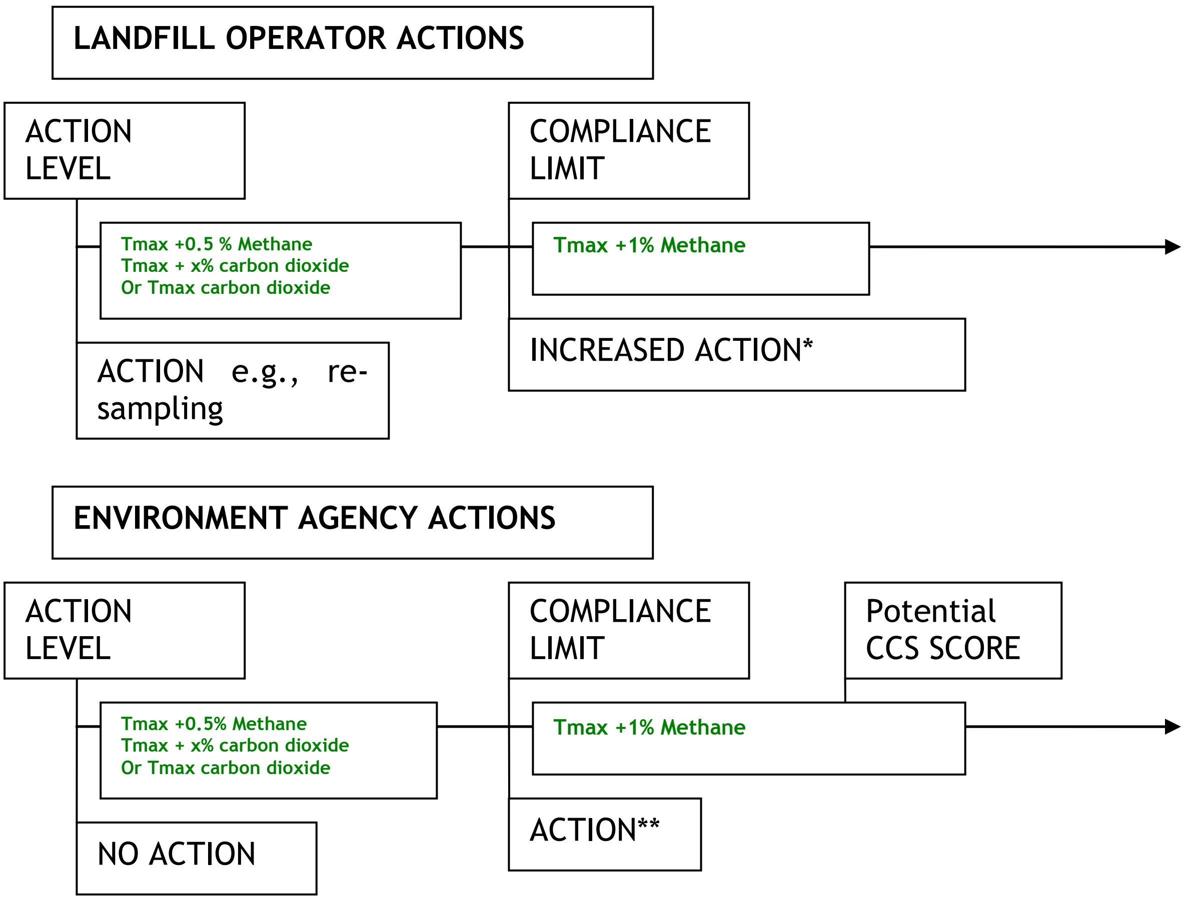
In this instance a compliance limit would not be set using the recommended approach because the background methane concentration is greater than 10%. However, for similar examples at lower concentrations, filtering these data to focus on the performance of the data > 20% might be a better technique, but would require clear and open discussion. Another possibility for assessing potential gas migration would be to use the maximum value plus the 5th percentile if there was a bell curve distribution of data. However, the presence of lots of low data (at 0%) shows the difficulties of using the 5th percentile.

The application of filtering and other statistical techniques that may enable an operator to better quantify the soil gas regime around any site can be used to assess unstable data sets. However, details and the extent of such data processing should be clearly documented to enable appropriate review by others. These approaches are not risk based threshold and ignore pathway attenuation (conservative approach).

In the event of exceedence of a compliance limit, the site's Contingency Action Plan will be followed, which will include notification of the Environment Agency/SEPA of the issue via the appropriate notification forms/schedules as per EPR notification timescales. Additional investigatory/assessment measures will be commenced as detailed in the Contingency Action Plan through to the resolution of the issue.

The process of further investigation will consider whether the levels of ground gas found constitute a significant environmental risk or risk to human health at specific wells, and/or are sourced from the landfill (see Section 3.1.7). The investigation may include a comparison of the empirical data (including both soil gas concentrations and flow rates of gas in the sub-surface) against the identified environmental risks associated with the monitoring point in question. Another practical approach for sites that do not fit a standard conceptual model is to collect detailed data (say every 15 minutes using an in-well datalogger) during a deviation from background conditions to demonstrate or not that there is no ongoing deterioration. This will also enable accurate data to be obtained that will characterise how the gases in the borehole respond to changes in barometric pumping. There is a risk that by interpolating periodic measurements that any lag in borehole response will be overlooked.

A perimeter gas risk assessment report will be the key basis of reference for the 'further investigation' described above, in order that observed concentration and flux measurements are put into the correct context for the site. A well-planned method of assessment, agreed between the Operator and the Environment Agency/SEPA, will help to both protect the environment and provide clarity and avoid ambiguity when compliance limits are exceeded. The flow chart summarising actions for both industry and the Environment Agency/SEPA are shown below:



*Increased action will include sending a Schedule Notice to the Environment Agency/SEPA that will detail when re-sampling will take place and when the contingency action plan has been enacted.

**The Environment Agency/SEPA can apply a score but it can be held in abeyance whilst investigation/action is being taken to deal with the non-compliance. If for example the re-sampling indicates that the methane concentration has returned to zero, the incident may not attract a CCS score. However, if compliance breaches occur regularly then a CCS score may be required. The Environment Agency/SEPA will make this decision on a site by site basis.

3.1.6 Regulating gas migration at old dilute and disperse landfill sites

At old dilute and disperse landfill sites where there is no or very limited engineered containment the only means of landfill gas migration control is through careful management of the gas extraction scheme within the site. Over-abstraction or the application of excessive suction in an attempt to create an inward pressure gradient to draw the gas back into the site may result in undesired consequences in the form of subsurface fires.

However there is still a need for action levels and compliance limits to be included in the operator's management systems and the permit conditions. The methods described above for setting background levels, action levels and compliance limits may be still appropriate but should accurately reflect the conceptual model of the site based on both technical assessment and also site performance to date. However, it is recognised that the conceptual model and identifying background soil gases is likely to be more complex which needs to be considered in the setting of action levels and compliance limits.

These sites may require targeted contingency action plans over and above the framework presented in Section 5 of this report to ensure appropriate actions are initiated in a response to changes in gas concentrations. In determining these contingency plans the risk assessment methodology proposed below (used to assess old landfills within the contaminated land regulatory regime) may be a useful tool allied with close scrutiny of the potential receptors in the conceptual model. It is also recognised that duration of contingency plans may be required for extended periods of time (years) and should recognise both the risks posed by the site and the historical rate of change of soil gas conditions in any monitoring well over the extensive monitoring period that is likely to exist at any closed site, see Section 6 onwards.

3.1.7 Proposed risk assessment methodology

The proposed method of risk assessment on landfill boundaries makes use of advances in understanding in the build up of hazardous atmospheres in buildings. This method relies on receptor point science and ignores the length of the pathway to the receptor, but this should add a significant margin of safety. This method is ill-suited to assessing the risk to underground utilities and culverts. If such structures exist close to the landfill boundary, then risk thresholds close to the flammable limit for methane would be more appropriate. Assessing possible crop damage is another approach where there are only agricultural receptors.

The suggested approach is British Standard 8485:2007. This uses the concept of **hazardous gas flow rate** Q_{hg}, which is the calculated flow rate of a specific hazardous gas from a borehole i.e. total gas flow (q) from a borehole measured in volume per unit time (typically litres per hour) multiplied by the concentration C_{hg} of a specific hazardous gas measured as a percentage.

$Q_{hg} = C_{hg}/100 * q$

The following table is used to asses the risk of methane/carbon dioxide:

Table 1 **Characteristic gas situation by site characteristic hazardous gas flow rate**

Characteristic gas situation	Hazard potential	Site characteristic hazardous gas flow rate, Q_{hgs} lh^{-1}	Additional factors
1	Very low	<0.07	Typically ⩽1% methane concentration and ⩽5% carbon dioxide concentration (otherwise consider an increased characteristic gas regime)
2	Low	⩾0.07, <0.7	Typical measured flow rate < 70 l/h (otherwise consider an increased characteristic gas regime)
3	Moderate	⩾0.7, <3.5	
4	Moderate to high	⩾3.5, <15	
5	High	⩾15, <70	
6	Very high	⩾70	

NOTE *The side characteristic hazardous gas flow rate is synonymous with the "gas screening value" in CIRIA C665 and NHBC Report no.: 10627-R01 (04) [3].*

Note spelling mistake in the above NOTE – should say site rather than side

A **hazardous gas flow rate** value provides a much better understanding of the hazard associated with the presence of the gas in the ground when compared to the historical practice of assessing ground gas concentration data only.

Although ground gas concentration measurements are relatively simple to make there are severe limitations in interpreting such readings in anything but an extremely conservative way. At some sites, the high and variable background concentrations of methane and carbon dioxide in the ground gas environment render impractical the use of concentration based management and regulatory assessment criteria, even if statistical methods are used to interpret the data.

Historically this methodology has had no application in landfill regulation. It is suggested that this methodology is the future for risk based landfill regulation because it more accurately reflects the risk posed to the environment beyond the landfill boundary. However, it is recognised that the move to risk based management is potentially more complex in terms of data collection and application.

The proposed method for perimeter well risk assessment is based on **hazardous gas flow rate**, which is the calculated flow rate of gas from a borehole measured in litres per hour multiplied by the methane concentration as a percentage. Examples of how this method would be applied are provided in Appendix 5.

This is a risk based threshold that ignores pathway attenuation (conservative approach), but it does not account for background methane sources. In applying a British Standard there can be adjustment of the site's risk assessment process based on site specific features such as culverts and drains.

There are two obvious disadvantages of this method:

- This mechanism does not give flexibility for lower standards for low risk sites and higher standards for higher risk sites. However, flexibility in the CCS scoring and the required response to gas migration would allow this to be taken into account.

- This mechanism does not take into account background sources of methane. The CCS scoring mechanism is outside the scope of this guidance, but it is hoped that the Environment Agency and SEPA will develop CCS scoring guidance taking this into account.

3.2 Data quality

In order to demonstrate compliance and identify any migration at an early stage to enable appropriate assessment and resulting actions for the management of the site, the data must be robust. There are three sources of error in perimeter well monitoring data and each source must be minimised. It is in the interest of both operator and regulator to ensure this occurs.

3.2.1 The monitoring well

Monitoring infrastructure is the first crucial requirement for obtaining quality monitoring data. The monitoring well must be of robust and appropriate construction with the screen typically in the first unsaturated zone encountered in the potential gas migration pathway, although a different construction may be appropriate depending on site specific conditions and risks. There must be plain casing for at least the top metre below ground level and the annulus opposite the solid casing must be sealed with properly hydrated bentonite or bentonite cement/other suitable sealing medium. The well cap must be firmly placed onto the casing with no possibility of air ingress. The gas tap must also seal with the well cap and must be able to be operated without the cap having to be removed or coming off. Failure to seal the well cap will allow air ingress into the well and cause the readings to be diluted and encourage carbon dioxide generation by respiration in the subsurface. It may also be the case that boreholes in which there are significant positive relative pressures could vent to atmosphere if the well cap is poorly sealed.

Part of the solution to this means that the well housing at surface needs to be wide enough to allow a hand to get to the gas tap and put the sample tubing over the connector.

One possible gas monitoring well specification is provided below, along with the CQA requirements pre and post drilling:

1. The gas monitoring borehole installation will normally comprise of a 50mm diameter HDPE pipe extending from the base of the borehole up to approximately 0.8m above the existing ground level.
2. The borehole will be ideally no greater than 150mm in diameter.
3. The pipework may consist of perforated pipe extending from the base to 2m below ground level and the remaining length of pipe will be solid un-perforated pipe extending to approximately 0.8m above ground level.
4. The perforated pipework may incorporate a geowrap in order to prevent any silting of the slotted sections.
5. The pipework will be fitted with an end cap at the base.
6. Following installation of the pipework, covers (end-caps) with ‘snap-on’ sample valves will be fitted to the top. Note: Both the end caps and gas sample valves must be gas tight.
7. A well casing will be installed once drilling works have been completed.

8. The slotted section of casing and 1 metre above the slotted section will be surrounded by a uniformly graded 10 millimetre sized clean non-calcareous gravel.
9. A bentonite seal will be installed above the gravel pack and will extend to surface level to prevent the ingression of surface water run off into the well.
10. The completed boreholes will be clearly labelled. If borehole specific action and emission limits are used it may be good practice to mark these on a tag affixed to the borehole.

Note: the maximum depth for the wells should be the base of the landfill unless groundwater is encountered or the gas permeable strata in the conceptual model starts at the same depth as the base of the landfill - in which case the base of the well should go a few metres below the base of the landfill. If groundwater is encountered, there is no rationale for drilling deeper for a gas monitoring well provided groundwater levels are stable.

On completion of the works the CQA Engineer will prepare a Validation Report for submission to the Environment Agency/SEPA to confirm that the works have been constructed in accordance with this specification. It will form a comprehensive record of the construction works and will include the following details:

- Description of the works carried out;
- Full details of all the quality assurance procedures and their implementation during the course of the works;
- The surveyed ground levels, target depths, and final depths and well completion details for each well;
- As-built plans of the works showing the locations of the installed wells;
- Borehole logs;
- Relevant records kept by the appointed Contractor and any sub contractors;
- Details of any non-conformant areas of work identified by the CQA Engineer and the remedial measures undertaken;
- Details of any non-conformant areas of work identified by the Environment Agency/SEPA and the remedial measures undertaken.

A reasonable CQA report might include:

Section 1 Introduction and Terms of Reference
Section 2 Contract Programme
Section 3 Fieldwork – Drilling, including well references, X, Y, Z co-ordinates at Ground Surface, depths drilled.
Section 4 Fieldwork – Installations, Diameter of casing actually installed, casing types, screen lengths, seals, dip to groundwater.
Section 6 Site Supervision
Section 7 Health and Safety Management

Appendices
Borehole Logs
Photographs
CQA Records
Drawings

As Built Survey Drawing of Borehole Locations (with the correct borehole reference linked to the borehole log).

The most common monitoring infrastructure faults reported by the Environment Agency/SEPA and operators are:

1. The valve or end cap is damaged, seized, open or missing prior to sampling.
2. The well cap is loose or it is a perished rubber bung.
3. If the well cap is threaded, it is not tight and it doesn't have an o-ring seal.
4. If it is a combined gas and water sampling well, Waterra tubing is protruding and there is no well cap.
5. There is no hydrated bentonite around the well.
6. The slotted screen section is visible above ground.
7. The annulus has cracked.
8. The ground has dropped away around edge of the well.
9. Location name missing.
10. Unable to open well head.

Monitoring wells deteriorate with time. It is suggested that operators instigate an ongoing housekeeping programme whereby such faults in monitoring well infrastructure are rectified. This will ensure that borehole condition does not compromise the quality of the monitoring data.

3.2.2 Sampling

The seal between the well and the field meter must be sound to prevent air ingress. This can be checked by turning the pump on with the gas tap closed. The pump should 'labour' and stall if the seal is good. Common sources of air ingress are at connection points with the well, in-line filters and any sampling pods fitted. The next crucial step is to agree and be consistent regarding when the reading is to be taken. If possible the well should be purged and the stabilised reading should be noted. However, many wells show an increasing concentration trend that levels out then decreases. The measurement when the readings were stable should be noted.

A possible monitoring procedure is provided below:

Initial Data Recording
Prior to the start of each sampling event the following information is recorded on the data record sheet:

- Site ID;
- Sample location and ID;
- Date and time;
- Equipment serial numbers;
- Equipment calibration/functionality check results;
- Sample point inspection details – is the sample point secure etc (see above for possible comments);
- Ambient gas conditions and temperature;
- Barometric pressure; and
- Weather.

Purging and data recording

1. If not already present a functioning well cap and valve must be fitted to the well.
2. Check that the gas analyser pump filter is clean, dry, and correctly attached.
3. The sample line of the gas analyser is attached to the gas tap.
4. The internal pump of the gas analyser turned on and the integrity of the gas tap tested (the pump should labour if the gas tap is closed and the sampling line is secure). This is sometimes called a pre leak check and should be recorded as such.

(If gas flow rate is required (for example for working out Hazardous Gas Flow Rate (Section 3.1.7) it must be measured prior to gas concentrations being measured:

5. Record the ambient atmospheric pressure in millibars & set up to record flow.
6. Zero flow and relative pressure. Connect tubing from GA2000 to gas valve & turn gas tap.
7. Record initial (Peak) flow (Instant reading) and steady flow (after max 2 minutes) in Litres per hour L/hr. Record steady relative pressure (millibars). If no gas flow is detected record "No Flow" or "<0.1" (l/hr). Gas flow rate can be negative or positive.)

For gas concentration measurement:

5. With the gas analyser pump turned off, the gas tap is opened and the pressure in the well should be noted.
6. Turn the gas analyser internal pump on and record the time.
7. The gas concentrations and temperature displayed by the gas analyser should be recorded every 30 seconds. Note: In certain circumstances the equipment may quickly evacuate the body of gas in the monitoring point. This would result in an initial peak that quickly reduces to a stable level. On these occasions, both the peak and settled readings must be noted.
8. When the readings have stabilised (usually within 3 – 4 minutes) the internal pump is turned off and the well pressure should be recorded. Note that on some instruments the readings need to be stored before taking a new differential pressure reading
9. The gas tap is closed and a post leak check should be completed and recorded.
10. Ensure that both methane and carbon dioxide return to zero and oxygen to 20.8% (+/- 1%) before switching off the pump or taking further readings.

An example table of observations during is shown below:

Well	Differential pressure before	Carbon dioxide %	Carbon dioxide trend	Methane %	Methane trend	Oxygen %	Differential pressure after	Comment
1	4.0	7.3	Stable	0	Absent	9.4	-12.6	Balance gas >85%
2	0.0	1.4	Stable	0	Absent	19.2	-0.3	Balance gas >82%
3	-0.3	3.7	Peaked then Slight fall	0	Absent	15.6	-81.1	Low permeability. Close to ambient air composition.
4	-0.9	0.8	Slight increase	0	Absent	20.6	-0.9	Similar to ambient air composition.
5	-1.0	0.3	Stable	0.6	Falling	21.0	-1.0	Similar to ambient air composition.
6	-1.0	8.9	Slight increase	2.2	Falling	1.9	-1.0	Balance gas >80.5%
7	-1.1	1.6	Stable	0	Absent	15.7	-5.5	Balance gas > 88%
8	-1.1	4.1	Stable	0	Absent	15.4	-10.4	Balance gas >80.5%
9	0.1	11.2	Stable	0	Absent	0.7	0.1	Balance gas >82.5%

Auto checking of databases can identify when air ingress was occurring e.g., Recording atmospheric gas of 0% methane, 0% carbon dioxide and 21% oxygen. However, if monitoring staff are sufficiently trained they should be able to realise this at the time of sampling and assess the situation (note the 0% methane, 0% carbon dioxide, 21% oxygen may be what the actual gas concentration is in permeable strata with good connection to atmospheric air.

3.2.3 Analysis

Most field analysers have maintenance schedules that are adhered to. The instruments should be calibrated and serviced by the manufacturer in accordance with their recommendations. However instruments drift and cells need checking and sometimes zeroing and re-calibrating. The frequency that this is required depends on instrument usage, but if a reading will trigger consequential actions, then instrument performance is one of the first things to check. The best way to ensure drift is not a factor is to perform calibrations on a daily and monthly basis to monitor the long term performance of the instruments.

The errors in commonly used gas analysers are:

Gas range	Methane	Carbon dioxide	Oxygen
0-5%	±0.5%	±0.5%	±1.0%
5-15%	±1.0%	±1.0%	±1.0%
15%-Full Scale	±3.0%	±3.0%	±1.0%

3.2.4 Failure to review and assess the data QA/QC

Some of this function can be performed by auto checking of databases, but these functions only have value if failures are investigated and resolved.

All of the above are covered in both the revised LFTGN03 and the gas management ICOP.

3.3 Case studies of problem scenarios

A number of case studies are presented in Appendix 1 that highlight the common issues facing operators and regulators.

4. Gas migration

One aim of a perimeter monitoring well adjacent to a landfill site is to enable changes in gas concentration in the sub-soil environment to be determined on each scheduled monitoring event. Where changes in soil gas concentration are observed, subsequent monitoring of the perimeter well will form part of the assessment as to whether the change is associated with any gas emission from the landfill or whether the change is associated with another source of gas. It is noted (as detailed below) that a change in soil gas concentration on its own may not give rise to an unacceptable offsite risk.

Vapour migration in soil is primarily controlled by pressure gradients. Vapour migrates along paths of least resistance, from areas of high to low pressure. The rate of soil vapour migration from a source into surrounding formations usually depends mainly on the gas pressure generated in the source area, and the intrinsic permeability multiplied by the relative permeability, or the 'effective gas-phase permeability' of the subsurface. Diffusive transport is typically much lower than pressure-driven flow in a permeable porous medium.

Under constantly changing pressure gradients (associated with barometric fluctuations and change in gas generation rates), the physical characteristics of the soil surrounding the vapour source control how and where vapour migrates. Controlling characteristics include:

- Length of flow path (distance to point of discharge);
- Formation permeability (equivalent to porous media or fracture controlled);
- Permeability variations (i.e., sand and clays);
- Presence of a near-surface capping layer (i.e., a clay topsoil, iron pans or hardstanding);
- Water table depth;
- Water table fluctuation;
- The presence of barriers to lateral flow (open ditches in continuity with groundwater); and,
- Preferential pathways (i.e., manmade structures such as drains, tunnels).

These considerations apply to the subsurface strata outside the landfill. Before these factors apply, vapour needs to migrate through the liner (clay, geomembrane, composite liner, cut off wall etc), if present. At operational and closed landfills the application of a negative pressure should mitigate against gas migration. The potential for gas migration out of the landfill only exists in pockets of waste that are not under the influence of the gas abstraction system. Whether the influence of the gas management system is sufficient to encompass the entire site is discussed in Section 5.4.

The largest natural factors influencing gas migration from a landfill are barometric pumping and seasonal variation in the ground gas cycle, although mines gas cycles can also be important.

4.1 Alternative gas sources

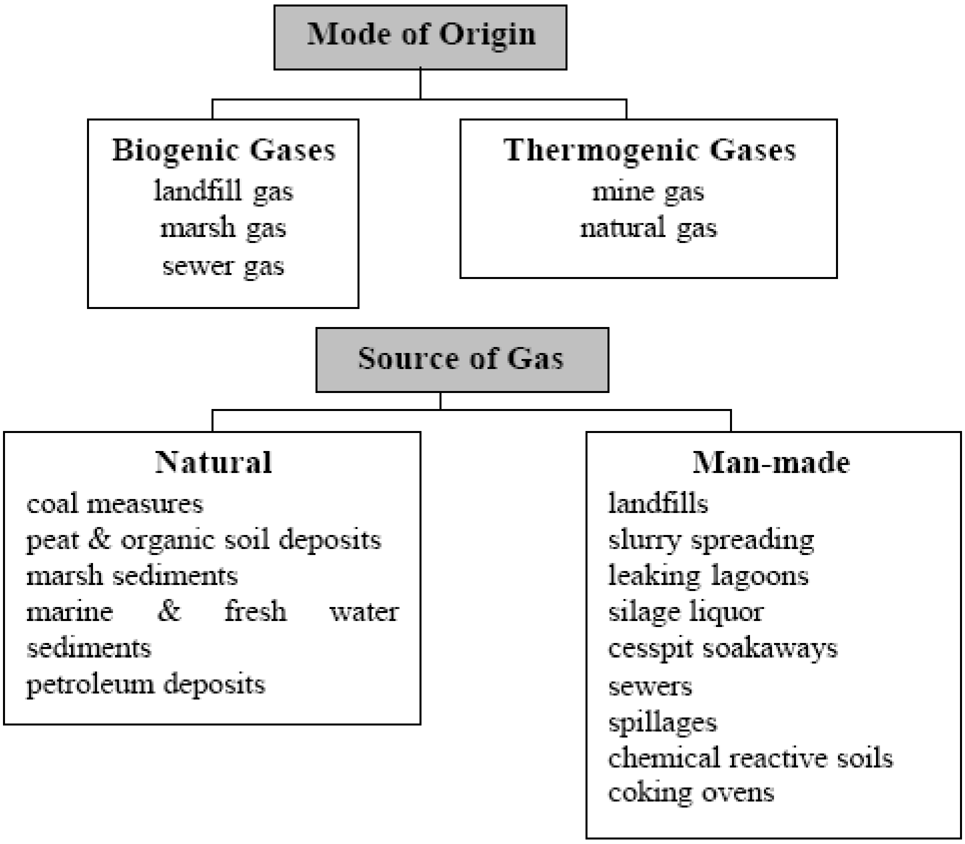
In addition to landfill gas, there are other sources of ground-based methane that may be of biogenic or thermogenic origin which include:

- natural mains gas;
- geologically-derived methane (mine gas);
- marsh gas; and,
- sewer gas.

Other sources of ground-based carbon dioxide that may be of biogenic or thermogenic origin include:

- aerobic respiration in topsoil;
- degassing limestone rich sediments;
- geologically-derived carbon dioxide (mine gas); and,
- oxidised methane from any of the above sources

This is summarised below from the technical guidance document (LFTGN03):



4.2 Case studies of gas migration

Case studies at operating landfills allow a good understanding how gas migration occurs, develops, and responds to mitigation over time. These examples show the scenarios that require compliance management and regulation. Case studies that have been published are presented in Appendix 1.

5. Initial activity associated with suspected gas migration

The first action after a reading is taken that exceeds a action level is to re-take the reading and start to increase scrutiny of conditions in the well by taking other contextual data. Depending on the risk profile of the monitoring well with an action level exceedance, the re-monitoring would be carried out at different timescales. For example, a target response time for re-monitoring on a high risk boundary might be 6 hrs, for a medium risk boundary a 24 hours response time might be appropriate and for a low risk boundary 48 hours might be acceptable. The required re-monitoring data are described in the following sections.

5.1 Minimum required monitoring

Considering that the main cost of gas monitoring is incurred in getting the person to site, then a few minutes extra time at each well collecting the necessary data is money well spent. Important things to record are:

- Changes in atmospheric pressure over two days preceding monitoring (this can be obtained from the site's weather station or the nearest weather station from the Met Office). This will help discern whether barometric pumping might be responsible for the elevated methane or carbon dioxide reading.
- Recent weather conditions. The condition of ground surface – saturated topsoil may prevent gas escaping to atmosphere and cause it to build up and migrate in the subsurface.
- Any activities in the area that may affect readings (e.g., dewatering or excavation).
- Pressure within the well - positive and negative pressures can show that gas has nothing to do with the landfill (and conversely it can obviously demonstrate that it is related to the landfill).
- Flow rate from or into the well - positive and negative flows can show that gas has nothing to do with the landfill (and it can obviously demonstrate that it is related to the landfill).
- Methane. This is the key risk driver.
- Carbon dioxide. This can be a marker for landfill gas migration if the methane is rapidly oxidised outside the landfill. However, it can also be generated in significant concentrations in natural sub-surface strata so care is required when interpreting the results.
- Oxygen. This provides an indication of subsurface conditions and possible respiration/oxidation activity.
- Balance gas. If at a preliminary stage the balance gas is assumed to be nitrogen, nitrogen is inert and provides an indication of external gas ingress or gas removal within the strata. Nitrogen gas concentrations similar to ambient air or enriched (>80% nitrogen) scenarios preclude significant gas migration from the landfill assuming that the borehole is fit for purpose and not in continuity with the atmosphere (see below). This is because not enough gas is migrating to displace the in-situ atmospheric nitrogen. That is, any input into the porespace of landfill gas comprising ~ 60% methane and 40% carbon dioxide would displace and reduce the 80% of nitrogen initially present in the porespace (If methane was escaping from the landfill, being oxidised to carbon dioxide and then the carbon dioxide was being removed by moisture, then a negative pressure would

develop and the methane concentration would increase to fill up to 100% of the porespace). In addition, it is important to note that interpretation of the balance gas should also consider the oxygen concentration. If the reading from the well is similar to the atmosphere (i.e., ~21% oxygen and ~80% nitrogen) then this may indicate that there is a poor seal on the perimeter monitoring well leading to atmospheric dilution of the sample.

- If readings are varying and by what degree. For example does the gas concentration record a peak and then reduce and over what time? Flow can be influenced by the gas reservoir being tapped. The behaviour of methane readings can sometimes be used to determine whether the gas reservoir is small (e.g., the well) or large (e.g., the surrounding strata).
- Any odours from the wells – fresh landfill gas has a particular odour although can be stripped out of the gas during migration.
- Groundwater levels. Changes in groundwater elevation can induce gas flow in the overlying unsaturated zone.
- Temperature within the well compared to ambient conditions. It may be possible to determine gas migration events using the temperature of the gas in the subsurface if the monitoring well is close to the waste. This may be a useful positive indicator of migration but it is not a reliable negative indicator.
- The date and time. All data should be date and time stamped.

Once gas migration is suspected there is an immediate requirement for more data to establish trends, which will in turn allow assessment of whether the gas might be from the landfill or an alternative source. Data are also required to assess the effectiveness of any mitigation measures. It is suggested that daily monitoring of the wells in question is useful. At high risk sites with potential receptors very close to the monitoring well, the frequency of monitoring may need to be higher.

Graphs should be used to identify trends. One common trend that has frequently been observed on sites where there is limited gas generation is for a peak in methane and carbon dioxide readings for the first month or so after a well is installed followed by a gradual reduction to negligible levels. This is generally because of disturbance caused by installation of the boreholes. In more highly gassing sites this effect may not be seen.

5.2 Data quality

One of the most common observations in sampling perimeter wells is that well caps are poorly fitting and the well seal at the sampling point is suspect. A good well seal is critical and representative sampling cannot take place until conditions in the well have reached equilibrium with a good well seal at surface.

Part of a good well seal at surface also involves a low permeability seal in the annulus between the well casing and the outside of the drilled borehole close to surface. The use of bentonite or concrete in the well annulus can usually be established by looking where the well casing enters the ground. A good seal around the annulus is also a pre-requisite for obtaining a representative sample.

All monitoring methods should be included within a sampling report, which should also include a section dedicated to assessing the QA/QC and uncertainties associated with the data within the report. The identified uncertainties should be reduced if cost effectively possible.

5.3 Checking the conceptual model

The risk associated with gas migration varies with:

- gas quality and volume;
- gas permeability of the wastes;
- site engineering works (e.g. control measures such as site liners and caps);
- proximity of buildings and services; and
- the surrounding geology.

If any of the above factors have changed since the permit was issued and the landfill gas risk assessment was undertaken, then the conceptual model of risk may require amendment.

For example, the location and spacing of landfill gas monitoring boreholes is site-specific and dependent upon the likely risks posed by off-site gas migration. The spacing of monitoring points should be based on the conceptual model. Off-site monitoring boreholes have historically been located relatively close to the edge of the waste fill. However, it is recommended that boreholes are sited at least 20 m from the boundary of the waste. Guidance on the spacing of monitoring boreholes is provided in Table 8.1 of LFTGN03, and is not reproduced here. However, it is worth noting that variable borehole spacing on particular areas of a site is compatible with risk based regulation.

5.4 Initial actions from gas management plan

For more information on gas management, attention is drawn to the Industry Code of Practice on Gas Management. The discussion below and in subsequent sections is a summary related specifically to addressing potential gas migration.

Gas management plans should adopt a phased and risk based approach. A draft contingency action plan is included as Appendix 3. The implementation of appropriate action should be considered in conjunction with an assessment of the severity of the event. Actions associated with severe events are discussed in more detail in Section 6, but might include immediate emergency measures to counter extraordinary events e.g. evacuation of buildings. In this section the response to exceedance of a action level are discussed. In addition to the minimum monitoring outlined in Section 5.1, there are initial gas management actions that should be instigated at the same time. One of the first actions that should accompany re-monitoring is an assessment of the on-site gas field management. This is to assess whether gas control conditions have changed and to ensure that all ‘easy’ fixes have been achieved. There needs to be a coherent and phased approach to assessing performance of in-waste collection systems. Assessment should include, but not be limited to:

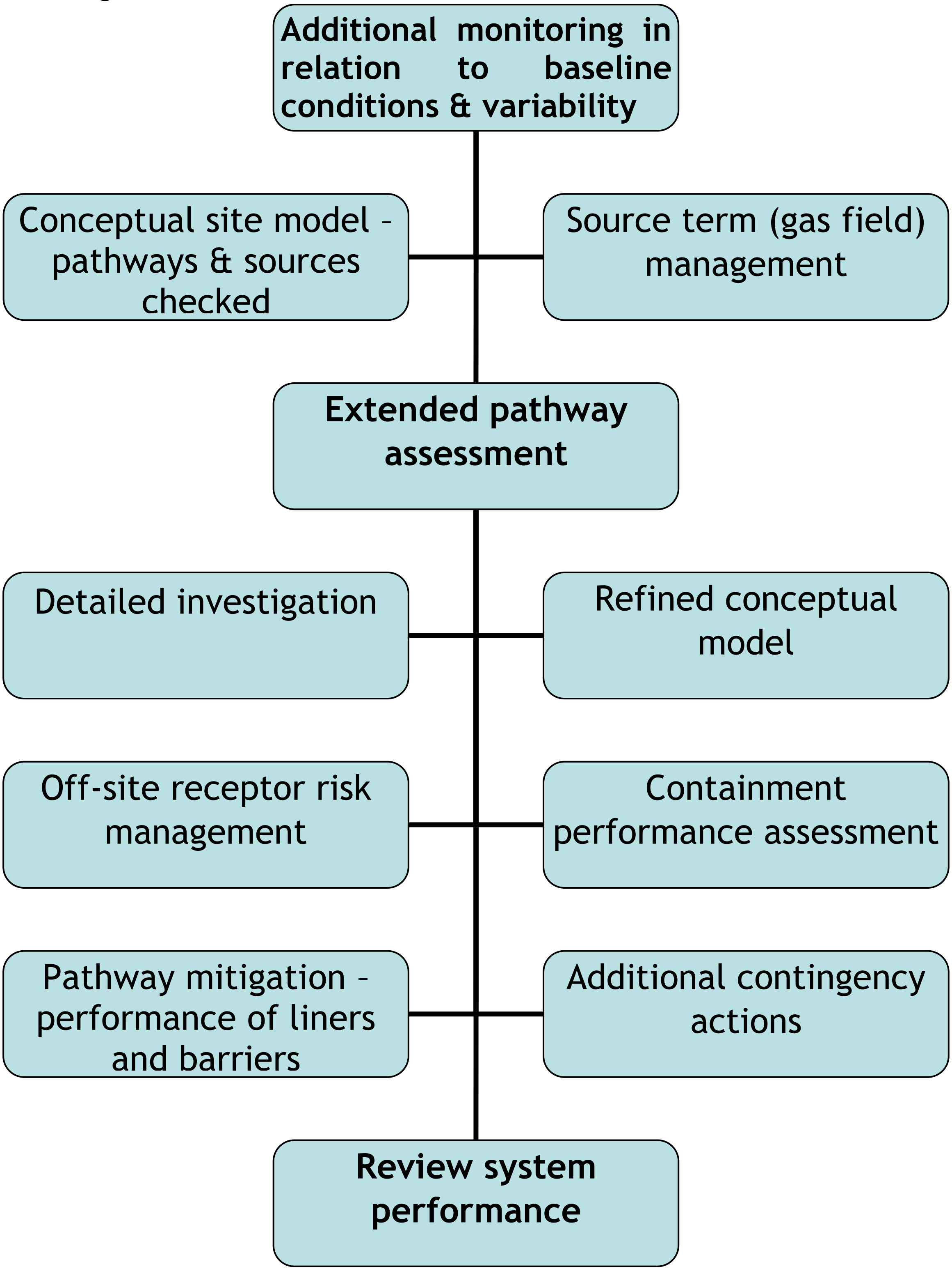
1. Parameters such as total volumes abstracted, overall site vacuum, operation of carrier / header mains, is the gas mix at the Plant richer than normal etc.
2. Assessing the status of gas extraction wells (open, percentage open, closed).
3. Confirming that the condition of all on-site and perimeter wells is satisfactory.

4. Looking at total abstraction volumes in recent months to determine if gas losses are occurring or gas production is increasing rapidly. Both scenarios would necessitate a management change and could have led to gas migration if previously not detected.
5. If the wells appear to be open and well-maintained, but perhaps gas production has increased dramatically for example, a second tier of testing involves checking whether the gas abstraction wells are fit for purpose i.e., there is interference suction on wells. If there is no interference suction, then additional abstraction wells may be required to control the gas field.
6. Build ups of condensate in the gas carrier pipe work.
7. A full performance assessment may be required if the sites operational model has changed. For example, have the extraction wells become compromised at certain depths by the build up of perched leachate

If any of the assessed parameters are not satisfactory, they should be rectified.

6. Preliminary assessment of suspected gas migration

Once additional data are available and the 'easy' fixes to the gas management system have been achieved, an assessment of the suspected gas migration event is required. Section 5 dealt with actions leading up to the extended pathway assessment in the flow diagram below. Before further work is commissioned it is worthwhile noting what simple evidence indicates that gas migration might be occurring.



The existing off-site perimeter gas risk assessment will form the baseline for comparing the new data.

If the gas extraction system parameters in Section 5.4 are not satisfactory, they should be rectified immediately while continuing to monitor the well(s) affected. Once the existing gas extraction system is deemed to operating efficiently, the monitoring well data should be assessed. There are many interpretations possible from data gathered in Section 5, which were collected because the action level was exceeded. The four most likely scenarios are presented below:

Observation	**Action**
Methane concentrations decline	Try to identify new source. If new source is anthropogenic, then manage/mitigate and continue to monitor until concentrations start to decline. Continue additional monitoring until three consecutive concentrations below action level. Return to monthly monitoring.
Methane concentrations staying elevated above action level but below compliance limit	If concentrations stablise, then try to identify new source. If new source is anthropogenic, then manage/mitigate and continue to monitor until concentrations start to decline*. If non-anthropogenic source such as new mines gas pathway then monitor until confident that elevated levels are 'new' background.
Methane concentrations increasing towards compliance limit	Try to identify new source. If new source is anthropogenic, then manage/mitigate and continue to monitor until concentrations start to decline. If non-anthropogenic source then monitor and report. Communicate possible risk to any potential receptors.
Methane concentrations above compliance limit	Communicate risk to receptors and Environment Agency/SEPA. Assume landfill source and undertake risk mitigation procedures. Urgently try to identify new source. If new source is anthropogenic, then urgently manage/mitigate and continue to monitor until concentrations decline. If non-anthropogenic source then monitor and report.

*A declining trend can take months or years to become evident in lower permeability strata.

If potential receptors are close to the landfill and if there is any uncertainty then take the safety first option, which would be to instigate actions in the next box down. Reactions can be more relaxed if there are no proximal receptors.

Outline timescales for re-monitoring and subsequent actions for high, medium, and low risk sites are shown below. Note a valid alternative to assessing the whole site as 'high, medium, or low risk is that each site should develop a risk matrix for every borehole because the detection of methane at one particular borehole might carry a far higher risk than another particular borehole at the same site.

Note that if using the templates below it is up to the operator to justify whether their sites fall into a high, medium, or low risk site using factors such as proximity to receptors and sensitivity of receptors. This justification is only required if the following example templates are to be followed rigourously. Site specific target actions and deadlines can be agreed between the operator and the regulator without the site necessarily being 'categorised'.

Example of High Risk Site/Monitoring location/Borehole Response Actions - Target Timescales/Deadlines etc

High risk site		
Outcome	**Action**	**Deadline**
Additional Monitoring		
Concentration above action level	Re-monitor every day	24 hours
Concentration above action level	Check gas field	48 hours
Concentration still above action level	Verify conceptual model and plan for extended pathway assessment, if required	1 week
Extended pathway assessment		
Concentration above action level	Investigate sources and pathway	1 week fieldwork, 3 weeks report
Concentration above action level	In depth assessment of containment performance	2 week fieldwork, 3 weeks report
Concentration still above action level	Verify conceptual model and review system performance.	4 week report

High risk site		
Outcome	**Action**	**Deadline**
Additional Monitoring		
Concentration above compliance level	Re-monitor	6 hours
Concentration above compliance level	Check gas field	24 hour
Concentration above compliance level	Verify conceptual model and plan for extended pathway assessment, if required	48 hour
Extended pathway assessment		
Concentration above compliance level	Off-site receptor analysis and risk action plan	1 week report
Concentration above compliance level	Investigate sources and pathway	1 week fieldwork, 3 weeks report
Concentration above compliance level	In depth assessment of containment performance	2 week fieldwork, 3 weeks report
Concentration still above compliance level	Verify conceptual model and review system performance.	4 week report
Concentration still above compliance level	Additional contingency actions	4 week report

Example of Medium Risk Site/Monitoring location/Borehole Response Actions - Target Timescales/Deadlines etc

Medium risk site		
Outcome	**Action**	**Deadline**
Additional Monitoring		
Concentration above action level	Re-monitor	48 hours
Concentration above action level	Check gas field	48 hours
Concentration still above action level	Verify conceptual model and plan for extended pathway assessment, if required	1 week
Extended pathway assessment		
Concentration above action level	Investigate sources and pathway	2 week fieldwork, 4 weeks report
Concentration above action level	In depth assessment of containment performance	3 week fieldwork, 4 weeks report
Concentration still above action level	Verify conceptual model and review system performance.	5 week report

Medium risk site		
Outcome	**Action**	**Deadline**
Additional Monitoring		
Concentration above compliance level	Re-monitor	24 hours
Concentration above compliance level	Check gas field	48 hours
Concentration above compliance level	Verify conceptual model and plan for extended pathway assessment, if required	1 week
Extended pathway assessment		
Concentration above compliance level	Off-site receptor analysis and risk action plan	2 week report
Concentration above compliance level	Investigate sources and pathway	2 week fieldwork, 4 weeks report
Concentration above compliance level	In depth assessment of containment performance	3 week fieldwork, 4 weeks report
Concentration still above compliance level	Verify conceptual model and review system performance.	5 week report
Concentration still above compliance level	Additional contingency actions	5 week report

Example of Low Risk Site/Monitoring location/Borehole Response Actions - Target Timescales/Deadlines etc

Low risk site		
Outcome	**Action**	**Deadline**
Additional Monitoring		
Concentration above action level	Re-monitor	7 days
Concentration above action level	Check gas field	7 days
Concentration still above action level	Verify conceptual model and plan for extended pathway assessment, if required	2 weeks
Extended pathway assessment		
Concentration above action level	Investigate sources and pathway	3 week fieldwork, 5 weeks report
Concentration above action level	In depth assessment of containment performance	3 week fieldwork, 4 weeks report
Concentration still above action level	Verify conceptual model and review system performance.	6 week report

Low risk site		
Outcome	**Action**	**Deadline**
Additional Monitoring		
Concentration above compliance level	Re-monitor	48 hours
Concentration above compliance level	Check gas field	1 week
Concentration above compliance level	Verify conceptual model and plan for extended pathway assessment, if required	2 week
Extended pathway assessment		
Concentration above compliance level	Off-site receptor analysis and risk action plan	3 week report
Concentration above compliance level	Investigate sources and pathway	3 week fieldwork, 5 weeks report
Concentration above compliance level	In depth assessment of containment performance	3 week fieldwork, 4 weeks report
Concentration still above compliance level	Verify conceptual model and review system performance.	6 week report
Concentration still above compliance level	Additional contingency actions	6 week report

7. Detailed investigation of gas migration

Current practice on well managed landfill sites is to contain the landfill gas and the first priority is to utilise it as a power source, then to flare it. However, it is still possible that some of the landfill gas will escape from the site with varying environmental consequences.

It is also possible that methane and carbon dioxide (the major components of landfill gas) not originating from that site can be found adjacent to a landfill.

To identify the source of gas found adjacent to a landfill it is important to understand the possible sources that could be generating the gas other than the landfill. It is therefore important to understand the history of the site and the under-lying strata.

- Are there any old mine workings? These do not have to be coal mines, since other types of mine could give rise to the generation of gases, or they may have been backfilled with waste before detailed records were kept.
- Are there any other landfills nearby? Many old quarries have been filled before the requirements to hold a waste management licence. Some of these sites may still be producing gas.
- Has there been any exploration for gas in the area? The foundations of old industrial sites, particularly brickworks, extend many metres underground and may have dried out sub-soils that allow gases trapped deep underground to escape to the surface.
- Has the adjacent land been used for burying dead livestock? This can give rise to gases in nearby boreholes.
- Are there any septic tanks or any sewage pipes that might be leaking?
- Are there any gas mains near by? Natural gas mains lose several percent of the natural gas each year.
- Is there any evidence of leachate migration? Dissolved methane can leave the site in leachate and then desorb into the soils. It is often necessary to use a number of techniques outlined below to investigate the presence of gas outside a landfill. Even when all of these techniques have been used it may not be possible to confirm the source of the gas beyond reasonable doubt.

Once there is a clear understanding of the area, a number of techniques can be used to try and determine the origin of gas found near a landfill site.

When using any of the techniques described below it is very important to understand the limits of detection and the accuracy of each one. A nil detect is not necessarily good evidence of the absence of that substance if the detection limits are too high. Confounding factors such as leaking well seals or caps left off wells can result in many man hours of wasted investigation.

Few if any of these techniques give an unequivocal answer on their own, but a well thought out programme of monitoring and testing can lead to a good understanding of sources and pathways.

7.1 Trace component testing

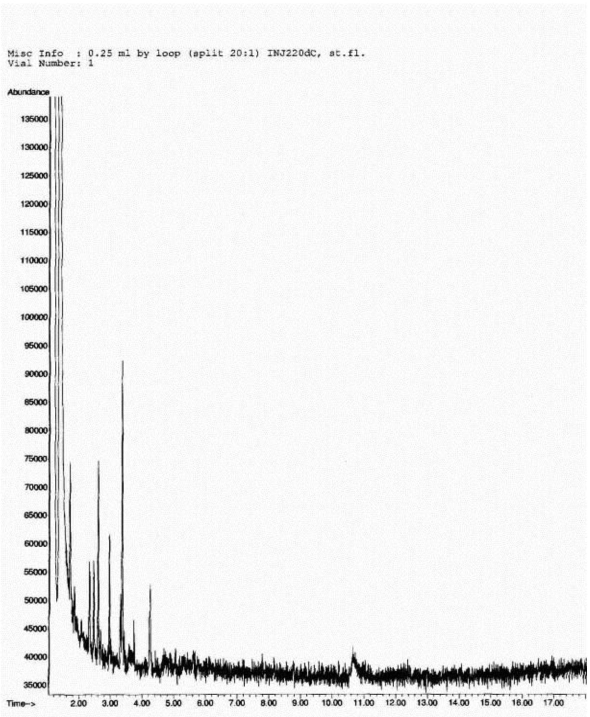
If the methane monitoring demonstrates that gas migration is occurring, then one of the better methods of confirming this is to sample for non-methane organic compounds (NMOCs) or ‘trace’ components. This approach will provide a good indication of the potential for off-site migration, as well as for the presence of substances that may pose human health risks.

Landfill gas is predominantly methane (CH_4) and Carbon Dioxide (CO_2), but it also contains ~1% of up to another 500 trace components. By careful and detailed analysis it is possible to compare the trace component profile of the landfill gas with that of the gas found outside. If there is a significant match (particularly with the chlorinated organics) then the off-site gas is likely to be from the landfill, because many of these components are rarely, if ever, found in the natural environment.

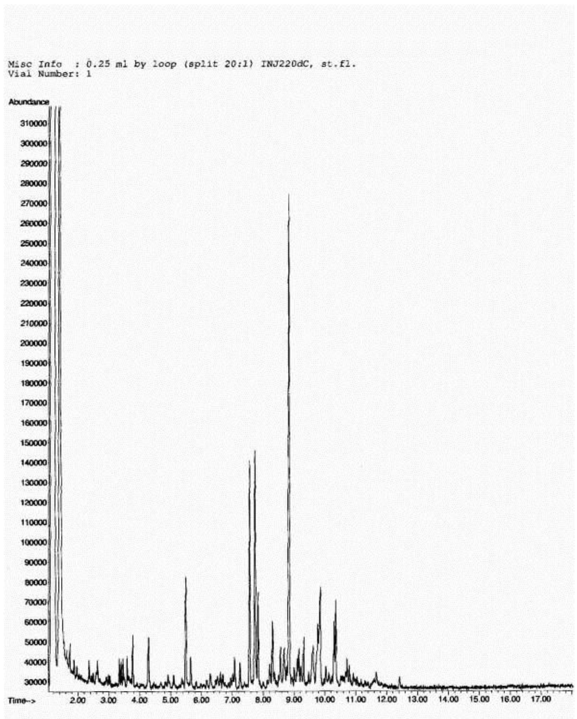
However, the lack of trace compounds in the gas found outside the landfill does not prove that the gas hasn’t come from the landfill because they may be adsorbed during transit to the monitoring point. Because trace component concentrations are relatively low to start with, the concentrations can be further reduced by being adsorbed onto the strata while the gas passes through.

The first stage of carrying out a trace compound assessment is to take samples from a perimeter borehole and the nearest gas well on-site and simply compare the two traces. It is also recommended that any other potential sources are also tested at this time e.g., neighbouring old landfills.

The figures below show two samples taken and analysed using Gas Chromatography – Mass Spectroscopy (GC-MS). Note that the left hand graph has a more sensitive scale.



GCMS Trace from outside a landfill



GCMS Trace of landfill gas

It is clear from the two traces that they are not similar. Note that the left hand Figure has most of its peaks in the first 4 ½ minutes. While the right hand side figure has peaks in this region, it has its major peaks much later on between 6 and 12 minutes.

Some landfill sites have accepted wastes that give rise to an unusual compound being present in the landfill gas. This should become apparent when a sample of the landfill gas is analysed by GC-MS. If this is the case then that compound can be used as a marker for gas migration.

Chlorinated Hydrocarbons commonly found in landfill gas.
Chlorinated Hydrocarbons or organochlorines are man made chemicals not often found naturally. They are and have been widely used by man and as such they are found in general waste. Because some of these chemicals are very volatile they are found in landfill gas and because their presence in the wider environment is limited, if they are found in the boreholes adjacent to the landfill it is likely they have migrated from it.

The top six (accounting for 90% or so of the organochlorine content of landfill gas) are;

Freon 12	cis 1,2-Dichloroethene
Chloroethene (Vinyl chloride)	Trichloroethene
Dichloromethane	Tetrachloroethene

However, if the waste has been in the site for many years these compounds may have already migrated from the site. If they are present in the landfill gas but not present in the borehole this does not prove that the gas present in the borehole does not come from the landfill because these compounds could be adsorbed into the soils en route to the sampling point.

Great care must be taken when sampling for Chlorinated Hydrocarbons and it is easy to contaminate equipment. It is also important to take tubing blanks with the sampling system to check for contamination.

If the sub-surface gas may be entering the breathing zone of a nearby receptor, the values in the H1 IPPC guidance (Environment Agency/SEPA 2002) can be used as screening values for trace gases in a Tier 1 risk assessment.

7.2 Methane: Carbon Dioxide ratio

Landfill gas is typically 60:40 CH_4: CO_2. This gives a ratio of 3:2. Methane is rarely seen in landfill gas above ~65% CH_4.

Looking at the ratio of CH_4 to CO_2 in gases found outside the landfill can be helpful. If the typical 3:2 ratio is seen then it is likely that it is landfill gas. But like the trace components, this ratio can be changed significantly by the strata that the gas is passing through. If the gas passes slowly through moist lime stone rich soils for example, most if not all the CO_2 can be removed leaving CH_4 levels approaching 90-95%. Likewise, if the soil is biologically active and oxygen is present then the CH_4 level could be significantly reduced and the CO_2 equally enhanced.

7.3 Helium

Helium is the end produce of radioactive decay and is often found in natural gas sources but it is rarely found in landfill gas. Finding measurable levels of Helium in gases found off site would indicate that another source gas is solely or partly contributing to the off site gas.

7.4 Pressure gradients

Gas flows will follow a pressure gradient moving from a high pressure to low pressure. Carefully measuring the differential pressure between the off site borehole and the landfill, (this might have to be the nearest gas well without a vacuum applied) can show whether there is a pressure gradient that will allow gas migration. Continuous monitoring of the pressure in an off site borehole while ambient pressure changes can illustrate whether changes in ambient pressure can temporally cause a pressure gradient that allows landfill gas to migrate.

Monitoring the pressure in an off site borehole while increasing the suction to the nearest gas wells on-site can demonstrate a linkage between the landfill and the off site borehole.

Gases can slowly diffuse against a pressure gradient so consideration must be given to the possibility of diffusion if the distances involved are small.

7.5 Borehole Purging/Pumping

Pumping a borehole clear or purging it with Nitrogen and then monitoring the recharge rate can be informative as to the speed and flux of gas migration. Refer to gas management ICOP for more detail.

7.6 Carbon isotopes

The major components of landfill gas (CH4 and CO2) have distinctive isotopic compositions relative to bacterially derived methane and carbon dioxide that forms in soils and other subsurface sediments.

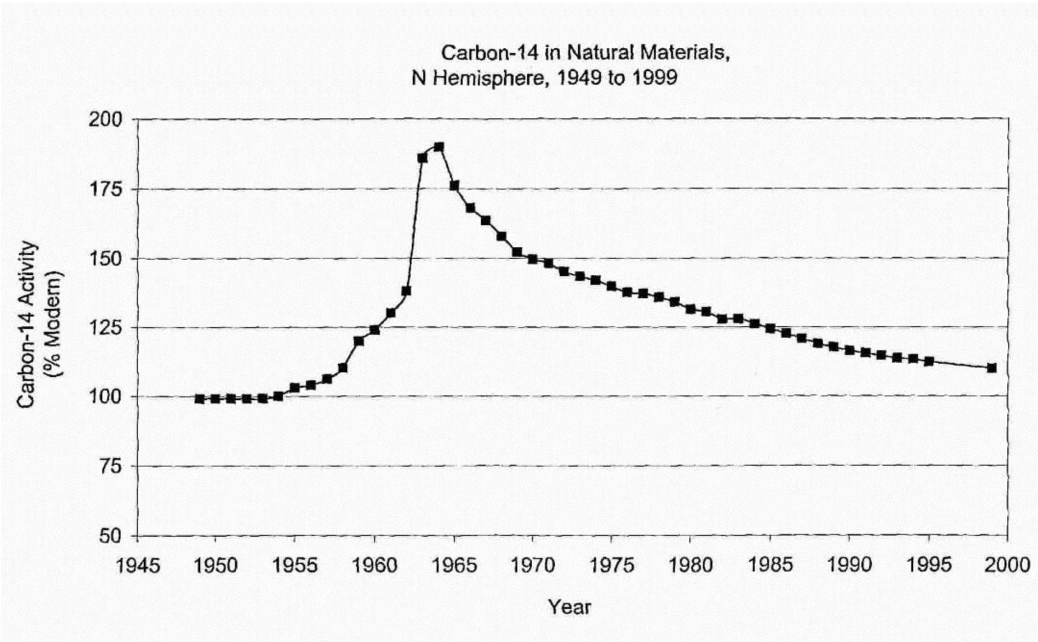
Carbon dating can be used to determine the age of the carbon in the methane proportion of the gas. This can be used to differentiate between ancient and modern gas (mines gases, peat bogs etc, or landfill gas). It is less effective at differentiating between different landfill gases where there are two or more sites close together. When there is a mixture of ancient and modern gas, it is not always possible to apportion that mix.

There are 3 common isotopes of Carbon ^{12}C ^{13}C and ^{14}C. ^{12}C ^{13}C are stable isotopes while ^{14}C undergoes radioactive decay with a half life of approximately 5568 years. Modern dating is carried out relative to 1950 when the atomic weapon testing resulted in putting large amounts of ^{14}C into the environment. This peaked in 1965 when testing slowed to low levels and then finally stopped.

Carbon from the atmosphere constantly exchanges with all living things and the ^{14}C levels in plants and animals reflect that of the levels in the environment. When a living thing dies this exchange stops and therefore by looking at the ^{14}C levels, it is possible to determine when the waste was isolated from the atmosphere and entered the landfill.

The concentrations of the radiogenic isotopes, carbon-14 (^{14}C) and tritium (^{3}H), in landfill leachates and gases are also distinct relative to the surrounding ground water (Liu et al., 1992). ^{14}C values are expressed as a percentage of the 1950 level (100%). If the level is higher than 100% then it is likely the material was alive after 1950 and is modern. If the level is low then it is likely that it is from an older source. The ^{14}C in landfill methane is significantly enriched relative to most other sources of CH_4 and ranges from approximately 120 to 150 pMC (percent modern carbon; Coleman et al., 1990; Liu et al., 1992; and Coleman et al., 1993). The elevated ^{14}C activities for gases and leachates are the direct result of atmospheric testing of nuclear devices that caused the increased radiocarbon content in the atmosphere and thus in the organic materials decomposing in modem landfills.

Carbon 14 as a % of Modern relative to 1950



The simple use of ^{14}C requires the sample to be from a single source. If there are a number of sources then the interpretation of the results becomes more difficult.

$\delta^{13}C$ is the ratio of ^{12}C to ^{13}C the stable isotopes. A reference material of Pee Dee Belemnite is used to give a value of zero (0‰). Biogenic gas is normally expected to have a value ranging from approximately -42 to -61 ‰, with most gases having a value of > -50‰. Organic petroleum products are in the range -20 to -30‰, while other minerals such as carbonates give positive values. 0 to + 20‰.

Landfill methane has a $\delta^{13}C$ of -70‰ ±30% (Coleman et al., 1993; Games and Hayes, 1976 and 1977; Liu et al. 1992). Methane gases with isotopic values within this range are also characteristic for shallow fresh-water environments (Whiticar et al., 1986), but are isotopically distinct from other sources, such as thermogenic methane and drift gas (Coleman et al., 1993). Most terrestrial plants and trees have $\delta^{13}C$ values of around -25‰.

Carbon dioxide produced from landfill gases has a distinct $\delta^{13}C$ and is significantly different than CO_2 in most soils and ground water. Once methanogenesis (acetate fermentation) is established, the $\delta^{13}C$ composition of CO_2 in a landfill becomes, isotopically, very heavy.

^{14}C and $\delta^{13}C$ tests can both be applied to Carbon Dioxide (CO_2) and Methane (CH_4). By comparing the data for the CH_4 fraction with that of the CO_2 fraction it may be possible to determine whether there is a single source of carbon generating the gases or multiple sources.

7.7 Tritium isotope

The third isotope measurement useful in gas migration investigations is the Tritium[1] (^3H) content of the gas. Studies by Coleman et al. (1993) have shown that the hydrogen of landfill CH_4 is enriched in ^3H, ranging from 160 to approximately 2800 TU (Tritium Units). Hackley et al. (1996) found values greater than 10,000 TU. Rank et al. (1992) measured the tritium content of leachate in samples from the Breitenau Experimental Landfill in Austria up to about 2000 TU. The elevated tritium levels observed in municipal landfills are too high to be explained by input from the local contemporaneous precipitation. The most probable source is luminescent paints (Coleman et al., 1993; Hackley et al., 1996) used in watch dials and clocks as well as other luminescent instrument dials (UNSCEAR, 1977). Luminescent paints contain tritiated hydrocarbons that could biodegrade in a landfill and add to the overall tritium concentration. According to the UNSCEAR (1977) report, luminescent timepieces contain approximately 1 to 25 mCi (milli-Curie). Note that 1 mCi is equal to approximately 3.125×10^8 TU.

Tritium levels above 5 Bq/litre H_2O (Approx 40TU - 1TU = 0.12Bq/L). should be considered high.

7.8 Isotope example

The table below shows results from two samples, Well 8952 and GA22 close to each other either side of the waste boundary in a landfill. Well 8952 is a gas well within the landfill site generating landfill gas and well GA22 is a perimeter monitoring well.

Radio Carbon Results (As produced by Radiocarbon dating 01235 833667)

	^{14}C Activity (Percent Modern)		$\delta^{13}C$ (‰)		^3H of the CH_4	
	CH_4	CO_2	CH_4	CO_2	Bq/litre H_2O	(TU)
GA 22	118 ± 1.2		-52.9			
		91± 3.6		-19.8		
					1730 ± 50	14670 ± 420
Well 8952	122 ± 1.3		-63.8			
		120 ± 1.4		+11.6		
					2040 ± 65	17270 ± 550

From the results it is clear that the two ^{14}C dates are similar for both the methane and the carbon dioxide inside the landfill (Well 8952). The ^{14}C of the methane outside the landfill is also similar and this would indicate that the methane is from a

[1] Tritium is a radioactive form of Hydrogen with a half-life of 12.3 years.

single source (the landfill). The $\delta^{13}C$ value for methane and the ^{3}H are consistent with expectations for landfill gas both inside and outside the landfill. The $\delta^{13}C$ and ^{14}C for carbon dioxide shows that carbon dioxide exchange is taking place both within and outside the landfill.

The lower ^{14}C and $\delta^{13}C$ for the carbon dioxide in GA22 shows that another source of gas is present (be it a gaseous, aqueous or solid source). Helium at low levels was also discovered in GA22 confirming the presence of a natural gas source.

It is not possible from the results in the table to determine the proportion of natural gas to that of landfill gas. However an assessment was made to determine the environmental significance of these results, which along with trace gas testing suggested that some migration was taking place. The appropriate control measures were taken.

7.9 Gas migration investigation assessment

Following the investigation, the monitoring results should be reviewed and the following questions considered:

1. Is there confidence that the data are reliable?
2. Has monitoring been carried out under varying conditions likely to influence the gas/vapour regime?
3. Are the results consistent/representative?
4. Can the source of the gas/vapour be identified? It is important to identify the sources but in the case of multiple sources it may not be possible or necessary to accurately attribute the proportional contribution from each source.
5. Can the extent of the source be established? It is important to identify the approximate extent of the source, but it may not be possible or necessary to accurately define this extent).

If the answer to any of the questions above is “No”, additional investigation and/or monitoring may be needed.

The box below summarises how gas migration results should be assessed.

Boxes shown in Red are strong indicators that landfill gas has migrated.
Boxes shown in Green are strong indicators that another source of gas is present.

Process	**Likely Gas Migration**	**Unlikely Gas Migration**	**Comments**
Differential Pressure greater than 30mB	High pressure in the landfill, low pressure in the Borehole	Low pressure in the landfill, High pressure in the Borehole	Diffusion can drive a gas against a pressure gradient.
Presence of Helium	If no Helium is found, this does not mean that the gas has migrated	Helium present in the borehole.	Not all non-landfill gas sources contain Helium.
Presence of Chlorinated hydrocarbons in off-site wells	Chlorinated hydrocarbons are most likely to have come from the landfill		If no chlorinated hydrocarbons are found, they may not be present in the landfill, or may be adsorbed en route.
Carbon isotopes	^{14}C is found to be modern and the gas is biogenic	Low ^{14}C level, not biogenic	Data is rarely conclusive for CO_2 because this does not discriminate mixed sources or influences
Tritium isotope	High Tritium level.	Background Tritium Level	Need enough methane to get adequate tritium sample
Carbon Dioxide ratio.	60:40 CH_4 : CO_2 ratio with high flow	High flow with either CH_4 or CO_2 but not both	If the gas is flowing quickly over a short distance the amount of adsorption or methane oxidation will be limited.

All of the above techniques can be used to investigate the presence of gas adjacent to a landfill. However, the environmental consequences of these events can vary considerably, from inconsequential to an emergency evacuation of neighbouring properties.

It is important that a responsible landfill operator along with the Environment Agency/SEPA quickly assess the risks associated with these events and put into place what ever actions are appropriate.

8. Mitigation Options

In this section it is assumed that all measures to maximise the efficiency of the on-site gas abstraction system have been taken, but gas migration is still ongoing. It is also assumed that plans to prevent gas migration during power outs and engineering works to the collection system are in place. The following text identify potential management strategies associated with specific off-site risks that may be followed by an operator in demonstrating good practice.

8.1 Mitigation strategy determination

The key to an appropriate mitigation strategy is that the response (cost) is proportionate to the risk i.e., a high cost option should only be countenanced if the risk is high. A qualitative cost/risk table is shown below:

Risk	**Risk Ranking**
Gas into building	Very high
Gas into confined space	High
Gas off-site	Medium
Adverse CCS score	High

Cost	**Cost Ranking**
Maximise gas field efficiency	Low
Additional monitoring	Medium
Additional on-site gas abstraction	High
Off-site gas abstraction	Very high

8.2 Off-site receptor analysis and risk management

There are four risk scenarios associated with gas migration including risks to people, infrastructure, and the landfill operator. These are detailed in following sections.

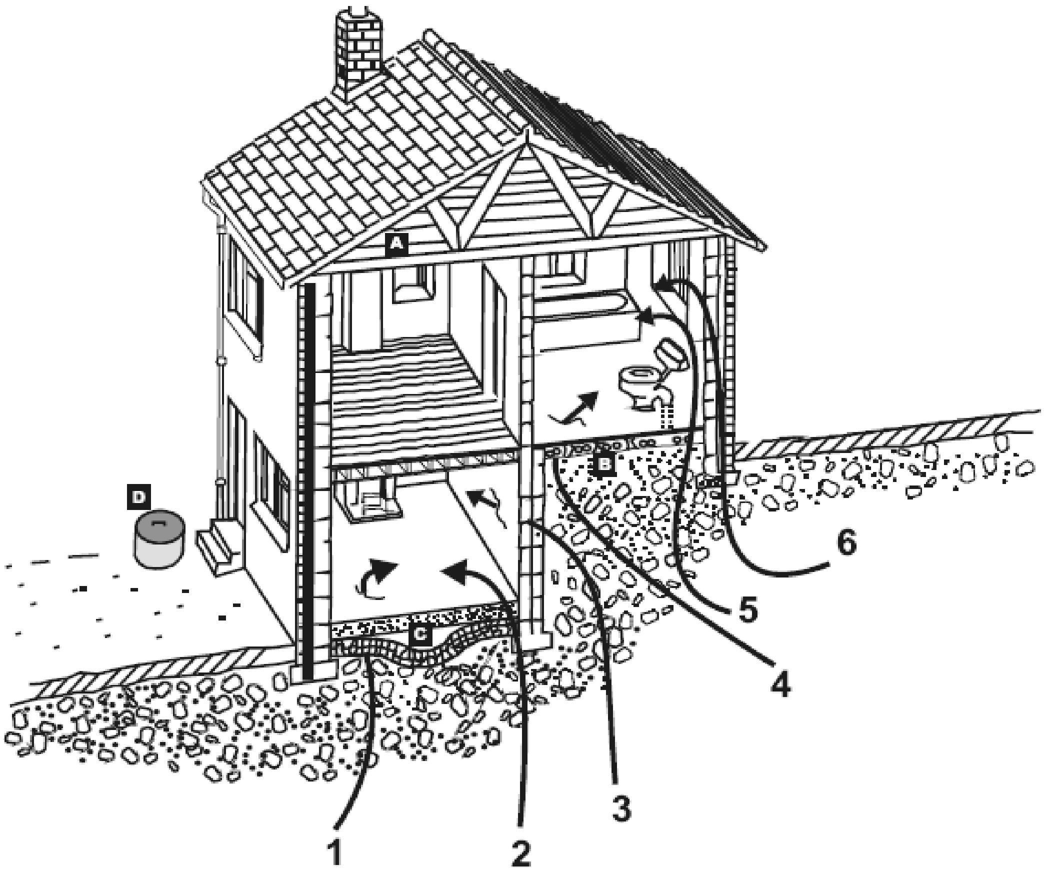
8.2.1 Gas into building

Landfill gas entering buildings is the most important potential risk scenario associated with gas migration. Almost all the work done in this area has focussed on flux of methane from the surrounding soil into the building. Other pathways do exist, with an example being US mines gas dissolving in groundwater and then degassing from the water spray in shower cubicles using local water wells for private water supply.

The CIRIA, 2007 Guidance document has good advice on assessing the risk of gas entering buildings. In it, it notes that soil gases can enter buildings via the following routes:

- cracks or gaps in both solid and suspended floors
- joints formed during the construction process
- fractures in sub surface walls
- entry points around service pipes and ducts
- wall cavities.

With the exception of specific joints, well constructed concrete slabs should not have cracks which can act as a pathway. However, there is always a potential for cracks to occur at any location across the slabs, generally as a result of induced stresses during or soon after construction, or from differential settlement or damage during use. Cracks can also occur at the floor/wall perimeter from the construction method, or as a result of shrinkage or building movement



Key to ingress routes:

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

Locations for gas accumulations:

A Roof voids.
C Within settlement voids.
B Beneath suspended floors.
D Drains and soakaways.

Figure 2.1 *Key gas ingress routes (Card, 1995 after BRE, 1991)*

There are many factors that can influence the migration of soil gases from the ground to the surface. The building structure itself can create pathways which alter the behaviour of soil gases. These may include:

- construction of piled foundations which may create a migration pathway linking a confined reservoir of gas, for example a peat layer and the underside of the building. Similarly some ground improvement methods, for example the forming of vibro stone columns in the ground can also create highly permeable pathways for soil gas.
- surface capping leading to accumulation of soil gas beneath the building and/or off-site migration
- pressure gradients between the ground and building interior may encourage soil gases to migrate towards buildings. Such negative pressure relative to atmospheric can exist in a building as a result of:
    - **The Stack effect**: if the internal temperature in a building is higher than that outside, air is drawn into the building due to pressure differential, either through the external envelope of the building or through entry points in the ground floor construction. In a well-insulated building the air and soil gas is preferentially drawn in through the ground floor. In a heated building, warm air, including soil gas, rises through stack effect which is then dissipated throughout the building.
    - **The Venturi effect**: positive air pressure occurs on the windward side of the building when exposed to wind pressure. On the leeward side, suction occurs. Therefore, if there are openings on the leeward side, the internal pressure is reduced as air is drawn out through openings on the leeward side. There develops a pressure gradient between the inside and the outside. Soil gases may then be drawn into the building through entry points in the ground floor.

The factors which influence the movement and mixing of soil gases in a confined space are:

- location of source relative to building
- existence of natural or artificial pathways
- gas density
- gas composition
- attenuation
- rate of ventilation with fresh air
- volume of confined space.

The purpose of measuring gas flow rates is to predict surface emissions and from these deduce the potential for gas ingress into buildings. The flow rate (measured as litres per hour or metres per second) can refer to both the volume of gas being emitted from a monitoring well per unit time and the movement of gas through permeable strata. A measured borehole flow rate is used to calculate the surface emission rate.

The surface emission rate beneath and into a building is then subject to dilution in vented underfloor void (if present) and air exchange rate with the building. These factors are discussed in Appendices 5 - 7 of the CIRIA Guidance.
In connection with pathways, consideration should be given to:

1. Is the ground beneath the site (made ground, drift and solid deposits) likely to have significantly high permeability promoting gas flow?

2. At what depth is the gas source present? Is it trapped in a layer with impermeable material above (as can occur with peat)?
3. Does contamination appear to have migrated away from the potential source?
4. Direction of migration of contamination: is this towards a receptor?
5. Is the contamination migrating along preferential pathways such as services or ducts beneath the site?
6. Are concentrations of contaminants undergoing attenuation along the migration pathway?
7. Are there any potential barriers to migration of contamination between the source and the receptor?

Relating to the potential receptor(s):

(a) Review site plans or development plans to see if there are defined areas on the site where boreholes have similar data (for example all boreholes in the west of the site have methane concentrations over 5%).
(b) Review surrounding land use to confirm other potential receptors.
(c) Consider characteristics and behaviour of receptors (are there small rooms or areas with ignition sources that are poorly ventilated, how much time do occupants spend in different areas, do foundations create pathways?).
(d) Confirm which receptors are of priority for the risk assessment.

8.2.2 Gas into confined space

As noted in Section 2.4.1., the majority of the incidents associated with landfill gas migration involve the accumulation of gas in confined spaces, such as within buildings, culverts, and manholes.

Construction and utility workers are particularly at risk during building and maintenance works next to a landfill where elevated landfill gas has accumulated. Particular areas of potential soil gas build up are:

- piped drains and sewers
- soakaways/cess pits

Monitoring confined spaces before any work commences should be part of the health and safety risk assessment associated with the method statements.

8.2.3 Gas in off-site strata

In the absence of proximal potential receptors, the presence of methane in off-site strata is not of concern from a residential point of view. However, there may be health and safety considerations for off-site workers if underground void spaces exist. There is also a corporate risk associated with possible loss of gas control and subsequent CCS scoring.

8.3 Containment performance assessment

Once an analysis of the potential receptors has been done and the results of the investigation have been assessed, the performance of the containment system can be put into context.

8.3.1 Enhancing on-site gas management

Balancing a landfill gas extraction system is a complex procedure that tries to reach a balance between applying sufficient suction to each well to collect the gas whist not drawing air into either the extraction system and or the waste. The balance point for each well can change due to a number of different factors. These factors are discussed in more detail in the gas management ICOP.

If the performance of the on-site gas management system is not believed to be adequate, then it will need to be updated until the on-site gas is under control. If on-site gas management is as good as it can be and there is still a loss of containment, then an off-site gas management plan will be required.

8.3.2 Off-site gas management

Two methods are typically employed to control landfill gas migration; passive and active systems. Passive systems depend on the pressure differential between the landfill gas and the gas collection wells and/or the atmosphere, for the gas to exit the landfill or structure. Active systems require mechanical blowers or compressors to create a negative pressure, drawing the landfill gas into the collection systems. Again, the choice and location is site-specific, and an experienced professional should be responsible for the decision.

8.3.2.1 Passive systems

Passive systems rely on highly permeable material, such as gravel, placed in the path of gas flow. **Passive systems are not normally used to manage gas and are now typically viewed as a poor solution.**

To control landfill gas migration, vents, barrier walls or a combination of trenches and walls are typically installed. The following is a description of various passive systems:

1. Vents can be installed on or around the landfill. There are two types: well vents and trench vents. Well Vents consist of 100 – 150mm diameter plastic piping, usually PVC, with an interval(s) of perforation in the lower part of the pipe. The pipes are placed into drilled boreholes and extend several feet above the landfill surface. The depth of these vents is dependent on the site characteristics. Trench vents are typically installed in areas where the likely migration pathway is relatively close to the surface. A trench is excavated to a confining layer and backfilled with a porous medium, such as gravel. The gas will follow the path of least resistance and migrate up to the atmosphere after entering the permeable zone.
2. Barrier systems are constructed outside the landfill area and extend to a low permeability bottom seal or natural barrier such as geomembranes or natural clays. The low permeability soils should be properly graded and maintained at a nearly saturated condition, to impede the convective and diffusive flow of

methane gas. Dry soils are ineffective, as they include voids through which the gas can migrate.

8.3.2.2 Active systems

In active systems, well or trench vents are equipped with an exhauster to extract gas and form a negative pressure gradient, or air is injected to form a positive pressure gradient. Air injection into natural soils is sometimes employed in areas adjacent to landfills and can also be used to dilute gas concentrations to non-hazardous levels.

Active systems installed in structures or foundations also use sub-slab ventilation techniques with vents and/or barriers. Again, 50 – 150mm PVC piping in gravel bedding is installed just below the foundation. The vents are connected to blower(s) and a vacuum is applied to extract sub-slab gases and ventilate them through a riser above the roof structure.

8.4 Review system performance

After the gas management system has been optimised, ongoing monitoring should demonstrate that gas containment is now working and gas migration has either ceased or is under control. There will be an iterative loop, such that if gas containment is not achieved, further improvements and monitoring will be required until containment is achieved.

9. Verification

To verify that gas migration has ceased, robust monitoring data are required that cover a range of meteorological conditions.

9.1 Length of time required to ensure gas migration has ceased

In permeable strata, gas migration can stop and be reversed within days or weeks. In contrast, in low permeability strata gas migration may have been ongoing for years before the gas migrates to the perimeter wells. In this situation, even if gas migration is halted immediately, it may take months or years for the trapped methane to dissipate and be removed.

It is generally believed that declining trends are more important than setting verification concentrations. It is suggested that a declining concentration of methane observed over a period of three months should be sufficient to determine that gas migration has ceased.

Stable concentrations following an increasing trend suggest that the gas is back under control and the risk to potential receptors is not increasing (assuming that methane concentrations do not reduce into the explosive range).

9.2 Parameters to monitor and reporting requirements

Until there is a 2 month declining or stabilised trend or it has been proven that the gas is not anthropogenic, then an increased monitoring requirement remains. Once a 3-month declining or stabilised trend, or it has been shown that the gas is not from the landfill then it is possible to return to monthly monitoring. Ongoing monitoring should include:

- Changes in atmospheric pressure over two days preceding monitoring (this can be obtained for the nearest weather station (ideally the ons-ite weather station) with confirmation from the Met Office web page).
- Recent weather conditions and the condition of ground surface.
- Any activities in area that may affect readings (e.g., dewatering or excavation).
- Pressure within the well.
- Flow rate from or into the well.
- Methane, Carbon dioxide, Oxygen, Balance gas.
- If readings are varying and by what degree.
- Any odours from the wells.
- Groundwater levels.
- Temperature within well compared to ambient conditions.
- The date and time.

Reduced monitoring on return from a gas migration event should include:

- Pressure within the well.
- Flow rate from or into the well.
- Methane, Carbon dioxide, Oxygen, Balance gas.
- The date and time.

10. Conclusions

In completing this ICOP the industry has attempted to set out best practice for perimeter well monitoring, analysis, and subsequent actions/management. Based on this work and in summarising potentially complex issues and 20 years of experience the conclusions are:

1. Carbon dioxide is a poor choice of gas to regulate emissions from landfills because there are alternative sources in the sub-surface. Because emission based regulation of a gas generated naturally in the environment at concentrations 0 – 20% is not logical, carbon dioxide should not be used for regulating the sub-surface strata outside a landfill unless there is a site specific high risk receptor nearby, such as an underground confined space. Where a high risk receptor is identified then any compliance limit should be proposed by the operator and agreed by the Environment Agency/SEPA on a risk basis. An alternative to regulating on compliance limits is to regulate on the reaction to exceeding a carbon dioxide action level.
2. Carbon dioxide data should continue to be collected and assessed against an action level because it informs the conceptual model and processes such as methane oxidation.
3. Methane is the obvious gas to monitor when trying to determine whether off-site gas migration is occurring from a landfill, because it makes up the largest proportion of the source gas and is subject to less interference than carbon dioxide.
4. In setting action levels that indicate possible gas migration events from a landfill, background methane concentrations need to be considered. Assuming there is no evidence of gas migration, it is suggested that only the previous two years data are used to ensure the background concentrations are up-to-date. If the operator has high quality pre-tipping data, this should be used unless it can be shown that other changes have occurred in the locality to affect soil gas concentrations. If gas migration from another source is identified, then the off-site gas contribution should be included in the regulated landfill site background.
5. The methane and carbon dioxide background concentrations should be set on a well by well (or zonal) basis rather than a site wide basis. After removing outliers, the Tmax statistical value should be set as the background concentration.
6. As an action level in stable conditions, a Tmax methane plus 0.5% concentration is proposed. Other statistical methods may be appropriate. As an action level, a carbon dioxide concentration 1% above the Tmax carbon dioxide concentration is proposed for carbon dioxide concentrations in the range 0 – 5% (higher carbon dioxide factors are suggested for higher concentration ranges – see below). For unstable conditions (variation in concentrations > 8%) the Tmax percentile methane or carbon dioxide concentrations may be used. These are not risk based, but should indicate whether the increase is the first indication of gas migration.
7. Methane or carbon dioxide concentrations above the action level concentration should instigate additional monitoring of the well(s) in question and an increased scrutiny of the data quality.

8. The exceedance of an action level should also lead to an assessment of the gas field operational efficiency.
9. Compliance limits may not be rational for scenarios where background methane concentrations are > 10%, but this should be determined on a site by site basis.
10. As a compliance limit, a methane concentration 1% above the Tmax methane concentration is proposed.
11. The previous compliance limits are based on an old British Standard determining risks to buildings (20% of Lower Explosive Limit for methane and 20% of Occupational Exposure Standard for carbon dioxide). It is logical that up-to-date perimeter methane risk assessment should be based on the up-to-date British Standard determining risks to buildings.
12. Hazardous gas flow rates (the calculated flow rate of gas from a borehole measured in litres per hour multiplied by the methane concentration as a percentage) are proposed for risk based assessment.
13. The hazardous gas flow rate threshold is not protective of confined spaces.
14. Exceedance of a compliance limits will instigate considerable effort to determine the source of the gas and an assessment of potential mitigation options. The timescales for reporting these efforts have been proposed and take into account the conceptual model and likely risk associated with the site.
15. The validation requirements for showing that gas migration has ceased have been loosely defined, recognising that the sub-surface can take many years to return to equilibrium.

Summary table for proposed assessment criteria

Stable conditions

Background concentration	**Carbon dioxide action level**	**Carbon dioxide compliance level**	**Methane action level**	**Methane compliance level**
Tmax	Tmax +1% (Tmax carbon dioxide concentrations in range 0 - 5%)	None	Tmax +0.5%	Tmax +1.0 %
Tmax	Tmax +2% (Tmax carbon dioxide concentrations in range 5 – 10%)	None	Tmax +0.5%	Tmax +1.0 %
Tmax	Tmax +3% (Tmax carbon dioxide concentrations in range 10 – 20%)	None	Tmax +0.5%	Tmax +1.0 %
Tmax	Tmax +4% (Tmax carbon dioxide concentrations 20 - 25%)	None	Tmax +0.5%	Tmax +1.0 %
Tmax	None (Tmax carbon dioxide concentrations >25%)	None	Tmax +0.5%	Tmax +1.0%

Unstable conditions (variation > 8%)

Background concentration	**Carbon dioxide action level**	**Carbon dioxide compliance level**	**Methane action level**	**Methane compliance level**
Tmax	Tmax	None	Tmax	Tmax +1%

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Appendix 1 Case studies of gas migration

Case studies of problem scenarios
A number of case studies are presented in Appendix 1 that highlight the common issues facing operators and regulators. For these case studies below it is worth noting that the work to date has tried to fit in with the existing concept of Action and Compliance limits for both Methane and Carbon Dioxide.

HSE Recorded Incidents 1970 - 1995
Although the standard of landfill design and operation has undergone a step change improvement in the last 6 or 7 years, much can be learned from historic incidents. In particular, the majority of the incidents associated with landfill gas migration involve the accumulation of gas in confined spaces, such as within buildings, culverts, and manholes. In most cases the gas did not ignite or reach a flammable concentration but the levels were sufficient to cause concern and in some cases the site was evacuated as a precaution (HSE, 2003). In the 25 years between 1970 and 1995, there were 60 incidents involving gas migration, with 5 from naturally occurring methane. A few selected incidents that relate to gas migration from a landfill are listed below:

- Crowborough, East Sussex, gas was detected below an industrial estate adjacent to a landfill site. Venting and monitoring was required.
- 1992 Inverness, Scotland, gas was detected below an industrial estate adjacent to a landfill site. Monitoring was required.
- 1992 Airdrie, Scotland, gas was detected in buildings adjacent to a landfill site requiring continuous monitoring and ventilation.
- 1990 Barnsley, South Yorkshire, landfill gas was detected in a factory adjacent to a landfill site.
- 1990 Thurmaston, Leicestershire, landfill gas entered houses built on a former landfill site. Venting and monitoring was required.
- 1988 Appleby Bridge, Lancashire, partial blockage of a gas venting trench thought to have allowed gas to migrate into an office building some 50m away. Resulted in explosion causing structural damage.
- Audenshaw, Manchester, landfill gas migration from former clay pit used as a landfill site. Gas alarms fitted to four properties after gas detected during routine inspection. Vent trench also installed (House of Commons debate, 1 Nov, 2005).

Incidents 1996 - present
There have been no similar, more recent studies into incidents on gas migration, but there are numerous instances of CCS scores being levied. Landfill gas migration has occurred and does occur. The key driver for this document is how landfills should be better managed and regulated.

Norfolk
There are elevated concentrations of carbon dioxide and/or methane in perimeter wells along one boundary of this landfill. The gas may be from the landfill or more likely is from an immediately adjacent dilute and disperse restored landfill. Perimeter wells on the sides of the landfill away from the dilute and disperse site

have little or no methane and carbon dioxide. The Environment Agency has suggested a site wide 5% carbon dioxide trigger threshold. Carbon dioxide in the wells next to the dilute and disperse landfill have consistently averaged over 20% since monitoring began and the average methane concentrations are over 30%. For landfill gas from the permitted site to migrate to the nearest receptor it would need to pass through the old landfill which is currently under abstraction. Further discussions with the Environment Agency on gas provenance in these wells have been suspended until more technical data are available.

West Sussex

This site has an old, closed landfill on the north-west boundary and has cement kiln deposits on the southern boundary. The presence of methane is minimal in the sub-surface environment through naturally occurring processes. However, the carbon dioxide concentrations within in-situ deposits have been observed to be between 0 and 10% v/v.

Statistical analysis and risk based review have been used to derive management/control and regulatory/compliance limits at the site based solely on gas concentrations in each perimeter borehole. Methane and carbon dioxide control and compliance limits have been proposed as follows having due regard to both the range of data (maximum to minimum) within the data set and the degree of natural variation of the data, both of which will affect the level of precision appropriate for a subsequent management level:

- A minimum control concentration of 0.7% methane;
- A minimum control concentration of 1.5% carbon dioxide;
- Methane control levels have been proposed at 0.7% where practical and appropriate. Where data sets are highly variable and influenced by external sources or where wells have been replaced, methane control levels have been proposed at the 95%ile using the past 36 months of monitoring data;
- Carbon dioxide control levels have been proposed (using where applicable the 95%ile of the past 36 months of monitoring data) having due regard for both the range of data and the environmental setting of the borehole;
- Where pre-critical gas production (CGP - the point at which methanogenic conditions are achieved) data are available, the background concentration in any borehole is proposed at the maximum level observed in that data set excluding outliers (as identified above);
- Where practical and appropriate, compliance limits have been proposed. It is noted that where the data sets are highly variable and influenced by external sources no compliance limits have been proposed. Where wells have been removed or replaced no compliance limits have been proposed;
- All methane compliance limits are proposed at a concentration of 1.0%;
- Following the guidance of LFTGN 3, all carbon dioxide compliance limits are proposed at an arbitrary 1.5% above the background concentration where pre gas production data exist. Where pre CGP data is not available, compliance limits have been proposed having due regard for both the range of data and the environmental setting of the borehole. It is noted that such an approach is broadly consistent with Table 8.2 of LFTGN 3, but does not take into account the risks associated with soil gas concentrations, nor the seasonal variability of data

sets in increasing soil gas concentrations by a nominal 1.5% above background levels. This approach suggests that compliance limits should be between 4 and 12%.

In summary, the proposed monitoring programme ignores the methane concentrations on the north western boundary. Also, the presence of methane within any monitoring well may not – in isolation – be indicative of any unexpected emission of landfill gas from the site. It is proposed that the range of carbon dioxide concentrations is reflected in the margin between the control level and the trigger level. These proposals have not yet been agreed, with Environment Agency staff who have yet to assess the data retained at the site against the risks posed.

The situation above has been replicated at a landfill in Hampshire, where the carbon dioxide trigger level has been set at 9% for all wells by the area technical officer, regardless of the well by well variation in concentrations between 6 and 13%.

Suffolk

For perimeter monitoring two different areas are proposed next to a) an old landfill next to the new landfill; and b) the new landfill only. The difference reflects the fundamental presence (or absence) of perimeter engineering.

With regard to soil gas concentrations for methane at the site, both the conceptual model and perimeter data sets suggest that the baseline concentration of methane in the environment is 0 %v/v, except for the area next to the old landfill.

Review of the statistical analysis indicates that during periods when methane is absent in the soil gas environment, that carbon dioxide concentrations are observed to range between:

1.6	and	18.5% v/v	at the 95th percentile concentrations; and
1.7	and	27.3% v/v	at the range of maximum concentrations.

Based on both the qualitative and quantitative analyses, the following assessment / management levels have been proposed with regard to the future management of soil gas concentrations at the site:

Methane. All perimeter wells:

- Control Level / Primary Action Level 0.7% v/v
- Trigger Level / Secondary Action Level 1.0% v/v

Carbon Dioxide. Dependent on location specific background

- Control Level / Primary Action Level 3 – 15 % v/v.
- Trigger Level / Secondary Action Level 10 – 15 % v/v.
- Wells next to old dilute and disperse landfill excluded from Trigger Level.

These proposals have not yet been agreed with Environment Agency staff.

Published case studies

Foxhall County Council Site (Ward, 1996)

This was a dilute and disperse landfill that allowed a gas plume to develop beneath an agricultural field and be studied. While this would not be allowed to happen at a modern, regulated, site it provides a good model of what can happen if gas migration is allowed to occur.

A gas plume emanating from the Foxhall Landfill in Suffolk was defined within unsaturated sands on the basis of elevated concentrations of methane, carbon dioxide, and volatile organic compounds (VOCs). The plume was relatively narrow, extended more than 100 m from the landfill boundary, and lay mainly between 2 mbgl (below ground level) and the water table at 9.5 mbgl. With increasing distance along the axis of the plume, the ratio of methane to carbon dioxide gradually decreased, while nitrogen increased. Oxygen appeared beyond 80 m from the landfill boundary. Stable carbon and hydrogen isotope ratios in methane became heavier with distance, while carbon dioxide became isotopically lighter with respect to stable carbon. This provided strong evidence for microbially mediated methane oxidation. Zones of black reduced sediment near the landfill suggested that ferric iron [Fe(III)] may have been acting as an electron acceptor for oxidation. No thermal anomaly was observed, thus suggesting that the rate of oxidation/flux of methane was low.

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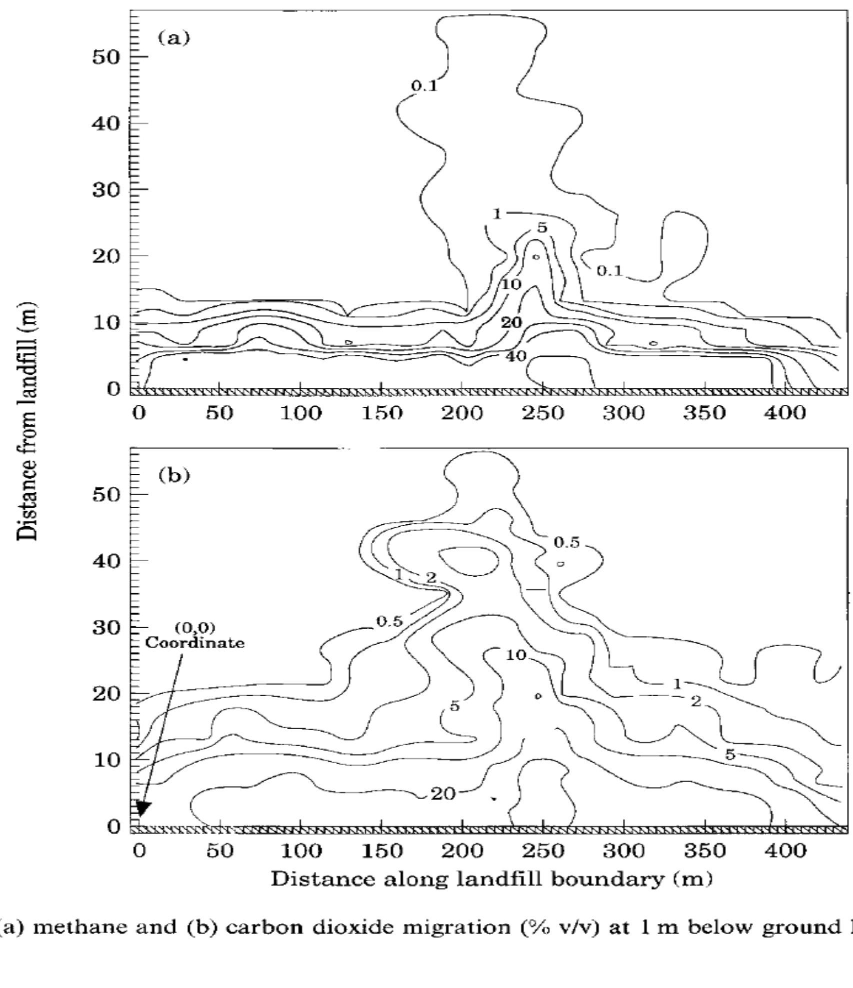


Fig. 4. Plan of (a) methane and (b) carbon dioxide migration (% v/v) at 1 m below ground level at Foxhall.

Volatile organic compounds in the plume were trapped using a combination of sorbants (Tenax GR, Haysep Q and Carbosieve S-III), and desorbed thermally into a GC/MS for semi-quantitative analysis. The 79 VOCs identified were similar to those found in other landfills, and their concentrations, both in the landfill and in the soil gas, were broadly related to their volatility. Only two compounds (vinyl chloride and dichlorofluoromethane) approached or exceeded the long-term exposure limit (LTEL, as defined by the U.K. Health and Safety Executive, 1992) outside the landfill. Halogenated compounds (dichlorodifluoromethane, dichlorofluoromethane and trichlorofluoromethane) were found to be most mobile but their concentration profiles suggest that they may have been flushed out of the landfill during its early stages. It was suggested that the association of volatile halogenated compounds with methane is good evidence that they are derived from a landfill.

Changes in landfill gas during subsurface migration 253

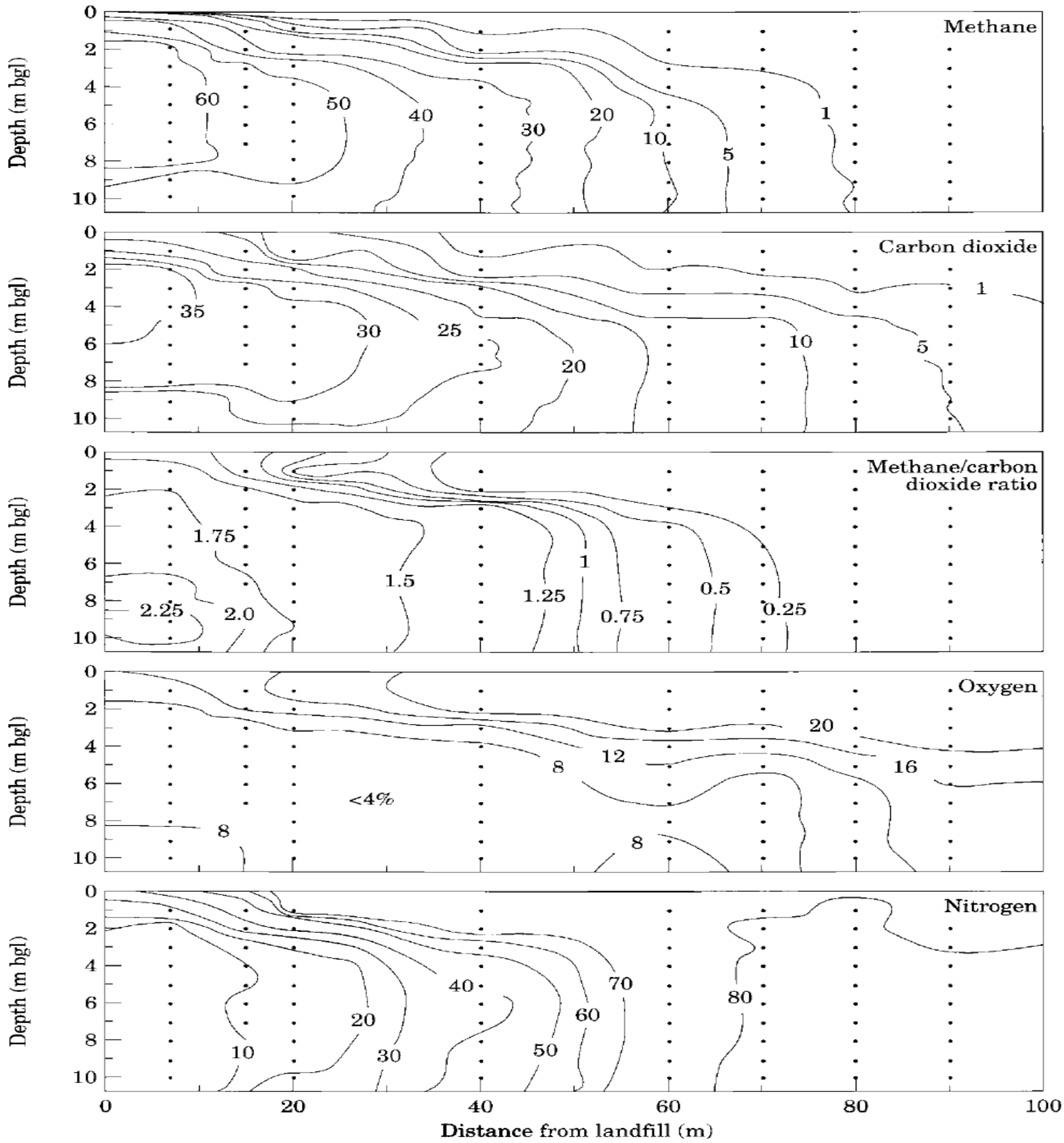


Fig. 7. Vertical profiles of gas concentration along the axis of the plume (in % by volume). bgl, below ground level.

The above graph suggests that nitrogen might be a valuable measure to indicate migration because it is the same in both the atmosphere and sub-surface away from the zone of migration.

Foxhall (Williams, 1999)
Continuing from previous work, in this paper a one-dimensional advection-diffusion model was used to describe the combined concentration of methane and carbon dioxide in the plume. Diffusion alone underestimated the concentration profile, but a good fit to the data was achieved with an advective flux of 4.5 $m.yr^{-1}$, indicating that advection due to a pressure gradient from the landfill as well as diffusion should be considered in gas migration modelling.

The kinetics of methane oxidation was studied by parameter-fitting a reaction rate into the advection-diffusion equation with first-order decay. A decay constant of -0.063 yr^{-1} (half-life 11 yr) produced a poor fit to the methane profile, suggesting that oxidation may not be constant throughout the plume. However, the stable isotope data allowed two rates of oxidation to be inferred:

1. A slow rate of oxidation with a half-life of the order of 4.3 to 7.6 yr was inferred in the centre of the plume where oxygen was absent.
2. A much faster rate with a half-life no longer than 0.76 to 1.21 yr occurred beyond 60 m of the landfill and around the top fringe of the plume where oxygen was present.

These rates were considered to reflect the difference between aerobic and anaerobic oxidation, the latter using iron (III) in the sediment as an electron acceptor.

The shape of the plume is asymmetrical, indicating a geological control on gas migration. In a two-dimensional model a poor fit to the observed data was obtained when the sand was assumed to be homogeneous and where the gas entered from a restricted part of the landfill boundary. However, a better model was produced by varying the diffusion coefficient in the sands over the range 5×10^{-7} to 2×10^{-6} $m^2.s^{-1}$ without the need to restrict the zone of gas release along the landfill boundary. Such a range in transport properties could be accounted for by normal variability in the porosity, tortuosity and water content of the sand.

The long-term dissipation of the plume assuming only diffusion was predicted to take up to 30 yr for the gas concentration to reduce to 10% of its initial value. However, the plume disappeared within a year after pumping from gas wells in the landfill, indicating that advection under an imposed pressure gradient was a major control on remediation.

This study shows that models can be used to explain landfill gas migration and to infer oxidation rates which can be used to predict gas migration at other sites. However, the need to obtain field data on gas permeabilities and diffusivities will always be a major limitation in predicting gas migration in permeable formations.

Skellingsted (Kjeldsen, 1995)
The background for a landfill gas explosion accident which happened at Skellingsted Landfill in Denmark was investigated. To understand the behaviour of the laterally migrating landfill gas in the area where the accident occurred, an intensive investigation was carried out after the explosion accident measuring time-series of gas composition in 30 wells over a 35-day period. The changes in gas composition in selected wells following a decrease in barometric pressure were measured over a 33hr period. The maximal distance for measured methane concentrations above 5% (vol.) in the pore gas was 90 m. The investigations showed that changes in barometric pressure have a great impact on the pore gas composition. Indications of methane oxidation were observed down to 2 m below ground at distances of more than 60 m from the landfill.

At this site the fluxes of landfill gas both horizontally and to the surface were measured and are presented below.

Landfill gas migration 481

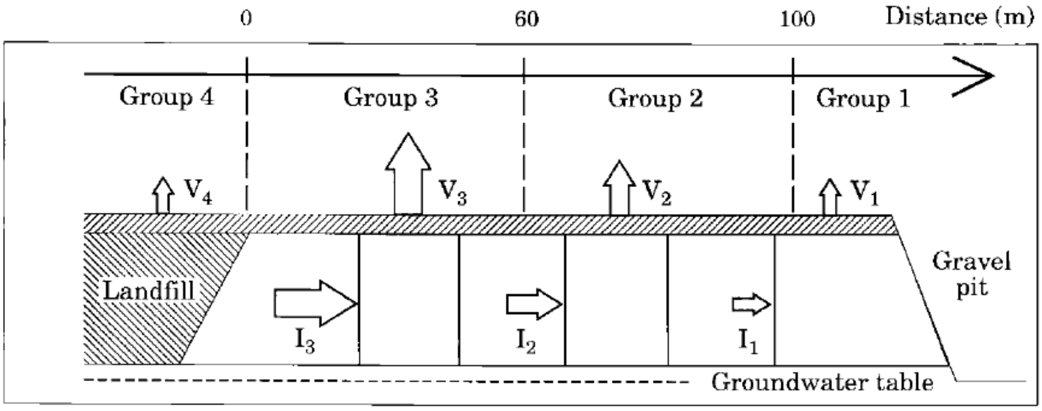


Fig. 8. Cross-section through area "D" from south to north. The area is divided into four groups (1–4). The magnitude of the vertical and horizontal gas fluxes are indicated with arrows.

The authors concluded that the gas explosion accident at Skellingsted Landfill was a result of several unfavourable factors in combination: A house surrounded by landfill on three sides; decreasing barometric pressure; heavy rain leading to low vertical permeability of the top soil; and, an open, unsealed floor construction in the house.

The investigations at Skellingsted Landfill showed that the vertical gas flow through the soil cover of the landfill was low, probably due to the low permeability of the soil used (clay soil). Changes in barometric pressure had a great impact on the pore gas composition at distances more than 60 m from the landfill. Closer to the landfill (less than 40 m) the effects from pressure changes were insignificant due to a steady advective flow driven by the higher pressure in the landfill.

Indications of methane oxidation were observed down to 120 cm (and in one case down to 250 cm) below ground in distances more than 60 m from the landfill. Close to the landfill, methane oxidation was probably observed in the top 10-20 cm of the soil profile. The methane oxidation together with transfer between pore gas and pore water dampened out the fluctuations in carbon dioxide concentrations created by the barometric pressure changes.

Pore gas concentrations above 5% (vol.) methane (the lower explosion limit) were not observed at distances further than 90 m from the landfill

Skellingsted (Christopherson & Kjeldsen, 2001)
Field experiments were conducted during a one-year period to investigate lateral gas transport in soil adjacent to the same landfill as previously described.

The landfill is situated in an abandoned gravel pit located in an area of alluvial sand and gravel sediments. The thickness of the unsaturated zone in the soils adjacent to the landfill varies between 10–20 m. There is no bottom liner in any of the landfilled sections.

Significant seasonal variation caused by methane oxidation was observed. Close to the landfill the concentration of methane was significantly lower and the concentration of carbon dioxide was significantly higher in the summer (May to October) compared to the winter (November to April). The seasonal variation was caused by oxidation of methane to carbon dioxide, which is a temperature dependent process. Methane oxidation was occurring throughout the year, but more methane was oxidised in the summer.

The concentration of both methane and carbon dioxide were significantly lower in the summer further away from the landfill border. During the winter, the soil moisture content was higher especially in the topsoil and that reduced the vertical gas permeability and increased the lateral migration distance.

There was a good correlation between pressure in the soil being above the barometric pressure and the methane concentration in the soil, indicating that advective flow was the controlling process. This was confirmed by calculations comparing diffusive and advective methane fluxes in a sandy soil, which showed that advective methane flow was much more important than diffusive methane flow.

Diurnal measurement during a drop in barometric pressure showed that lateral migration of landfill gas was very dynamic and the concentrations of landfill gas at a specific place and depth changed dramatically within a very short time. The advective flow increased during the barometric depression leading to a substantially higher landfill gas migration rate.

Montreal (Franzidis, 2008)
An evaluation of lateral landfill gas migration was carried out at the City of Montreal Landfill Site, Canada, between 2003 and 2005. Biogas concentration measurements and gas-pumping tests were conducted in multilevel wells installed in the backfilled overburden beside the landfill site.

A migration event recorded in autumn 2004 during the maintenance shutdown of the extraction system was simulated using software. Eleven high-density instantaneous surface monitoring (ISM) surveys of methane were conducted on the test site. Gas fluxes were calculated by geostatistical analyses of ISM data correlated to dynamic flux chamber measurements.

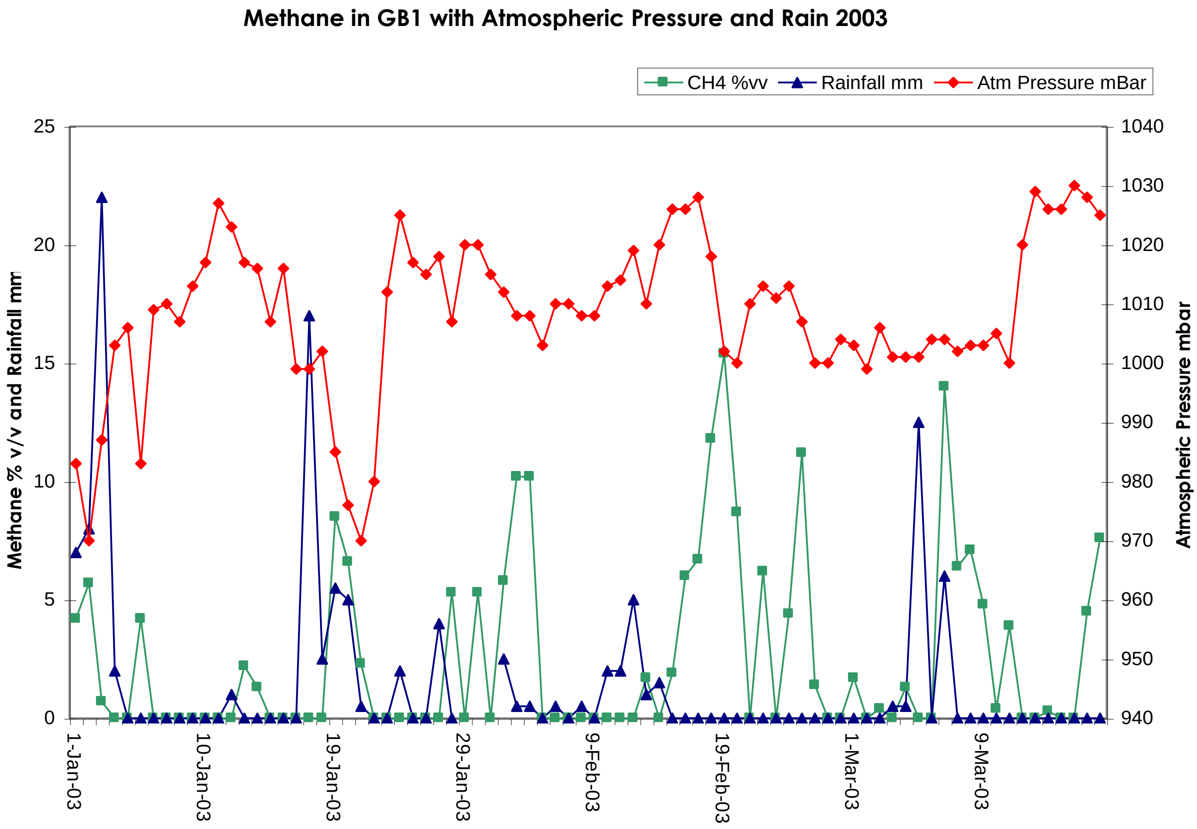
Measurement-based estimates of yearly off-site surface emissions were two orders of magnitude higher than modeled advective lateral methane flux. Nucleodensimeter measurements of the porosity were abnormally high, indicating that the backfill was poorly compacted. Kriged porosity maps correlated well with emission maps and areas with vegetation damage. Pumping tests analysis revealed that vertical permeability was higher than radial permeability. All results suggest that most of the lateral migration and consequent emissions to the atmosphere were due to the existence of preferential flow paths through macropores. In December 2006, two passively vented trenches were constructed on the test site. They were successful in countering lateral migration.

Confounding factors

An example of barometric pumping and seasonal variation influences on gas migration are outlined below, based on Parker et al., 2005. This used vapour modelling and meteorological data to assess the risk posed by a closed landfill.

Outside this closed landfill site, landfill gas was only detectable for a day or so in the early months of the year after a prolonged period of heavy rainfall had increased both the water level in the landfill and the moisture content of the restoration/capping materials. Measurable methane off-site also appeared to be triggered by a drop in atmospheric pressure and/or rainfall. During these events, methane concentrations were highest inside the landfill, and were also measured outside the landfill boundary.

The graph below shows the off-site methane concentrations (in green) only rising above zero after rainfall (blue) and/or falling atmospheric pressure (red). It is believed that the rainfall ‘seals’ the surface of the ground preventing gas from venting to atmosphere causing a pressure build up in the sub-surface and lateral migration.



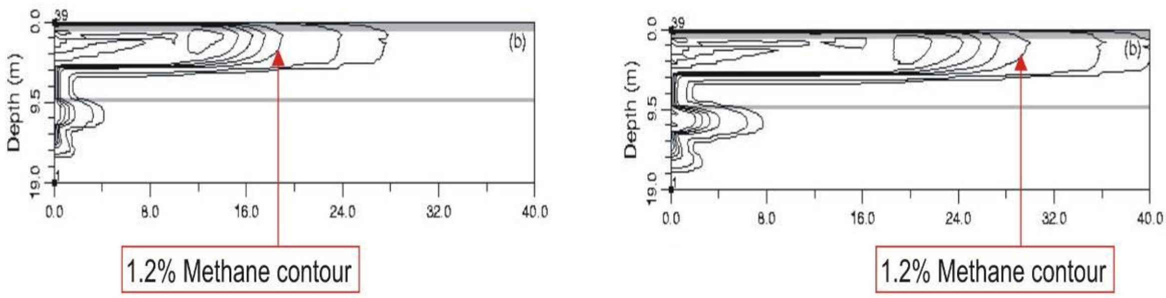
The conceptual model for the site indicated that elevated concentrations of methane and carbon dioxide in the landfill represented a potential source of risk to residents of houses 25 metres from the landfill boundary if there was a viable gas migration pathway.

The analysis of the gas migration pathway used known conditions combined with estimated physical parameters. In this scenario, gas migration is related to both air permeability and applied pressure. Given that field-measured values were not available for the expected shallow gas pathway, a reasonable permeability value was assumed. Two scales of applied pressure (barometric pumping) were evaluated, by comparing model-determined and field measured methane concentrations at two locations. The model results were not intended to be predictive, but rather to provide an insight into the potential for gas migration.

Simulations were performed using VAPOURT, a numerical model for gas migration and/or soil vapour extraction. The domain was simulated using a 2 dimensional vertical cross-section away from the landfill boundary in Cartesian coordinates. The model assumes that the landfill is relatively wide in the 3rd dimension, perpendicular to the line of cross section. The model boundary (landfill edge - source of landfill gas) was assumed to be a vertical, fully-penetrating source, except for a thin surface cap (<1 m). The stratigraphy was input as horizontal layers to represent geological conditions. Methane concentrations were reported as relative concentrations.

The best and worst case diagrams below show depth on the y axis against distance from the landfill on the x-axis, with the methane concentration contours after 4 days of applied pressure (barometric pumping). The landfill boundary is the left hand axis and the methane is migrating to the right.

Base Case– applied pressure = 300 Pa. Worst-case (Increased pressure) = 1,000 Pa



The results indicated that gas migration may exceed 30 m from the landfill, depending on input parameters. This migration was likely only during winter months after periods of heavy rainfall, when the landfill was more actively producing methane and when a low pressure weather front moved through. This conjoining of factors only occurred on a few days each year.

In the area where the surficial topsoil/clay thickness was less than 0.75m, gas concentrations in the interpreted shallow pathway of concern could pose a risk (> 1% v/v methane) under reasonably expected conditions. Modelling suggested that gas migration within the shallow pathway was also possible beneath areas with a surficial clay thickness of 3 m. The presence of a thicker confining layer in this area would mitigate the risk of methane concentrations reaching the houses, assuming that there were no vertical pathways connecting the gas migration pathway and the house foundations.

Appendix 2 International approaches to perimeter gas regulation

US/Canadian approach
In the U.S., pertinent regulations were developed at a federal level by the US Environmental Protection Agency (US EPA Resource Conservation and Recovery Act (RCRA), Subtitle D, October, 1991). For soil gas monitoring at the perimeter of the landfill the number and location of gas probes is site-specific and dependent on subsurface conditions, land use, and location and design of facility structures. Required monitoring frequency is quarterly. State agencies in New Jersey, Pennsylvania, Illinois, Alabama and California further developed their own advice, relevant extracts of which include:

- **New Jersey**: Methane gas survey shall be performed on a quarterly basis around the perimeters of the buffer zone, and the maximum interval between sampling points should be 100 metres (300 feet). The maximum interval between sampling points for structures shall be 15 m (50 feet), with at least one sampling point along each side of the structure. The minimum sampling depth is 1 metre (3 feet) below the ground surface or above the water table, whichever is higher.
- **The California Integrated Waste Management Board (CIWMB)** - At a minimum, quarterly monitoring is required.
- **USEPA & CIWMB** – The lateral spacing between adjacent monitoring wells shall not exceed 305 m (1,000 feet), unless it can be established to the satisfaction of the Environmental Agency.

Methane concentrations on the landfill boundary
Several jurisdictions have established soil gas limits at the landfill property boundary and beyond. British Columbia, Quebec and USEPA regulations require that landfill owners control methane in soil gas so that it does not exceed the LEL (50,000ppm – 5%) at the property boundary.

The rational for this approach in Canada (Alberta Environmental Protection, 1999.) is: '*To minimize the potential for off-site migration of potentially hazardous concentrations of methane, an action level criterion of 50,000 ppm (100% LEL or 5% by volume) methane in soil gas is recommended. Limiting the landfill boundary concentration to the LEL will effectively prevent the accumulation of dangerous levels of methane in off-site structures. This approach is consistent with the risk assessment approach to contaminated site management, which requires that sites be managed in such a way to prevent ecological and human health impacts from hazardous materials on the site or migrating off-site*'.

Ontario regulations require that landfill owners control methane in soil gas to achieve the following criteria:

- Methane concentration below the surface of the soil at the boundary of the site should not exceed 50,000 ppm – 5% (100% LEL).
- Methane gas concentration in soil immediately outside the foundation of an on-site building that is accessible by any person or contains electrical equipment or potential source of ignition, should not exceed 10,000 ppm – 1% (20% LEL)

- Methane gas should not be present in soil immediately outside the foundation of an off-site building that is accessible by any person or contains electrical equipment or potential source of ignition – 0%.

Methane concentrations in receptor buildings

Almost all municipalities deal with methane gas problems on a case-specific basis. A review of the collected legislation and background literature (Alberta Environmental Protection, 1999) indicates that the action level criteria are generally selected to provide a comfortable margin of safety compared to the methane lower explosion limit (LEL) of 50,000 ppm. **The key difference to the UK is that action levels are derived for inside buildings, not in the ground.** In most cases, safety factors of 4 or 5 (i.e., 25 and 20% of LEL, respectively) are applied resulting in corresponding action levels of 12,500 and 10,000 ppm (1.25 or 1 %, respectively). Most jurisdictions do not provide any specifics on frequency or locations where the samples should be collected, as these are required to be determined by a qualified professional on a site specific basis. If the selected criteria are exceeded, most jurisdictions require that methane gas migration control measures be implemented. Again, appropriate control measures should be recommended by a qualified professional on a site-specific basis. Both the monitoring programs and migration control measures need to be approved by the relevant regulatory body before they can be implemented.

A summary of action limits from various jurisdictions (Alberta Environmental Protection, 1999.) is shown below:

ACTION LEVEL CRITERIA FOR METHANE CONCENTRATIONS

Jurisdiction	Methane Concentration Limit	Required Action if Limit Exceeded	Regulation/Guideline
Canada			
Ontario	10,000 ppm (20% LEL) in any on-site building or in the area immediately outside the foundation of the building	Monitoring program required to record and monitor methane concentrations; if methane concentration exceeds 1% by volume, methane gas migration control measures must be put in place	New Standards for Landfill Sites, Proposed Regulatory Standards for New Landfilling Sites Accepting Non-Hazardous Waste (June, 1996)
	Zero in any off-site building or in the area immediately outside the foundation of the building	Monitoring program required to record and monitor methane concentrations; if methane concentration exceeds 1% by volume, methane gas migration control measures must be put in place	
British Columbia	12,500 ppm(25% LEL) in any on- or off-site building	Monitoring program must be prepared and approved by BC Environment authorities	Landfill Criteria for Municipal Solid Waste (June, 1993)
Quebec	12,500 ppm (25% LEL) in air in buildings on or near a landfill	Monitoring program required to record and monitor methane concentrations; if methane concentration exceeds 1% by volume (20% LEL), methane gas migration control measures must be put in place	Projet de reglement sur les dechets solides, version technique (March 1994)
City of Winnipeg	2,500 ppm (5% LEL) mid-air level in a portion of a building	Alarm situation – advise occupants of the building to vacate the premises; provide extra ventilation; shut off sources of ignition; call 911; if the conditions cannot be alleviated, the building will remain vacated. If the situation is stabilized, the City will test the premises daily until long-term protection is provided.	Standards and Guidelines for the Mitigation of Methane Gas at Buildings and Utilities (May 1997)
	10,000 ppm (20% LEL) at any point source in the building	If this concentration is exceeded consistently (i.e., on a monthly basis during a one-year period), measures to mitigate methane gas infiltration must be implemented	
United States			
US EPA	12,500 ppm (25% LEL) in any on-site structure	Must ensure monitoring program is implemented and performed quarterly	Resource Conservation and Recovery Act (RCRA), Subtitle D (October, 1991)
New Jersey	12,500 (25% LEL) inside buildings	Induced draft or active venting system must be installed	Solid and Hazardous Waste Management Regulations, Title 7
California	No criteria for methane; regulate non-methane organic compounds (NMOCs)		Control of Gaseous Emissions from Active and Inactive Landfills (Regulation XI)

Typically, landfill owners are required to operate their landfills in a manner that will ensure that the concentration of methane gas in on- or off-site buildings does not exceed a pre-determined limit. The owners are expected to monitor periodically concentrations of methane gas within the perimeter of the landfill. If the compliance limits are exceeded, the landfill owner is responsible for implementing methane gas migration control and mitigation measures.

The table below shows action levels for inside buildings in specific cases.

ACTION LEVEL CRITERIA DEVELOPED FOR SPECIFIC CASES

Location	Methane Concentration	Action
Cape Breton, Nova Scotia	5,000 ppm	Evacuation
Kitchener, Ontario	5,000 ppm	Evacuation
Seattle, Washington	5,000 ppm	Evacuation
West Covina, California	Methane > 5% GAS	Evacuation

ACTION LEVEL CRITERIA FOR INDOOR METHANE CONCENTRATIONS (ESTABLISHED AD HOC FOR MIDWAY LANDFILL VICINITY, NEAR SEATTLE, WASHINGTON)

Methane Concentration	Action
0 – 50 ppm	Normal conditions
50 – 100 ppm	Monitor as frequently as staff size permits
100 – 500 ppm	Monitor daily
500 ppm and up	Monitor daily, seal cracks, request owner to ventilate
1,000 ppm and up	Verify with second instrument and methane unit, seal cracks, install alarm and a fan, monitor daily, notify Health Department and Fire Department
5,000 ppm and up in atmosphere	Evacuate, call 911
10,000 ppm and up in wall or small confined places	Evacuate, call 911
40,000 ppm and up	Point source, evacuate, call 911

Point-of-Entry methane concentration
The City of Winnipeg was the only jurisdiction identified that set a limit for the point-of-entry concentration in buildings near landfills. The City identified a methane concentration of 10,000 ppm - 1% (20% LEL) as a level that requires implementation of measures to mitigate methane infiltration, provided this concentration is encountered consistently at any point source within a building. A point source is defined as a measurement obtained at a floor crack, floor joint, floor drain, column base, utility access penetration, base grade crack or pile base. To encounter a certain concentration “consistently” would mean that that concentration has been exceeded in a majority of monthly methane gas measurements over a period of one year.

Methane concentration adjacent to buildings
The reviewed literature indicates that some jurisdictions use the same criterion for methane in soil adjacent to buildings as for the ambient air, while some others have developed separate sets of standards for "soils adjacent to buildings".

When using the technique of monitoring for methane adjacent to buildings, it is important to consider the pressure of the gas in the soil pore space, in addition to methane concentration. The rate at which gas can move from the soil into the building is controlled by the soil gas pressure. Furthermore, detection of measurable soil gas pressures adjacent to a building suggests that a significant flux of gas through the soil from the landfill may be occurring. In this case, the gas concentrations may change quickly as the gas plume moves toward the building.

Gas pressure measurement is included in very few standards, but is critical in controlling the rate of gas migration. Therefore, some consideration should be given to including monitoring of gas pressure when evaluating the need for controls. The literature indicates that negligible gas flows occur if the gas pressure in the soil is less than 0.249 kPa, and that at pressures above 0.249 kPa the gas flows become significant. In Alberta, it was recommended that the following criteria be considered for soils adjacent to buildings:

- Methane concentration of 50,000 ppm - 5% (100% LEL), if the soil gas pressure is less than 0.249 kPa (there will likely be little if any gas flow, and dilution of the gas will occur rapidly);
- Methane concentration of 5,000 ppm - 0.5% (10% LEL) if the pressure is 0.249 kPa or greater (significant gas flows can occur, and dilution may not be sufficient to mitigate the potential explosion hazard).

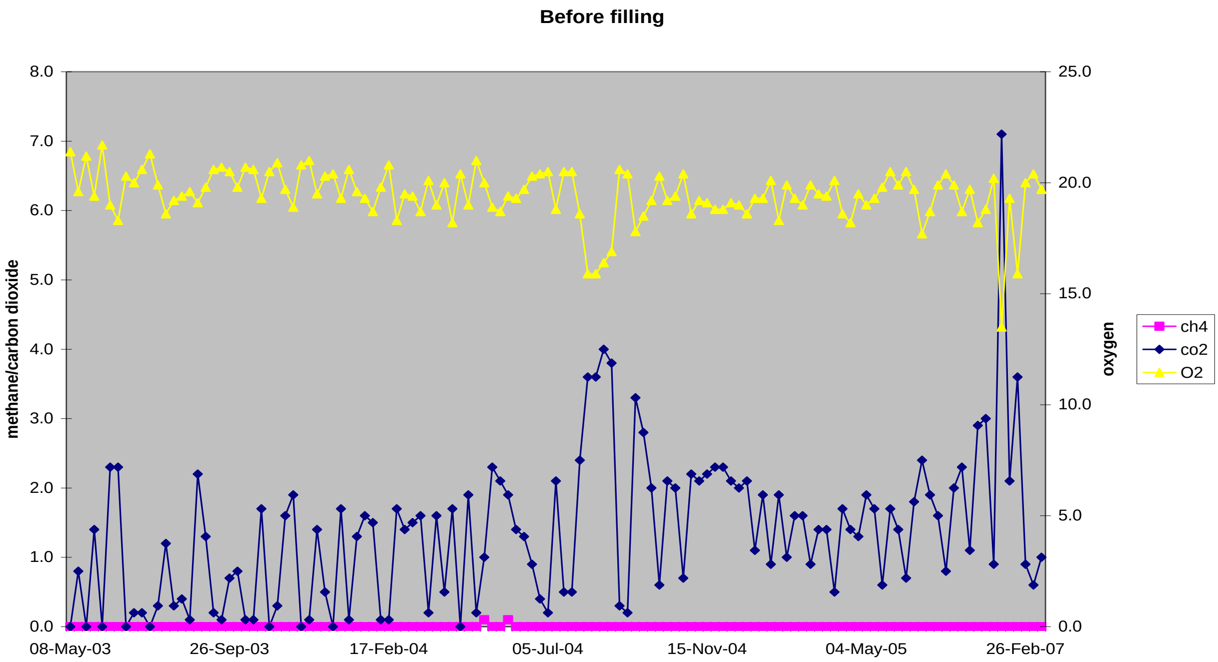
Danish approach
Because of the difficulties in applying conventional risk assessment methods to landfill gas migration, the Danes (Miljøstyrelsen, 2001) decided to use a barrier diagram method to the risk assessment (no English version available). This allows the visualisation of complicated risk assessments.

There are several factors that cause a gas explosion including the conditions that influence gas production, gas migration, and gas escape from the ground. These are described and analysed systematically as a sequence of events. Each event is evaluated and those parameters (barriers) which can stop the event before the accident (gas explosion) happens are identified. Barriers able to reduce, or prevent, the sequences of events are described, and for each barrier solutions are suggested. Barriers can be physical arrangements, for example remedial actions, but can also be reduction of gas escape from the ground into the houses; reduction of gas concentration in the house, or a combination of the two.

Finally, the risk the event causes has to be evaluated. Types of consequence are included in the evaluation of the safety level for a specific landfill. The recommended safety level has to be met for each building/house assessed.

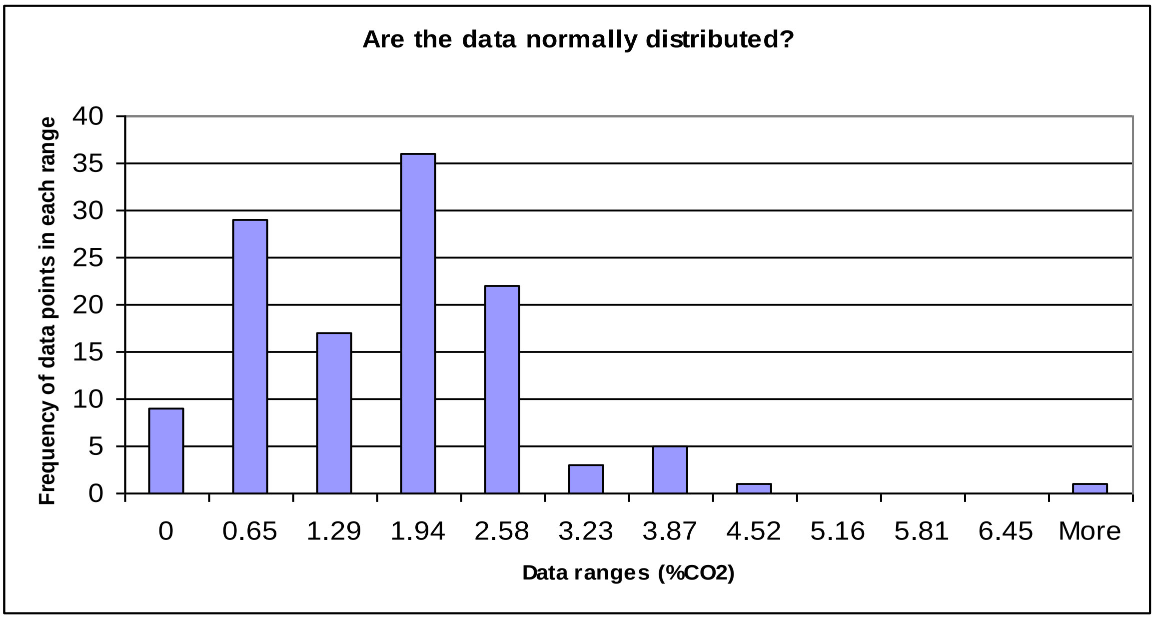
Appendix 3 Examples of Using Statistical Techniques

As much reliable (real) data as possible should be obtained prior to undertaking the analysis. If using a statistical technique as proposed below, no outliers should be removed manually before commencing the statistical analysis. A graph of an example background dataset is shown below (full dataset follows). The application of two possible statistical techniques follows in Appendices 3A and 3B.



Discussion of whether the carbon dioxide data follow a 'normal' distribution

The chart below is a histogram of the data values - and can be used to provide a pictorial view of whether the data is likely to be normally distributed. It can be interpreted that the data set looks acceptable as a normal distribution. However, this is with the caveat that the left hand tail stops suddenly at zero and there is an obvious data point well away from the right hand tail.



However, using the D'Agostino's method as recommended in the Techniques for the Interpretation of Landfill Monitoring Data Guidance (P1-471) the data do not appear to be consistent with a normal distribution. One of the issues is that the left hand side ends at zero and does not allow the left hand 'tail' to extend to its natural conclusion (if, for example, the gas analysers actually recorded negative readings).

This skews the readings so that when the D'Agostino's method is used the result indicates that the hypothesis that the data set has been drawn from a normal distribution can be rejected (i.e. the calculated value does not fall between the 1% and 99% critical values).

However, if the higher concentrations are removed (the last 3 columns in the chart above) then the remainder of the distribution would not be rejected and may be considered to be taken from a normal distribution.

This highlights the problem that if there are significant outliers it is very unlikely that the data set would be considered to fall within a normal distribution - because any data that is unexpectedly far from the mean will make the normal distribution less likely.

Therefore, it is recommended that the following is always considered (taken from outlier assessment section of the P1-471):

Recommended statistical methods make the assumption that the data is Normally distributed (after logging where appropriate). For outlier detection the assumption is particularly critical, because the method is concerned with the extreme tails of the distribution - which is precisely where the assumption is most likely to breakdown. For this reason, **outlier tests should be regarded as providing no more than a rough screen of the data, with an element of judgement applied in marginal cases**. Nevertheless, experience shows that outlier tests are extremely useful for flagging up gross outliers (such as those in error by a factor of 1000), and in general the routine use of such tests is highly recommended.

Therefore, for the data set below, an assessment of whether the data set is taken from a normal distribution should be considered before any statistical assessment takes place. Then a judgment should be made as to the applicability of statistical methods. Alternatively a histogram plot or many other methods will indicate that the one or a few elevated results from the data set are probably outliers.

Example background dataset

	Methane	Carbon dioxide	OxygenO2
08-May-03	0.0	0.0	21.4
15-May-03	0.0	0.8	19.6
21-May-03	0.0	0.0	21.2
29-May-03	0.0	1.4	19.4
05-Jun-03	0.0	0.0	21.7
10-Jun-03	0.0	2.3	19.0
18-Jun-03	0.0	2.3	18.3
24-Jun-03	0.0	0.0	20.3
03-Jul-03	0.0	0.2	20.0
11-Jul-03	0.0	0.2	20.6
18-Jul-03	0.0	0.0	21.3
24-Jul-03	0.0	0.3	19.9
31-Jul-03	0.0	1.2	18.6
05-Aug-03	0.0	0.3	19.2
13-Aug-03	0.0	0.4	19.4
22-Aug-03	0.0	0.1	19.6
29-Aug-03	0.0	2.2	19.1
04-Sep-03	0.0	1.3	19.8
10-Sep-03	0.0	0.2	20.6
19-Sep-03	0.0	0.1	20.7
26-Sep-03	0.0	0.7	20.5
01-Oct-03	0.0	0.8	19.8
16-Oct-03	0.0	0.1	20.7
24-Oct-03	0.0	0.1	20.6
29-Oct-03	0.0	1.7	19.3
04-Nov-03	0.0	0.0	20.5
13-Nov-03	0.0	0.3	20.9
20-Nov-03	0.0	1.6	19.7
26-Nov-03	0.0	1.9	18.9
03-Dec-03	0.0	0.0	20.8
11-Dec-03	0.0	0.1	21.0
16-Dec-03	0.0	1.4	19.5
22-Dec-03	0.0	0.5	20.3
30-Dec-03	0.0	0.0	20.4
06-Jan-04	0.0	1.7	19.3
13-Jan-04	0.0	0.1	20.6
22-Jan-04	0.0	1.3	19.6
28-Jan-04	0.0	1.6	19.3
04-Feb-04	0.0	1.5	18.7
12-Feb-04	0.0	0.1	19.8
17-Feb-04	0.0	0.1	20.8
26-Feb-03	0.0	1.7	18.3
03-Mar-04	0.0	1.4	19.5

	Methane	Carbon dioxide	OxygenO2
10-Mar-04	0.0	1.5	19.4
16-Mar-04	0.0	1.6	18.7
24-Mar-04	0.0	0.2	20.1
31-Mar-04	0.0	1.6	19.0
06-Apr-04	0.0	0.5	20.0
14-Apr-04	0.0	1.7	18.2
20-Apr-04	0.0	0.0	20.4
29-Apr-04	0.0	1.9	19.0
06-May-04	0.0	0.2	21.0
10-May-04	0.1	1.0	20.0
19-May-04	0.0	2.3	18.9
26-May-04	0.0	2.1	18.7
04-Jun-04	0.1	1.9	19.4
09-Jun-04	0.0	1.4	19.3
14-Jun-04	0.0	1.3	19.7
21-Jun-04	0.0	0.9	20.3
28-Jun-04	0.0	0.4	20.4
05-Jul-04	0.0	0.2	20.5
12-Jul-04	0.0	2.1	18.8
19-Jul-04	0.0	0.5	20.5
27-Jul-04	0.0	0.5	20.5
03-Aug-04	0.0	2.4	18.6
03-Aug-04	0.0	3.6	15.9
12-Aug-04	0.0	3.6	15.9
17-Aug-04	0.0	4.0	16.4
24-Aug-04	0.0	3.8	16.9
31-Aug-04	0.0	0.3	20.6
06-Sep-04	0.0	0.2	20.4
13-Sep-04	0.0	3.3	17.8
20-Sep-04	0.0	2.8	18.5
30-Sep-04	0.0	2.0	19.2
07-Oct-04	0.0	0.6	20.3
13-Oct-04	0.0	2.1	19.2
22-Oct-04	0.0	2.0	19.4
26-Oct-04	0.0	0.7	20.4
03-Nov-04	0.0	2.2	18.6
08-Nov-04	0.0	2.1	19.2
15-Nov-04	0.0	2.2	19.1
22-Nov-04	0.0	2.3	18.8
29-Nov-04	0.0	2.3	18.8
08-Dec-04	0.0	2.1	19.1
13-Dec-04	0.0	2.0	19.0
20-Dec-04	0.0	2.1	18.6
31-Dec-04	0.0	1.1	19.3
05-Jan-05	0.0	1.9	19.3

	Methane	Carbon dioxide	OxygenO2
13-Jan-05	0.0	0.9	20.1
18-Jan-05	0.0	1.9	18.3
24-Jan-05	0.0	1.0	19.9
31-Jan-05	0.0	1.6	19.3
07-Feb-05	0.0	1.6	19.0
15-Feb-05	0.0	0.9	19.9
22-Feb-05	0.0	1.4	19.5
28-Feb-05	0.0	1.4	19.4
07-Mar-05	0.0	0.5	20.1
15-Mar-05	0.0	1.7	18.6
22-Mar-05	0.0	1.4	18.2
01-Apr-05	0.0	1.3	19.5
04-May-05	0.0	1.9	19.0
03-Jun-05	0.0	1.7	19.3
11-Jul-05	0.0	0.6	19.8
04-Aug-05	0.0	1.7	20.5
06-Sep-05	0.0	1.4	19.9
14-Oct-05	0.0	0.7	20.5
10-Nov-05	0.0	1.8	19.7
16-Jan-06	0.0	2.4	17.7
06-Feb-06	0.0	1.9	18.7
13-Mar-06	0.0	1.6	19.9
27-Apr-06	0.0	0.8	20.4
25-May-06	0.0	2.0	19.9
16-Jun-06	0.0	2.3	18.7
21-Jul-06	0.0	1.1	19.7
16-Aug-06	0.0	2.9	18.2
15-Sep-06	0.0	3.0	18.8
13-Oct-06	0.0	0.9	20.2
16-Nov-06	0.0	7.1	13.5
15-Dec-06	0.0	2.1	19.3
17-Jan-07	0.0	3.6	15.9
26-Feb-07	0.0	0.9	20.0
20-Mar-07	0.0	0.6	20.4
16-Apr-07	0.0	1.0	19.7

End of background data collection

Appendix 3A Tmax statistical methodology

Standardising the dataset
Prior to considering the Tmax value the dataset must be 'standardised'. This requires the 'mean' and the 'standard deviation' of the dataset to be calculated.

METHANE:
Mean of background dataset: 0.001626
Standard deviation of background data set: 0.012699

For each data value: subtract the 'mean' from the data value and then divide by the 'standard deviation'. For example, 0% methane is -0.128 and 0.1% methane is 7.746.

No. of data points (background data): 123. Critical value (P=1%) for 123 data points: 3.66 (Taken from Techniques for the Interpretation of Landfill Monitoring Data Report P1-471)

Most extreme value of 7.746 is greater than the Critical value (P=1%) of 3.66 and is an outlier.

2nd most extreme value of 7.746 is also greater than the Critical value (P=1%) of 3.66 and is an outlier.

The 3rd most extreme value -0.128 is less than the Critical value (P=1%) of 3.66 and is not an outlier (all values the same after this). The third highest concentration is therefore the true Tmax concentration. The third highest concentration (corresponding to the -0.128 standardised datapoint) is 0.0% and therefore the Tmax concentration for methane is 0.0%.

CARBON DIOXIDE
Mean of background dataset: 1.3585
Standard deviation of background data set: 1.0893

For each data value: subtract the 'mean' from the data value and then divide by the 'standard deviation'. For example 1.4% carbon dioxide is 0.0380 and 3.6% carbon dioxide is 2.057.

No. of data points (background data): 123. Critical value (P=1%) for 123 data points: 3.66 (Taken from Techniques for the Interpretation of Landfill Monitoring Data Report P1-471).

Most extreme value of 5.270 is greater than the Critical value (P=1%) of 3.66 and is an outlier

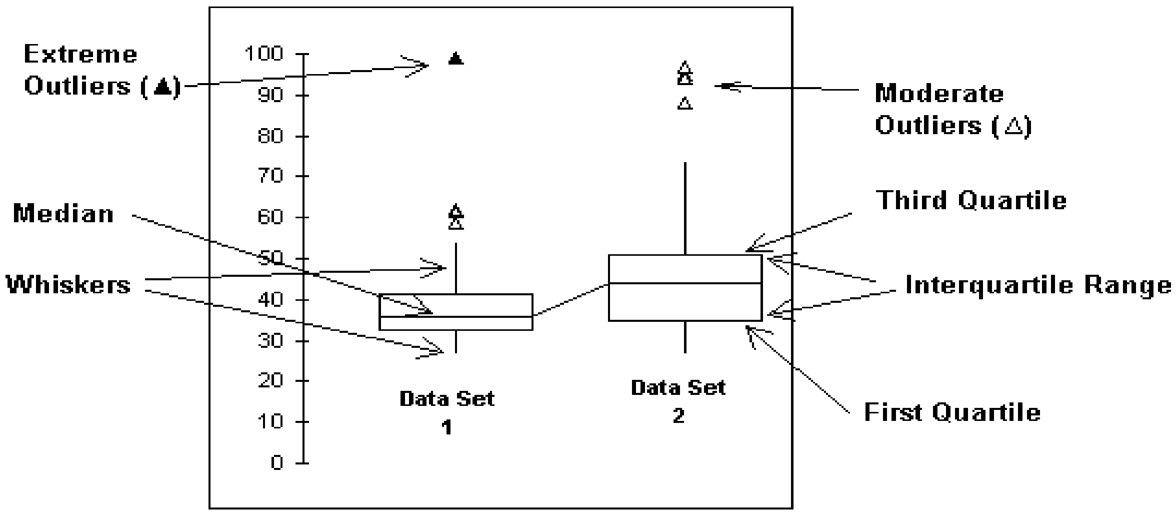
2nd most extreme value of 2.424 is less than the Critical value (P=1%) of 3.66 and is not an outlier. The second highest concentration is therefore the true Tmax concentration. The second highest concentration (corresponding to the 2.424 standardised datapoint) is 4.0%.

The Tmax concentration for carbon dioxide is 4.0%.

Appendix 3B Alternative box plot statistical methodology

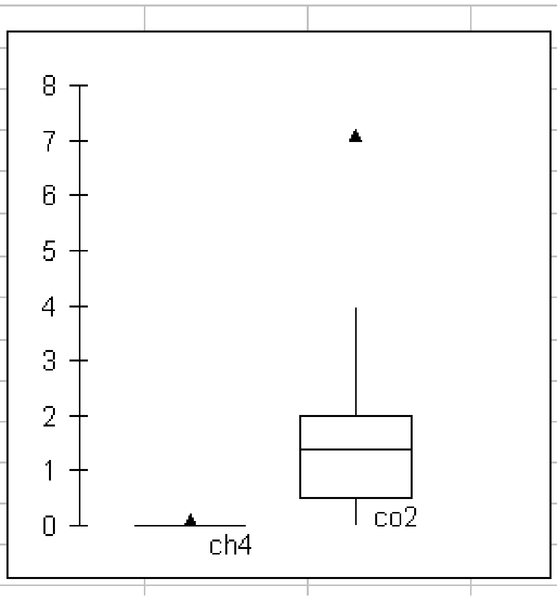
Using this method, the first quartile, median, third quartile, and interquartile range are specified for each column of values. The interquartile range is the range between the first and third quartile.

Also the number of moderate and extreme outliers are provided. The whiskers extend up to 1.5 interquartile ranges from the first and third quartiles. Moderate outliers are outliers closer than 3 times the interquartile range and the extreme outliers are outliers further than 3 times the interquartile range. The following is a generic boxplot output, representing two columns of numbers.



By applying the box plot methodology to the data in Appendix 3, the following outliers are identified. If difficulty is encountered in identifying the data points to remove, simply rank the data i.e., put in value order and then remove however many are classed as outliers from the end of the dataset. Note that this could be off the lower end of the dataset in extreme cases.

Boxplot Output	ch4	co2
First Quartile	0.0000	0.5000
Median	0.0000	1.4000
Third Quartile	0.0000	2.0000
Interquartile Range	0.0000	1.5000
Moderate Outliers ( )	0	0
Extreme Outliers ( )	2	1



For methane in this example, there are 2 outliers @ 0.1%.

For carbon dioxide there is 1 outlier @ 7.1%.

Note. This method comes up with the same outliers as the technique applied in Appendix 3A.

By removing these "outliers" (remove moderate ones as well if they exist) the 95th or 99th percentile can then be identified.

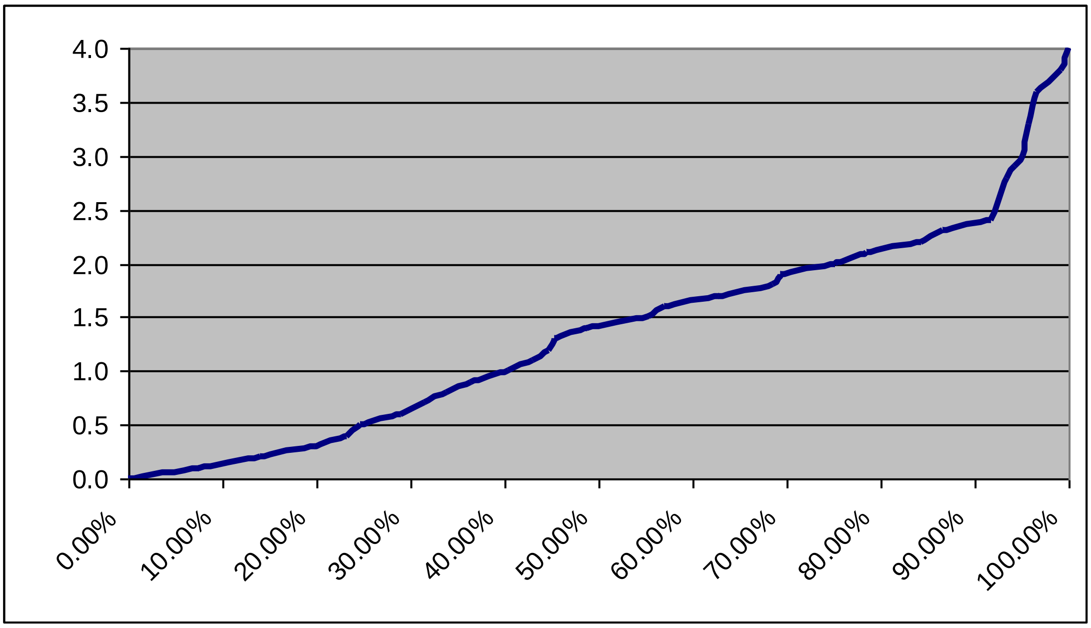
For the boxplot Kaddstat is an excel add in, that was part of a Wiley book (http://eu.wiley.com/WileyCDA/WileyTitle/productCd-0471239836.html)

For clarity the 100th (max), 99th and 95th percentile of the data (with outliers removed) is given below.

%ile	CH4	CO2
100th	0	4.0
99th	0	3.758
95th	0	2.995

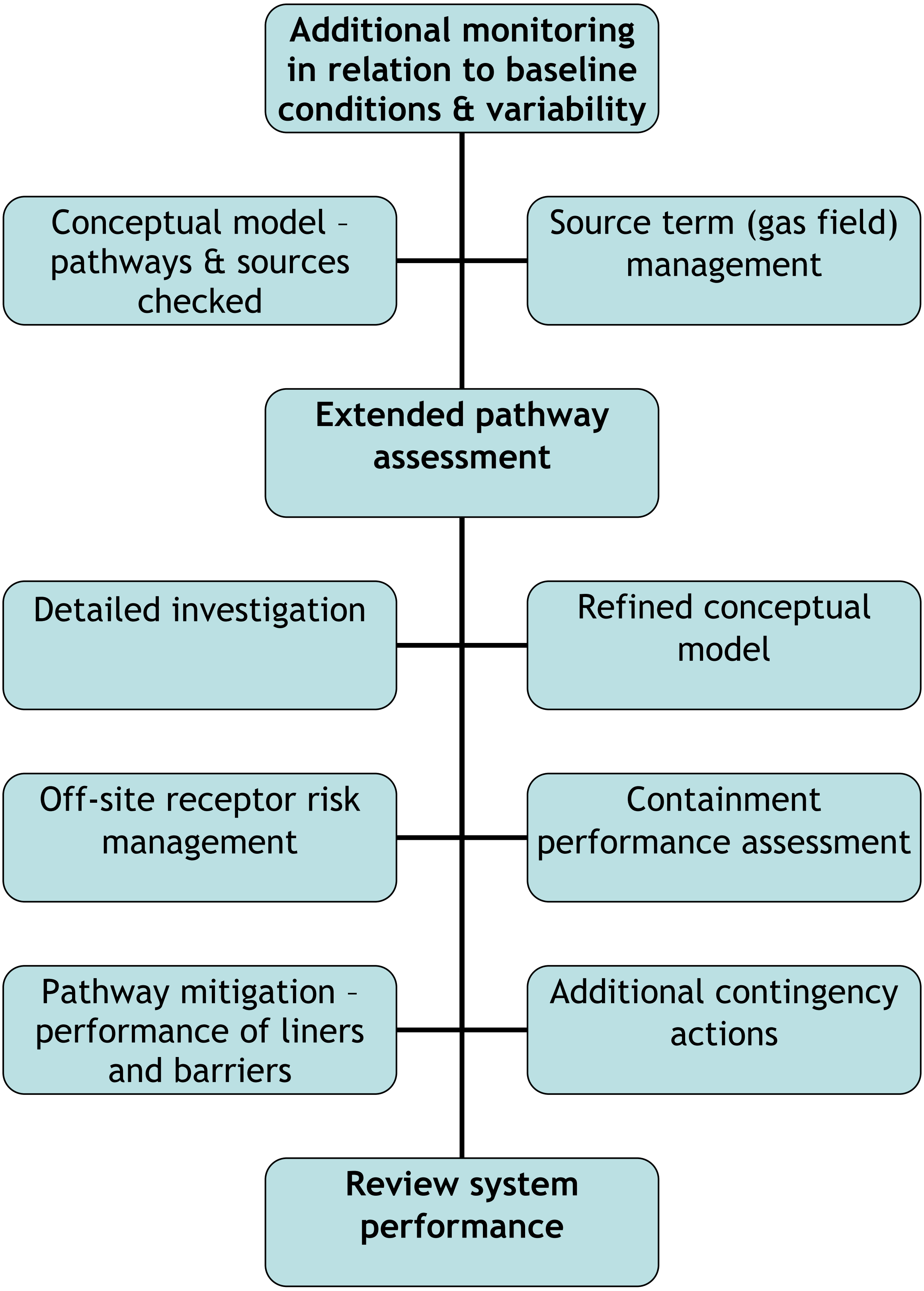
A judement can then be made about which level should be used i.e. 99th or 95th percentile. It should also be noted that this is ranked percentile data. The percentile function used in Excel© returns the k-th percentile of values in a range.

The graph below is of the ranked data (raw data included as appendix 3), using the rank and percentile function within Excel©. As the data is not likely to give an exact value for the ranked data i.e. 95.0, the percentile function should be used.



Appendix 4
Example Contingency Action Plan

The contingency action plan is based on the following flowchart:



1. Re-monitoring - gather a robust dataset
To understand the elevated reading it is necessary to put it into context of baseline conditions and variability. Important things to record when returning to a monitoring well with a concentration exceeding a management level are:

- Changes in atmospheric pressure over two days preceding monitoring (this can be obtained for the nearest weather station (ideally from an on-site weather station) with confirmation from the Met Office).
- Recent weather conditions and the condition of ground surface.
- Any activities in area that may affect readings (e.g., dewatering or excavation).
- Pressure within the well.
- Flow rate from or into the well.
- Methane, Carbon dioxide, Oxygen, Balance gas.
- If readings are varying and by what degree.
- Any odours from the wells.
- Groundwater levels.
- Temperature within well compared to ambient conditions.
- The date and time.

2. Assessing the gas field infrastructure
One of the first actions that should accompany re-monitoring is an assessment of the on-site gas field management. Assessment should include, but not be limited to:

- Assessing the status of all gas management wells (open, closed, percentage open).
- Confirming that the condition of all on-site and perimeter wells is satisfactory.
- Looking at total abstraction volumes in recent months to determine if gas losses are occurring or gas production is increasing rapidly.
- If the wells appear to be open and well-maintained, but perhaps gas production has increased dramatically for example, a second tier of testing involves checking whether the gas abstraction wells are fit for purpose i.e., there is interference suction on wells. If there is no interference suction, then additional abstraction wells may be required to control the gas field.

If any of the assessed parameters are not satisfactory, they should be rectified immediately.

3. Conceptual model - sources and pathways checked
The risk associated with gas migration varies with:

- gas quality and volume;
- gas permeability of the wastes;
- site engineering works (e.g. control measures such as site liners and caps);
- proximity of buildings and services; and
- the surrounding geology.

If any of the above factors have changed since the permit was issued and the landfill gas risk assessment was undertaken, then the conceptual model of risk should be amended.

4. Extended pathway assessment

To identify the source of gas found adjacent to a landfill it is important to understand the possible sources that could be generating the gas other than the landfill and the potential pathways to the landfill perimeter. It is therefore important to understand the history of the site and the under-lying strata.

- What is the detailed underlying geology?
- Are there any old mine workings?
- Are there any other landfills nearby? Is there any buried waste within the boreholes?
- Has there been any exploration for gas in the area?
- Has the adjacent land been used for burying dead livestock?
- Are there any septic tanks or any sewage pipes that might be leaking?
- Are there any gas mains near by?
- Is there any evidence of leachate migration?

It is often necessary to use a number of techniques outlined below to investigate the presence of gas outside a landfill. Even when all of these techniques have been used it may not be possible to confirm the source of the gas beyond reasonable doubt.

5. Detailed Investigation of gas migration

Many techniques are available to assess potential gas migration. These include:

- Trace component testing
- Methane: Carbon Dioxide ratio
- Helium
- Pressure gradients
- Borehole Purging/Pumping
- Carbon isotopes
- Tritium isotope

The best method is dependent on site circumstances. For example, carbon and tritium isotope analysis requires high concentrations of methane/carbon dioxide to ensure that there is enough elemental mass in a practical sampling volume.

The box below summarises how gas migration results should be assessed.

Boxes shown in Red are strong indicators that landfill gas has migrated.
Boxes shown in Green are strong indicators that another source of gas is present.

Process	**Likely Gas Migration**	**Unlikely Gas Migration**	**Comments**
Differential Pressure greater than 30mB	High pressure in the landfill, low pressure in the Borehole	Low pressure in the landfill, High pressure in the Borehole	Diffusion can drive a gas against a pressure gradient.
Presence of Helium	If no Helium is found, this does not mean that the gas has migrated	Helium present in the borehole.	Not all non-landfill gas sources contain Helium.
Presence of Chlorinated hydrocarbons in off-site wells	Chlorinated hydrocarbons are most likely to have come from the landfill		If no chlorinated hydrocarbons are found, they may not be present in the landfill, or may be adsorbed en route.
Carbon isotopes	^{14}C is found to be modern and the gas is biogenic	Low ^{14}C level, not biogenic	Data is rarely conclusive for CO_2 because this does not discriminate mixed sources or influences
Tritium isotope	High Tritium level.	Background Tritium Level	Need enough methane to get adequate tritium sample
Carbon Dioxide ratio.	60:40 CH_4 : CO_2 ratio with high flow	High flow with either CH_4 or CO_2 but not both	If the gas is flowing quickly over a short distance the amount of adsorption or methane oxidation will be limited.

All of the above techniques can be used to investigate the presence of gas adjacent to a landfill. However, the environmental consequences of these events can vary considerably, from inconsequential to an emergency evacuation of neighbouring properties.

6. Off-site receptor analysis and risk management

There are four risk scenarios associated with gas migration including risks to people, infrastructure, and the landfill operator.

Risk	**Ranking**
Gas into building	Very high
Gas into confined space	High
Gas off-site	Medium

These should be assessed in some detail before determining the optimum risk management options.

7. Containment performance assessment

Once an analysis of the potential receptors has been done and the results of the investigation have been assessed, the performance of the containment system can be put into context. If the gas field management can be improved it should be. If it cannot be further improved, then off-site gas containment may be the only option to address risks to sensitive nearby receptors.

Once these improvements have been made the system performance needs iterative monitoring until gas migration is controlled.

Appendix 5 Case Studies of Hazardous Gas Flow Rate

CASE STUDY 1 – Evidence for Naturally Occurring Ground Gas Flows
The site is located in NW England and is a former quarry excavated into a thick bed of sand capped by boulder clay. It was landfilled with asbestos, non hazardous commercial and demolition wastes to a depth of 9 metres during 1970-1990. The wastes have a low biodegradable fraction compared to that deposited in a typical non-hazardous waste landfill. During 1998-2005 the wastes were capped with in excess of 3 metres of excavated soils (inert). There is no containment lining on the base or sides and the total site volume is around 800,000 m^3.

Geological Setting
A site plan and schematic cross section through the southern edge of the site is included as Figures CS1.1. and CS1.2

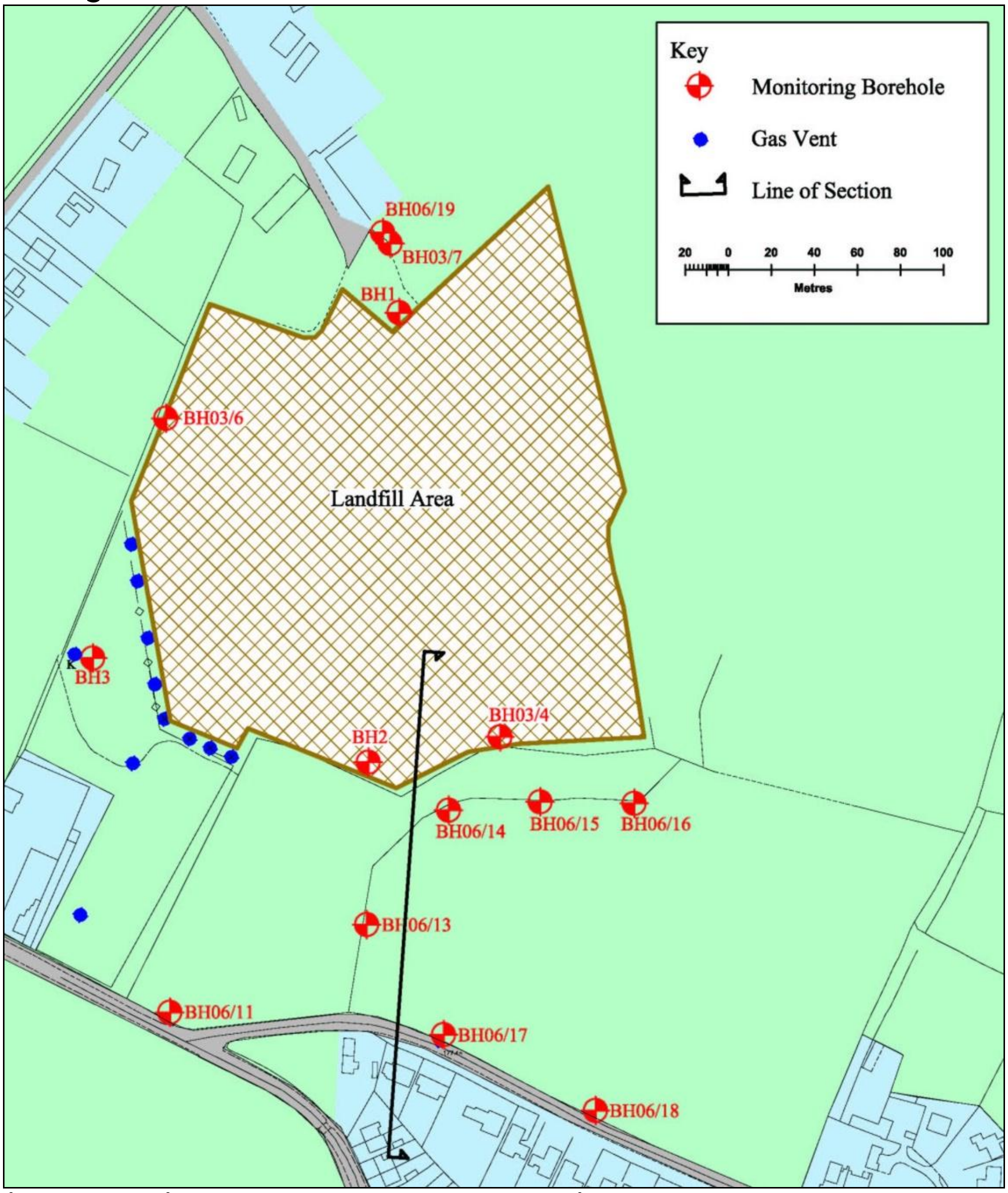


Fig CS1.1 Site plan and borehole locations

The local geology comprises a glacial drift sequence, comprising an upper unit of clay (1-4m thick), a middle sand sequence (12-15m thick) and lower clay, over

Triassic strata. Groundwater is present at the base of the middle sands but there is a substantial unsaturated zone.

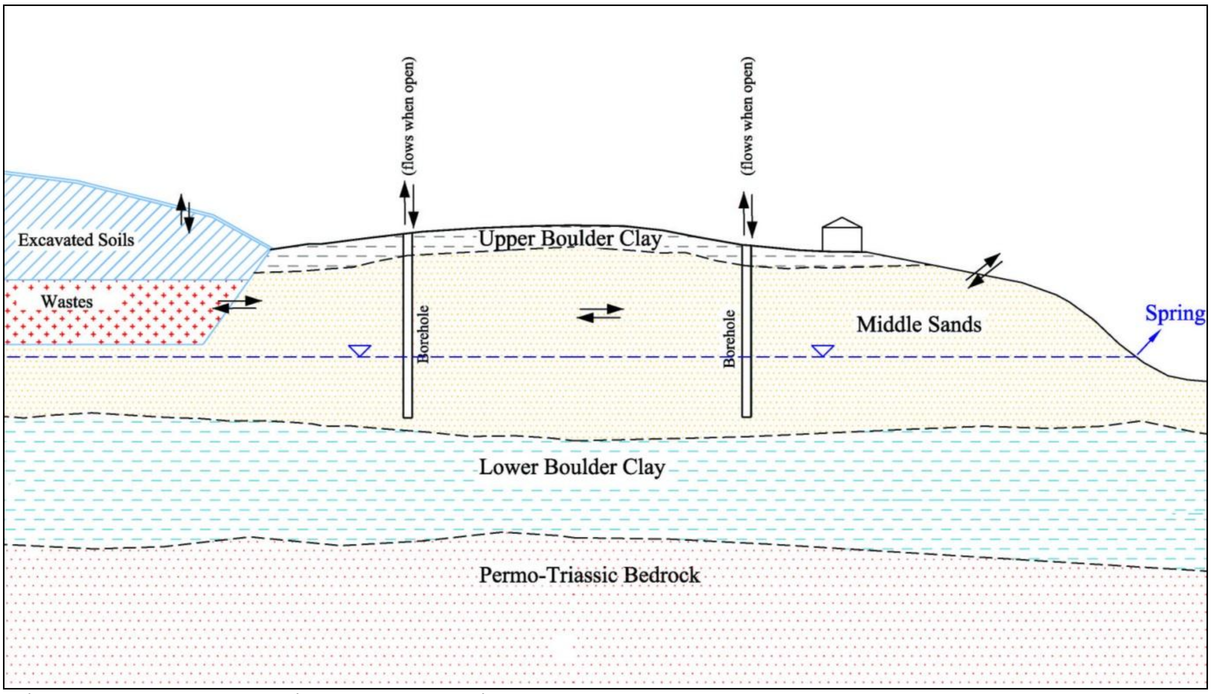


Fig CS1.2 Schematic cross section

Source Term

Concentrations of methane in the landfill can reach 60 % v/v, however production of landfill gas at the site is very low, roughly estimated to be of the order of 10-30 m^3/hr in total. Migration of landfill gas into the adjacent unsaturated sands occurs because there is no containment lining system. There is neither active nor passive gas control within the waste. A series of 8 No. 160 mm diameter out of waste passive gas vents / boreholes are located along a 120 m section of the site boundary.

External Ground Gas Conditions

Monitoring of boreholes external to the site for ground gases (methane, carbon dioxide, and oxygen) and groundwater quality has been undertaken consistently since 1998. Prior to that some limited ground gas monitoring was carried out in the period 1990-1992. Additional monitoring boreholes were installed in 2003 & 2006. Long term flow monitoring has been carried out. During 2008-2009 some of the boreholes were instrumented for periods with a data logging multisensor gas monitor (GasClam) which measured ground gas and relative pressures in addition to gas concentrations.

A general plan of borehole locations is provided as Fig CS1.1. Each of the boreholes has been constructed with a response zone which allows the ground gas in the unsaturated middle sands unit to be sampled. Good external monitoring borehole coverage is limited to the southern half of the site.

Figure CS1.3 shows an example of the logged time series data obtained from the GasClam instrument. This was located in a monitoring borehole where methane from the landfill site was not being detected in the ground gas.

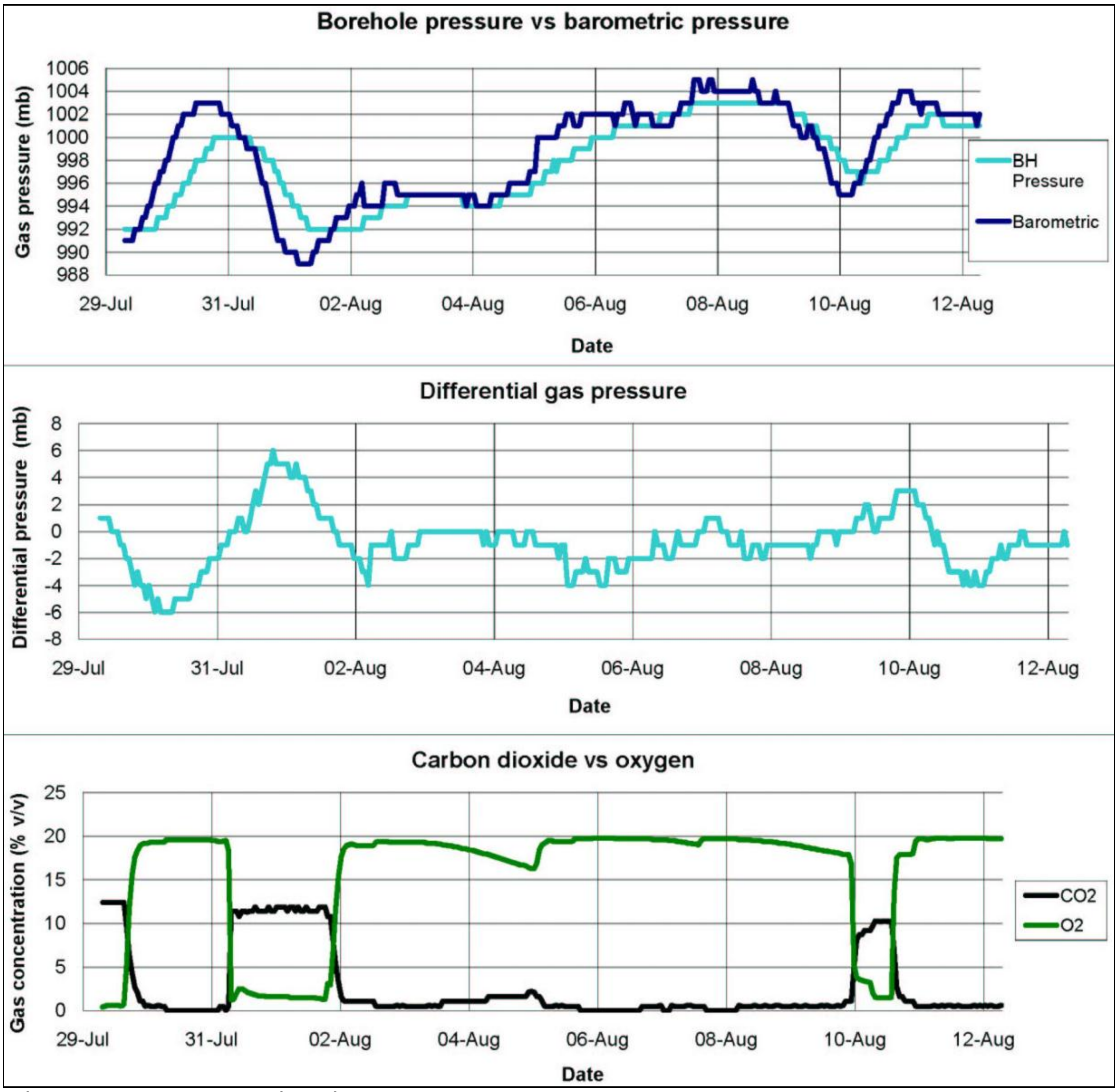


Fig CS1.3 Gas monitoring data from BH06/16 (GasClam logger output)

The monitoring has revealed the following ground gas conditions to be present:

i) The boreholes with response zones in the unsaturated sands external to the landfill exhibit fluctuating positive and negative flows, which correlate strongly with atmospheric (barometric) pressure changes.
ii) Within a 30 m zone close to the landfill there are fluctuating concentrations of methane and carbon dioxide in the ground gases in the ranges; Methane: 0 - 54 % v/v; Carbon dioxide 0 – 10 % v/v).
iii) Further away methane is not found but high, fluctuating concentrations of carbon dioxide continue to be found in the range 0 – 14 % v/v.
iv) Beyond around 60 m from the landfill the concentrations of carbon dioxide reduce to the range 0 – 4 % v/v.

v) Gas flow rates in all external boreholes, whether methane is present or not, fluctuate in the range -8 l/hr to +19 l/hr.
vi) The fluctuating composition of the ground gases correlates closely with changes in barometric pressures. During periods of rising barometric pressure oxygen concentrations in the ground are seen to rapidly rise and carbon dioxide levels rapidly fall. When the barometric pressure drops the reverse occurs with ground gases rich in carbon dioxide and low in oxygen flowing out of the opened valve of any monitoring borehole.

Barometric Pumping - General

- At this example site the ground gas regime external to the landfill is strongly influenced by the effects of atmospheric pressure changes, a phenomenon referred to in the literature as Barometric Pumping [refs 1 – 9].
- The effect is generally associated with the presence of an unsaturated zone where there are voids in the subsurface strata such as in granular soils (e.g. sands / gravels), fissured rock or mineworkings. Its effect is enhanced where the surface is covered by a low permeability soil (e.g. clay). The enhancement effect can be transient, i.e. when rainfall periodically wets the overlying soil making it less permeable.
- The phenomenon occurs naturally, i.e. whether or not a landfill is present.
- The phenomenon may often have a very limited effect, e.g. where the subsurface strata have a low porosity and/or the unsaturated zone is thin.
- As can be seen in Fig CS1.3 above, the effect is most pronounced where large and rapid changes in barometric pressure occur, giving rise to greater pressure differentials between that in the atmosphere and that exhibited by the ground gas.
- The Barometric Pumping effect results in cyclical flows of gas between the atmosphere and ground. This induces complex three dimensional subsurface flow patterns as the gas flows in and out of the ground at points where the cover soils have a lower permeability, are absent or are penetrated for example by a well or service trench.
- The cyclical gas ingress / egress pattern can affect the composition of the ground gas in a direct and indirect way. It directly results in the dilution of the ground gases by air which is rich in oxygen and nitrogen.
- Indirectly, the injection of oxygen into the ground can induce significant biological activity which gives rise to the production of high concentrations of carbon dioxide in the ground gas. There are three likely biogenic mechanisms for this, which may be acting separately or in conjunction with each other. These are:
  i) the microbial degradation of organic materials in the cover soils and/or in the unsaturated zone;
  ii) carbon dioxide emissions from the roots of plants into the soil which are then flushed into the underlying porous strata during the barometric pumping cycle (a soil in the UK can produce in the range 30 – 190 m^3 of carbon dioxide per hectare per day [ref 10]);
  iii) It may also be produced as a result of the oxidation of one or more sources of methane in the ground gas (e.g. landfill or other biogenic gas, geogenic and thermogenic sources);

- The degree of biogenic activity affecting the ground gas composition is most simply observed by high carbon dioxide and low oxygen concentrations in gases emitted from the ground during part of the barometric pumping cycle. It is also evidenced by high nitrogen to oxygen (N_2/O_2) ratios. A N_2/O_2 ratio higher than that found in air is indicative of preferential removal of oxygen compared to nitrogen, after air is drawn underground by the Barometric Pumping effect and biogenic activity takes place.
- The high carbon dioxide, low oxygen conditions are transient, as following the next barometric cycle air is introduced back into the ground and the situation reversed. It is a common misconception that high oxygen levels in a ground gas are indicative of a poorly constructed monitoring borehole, although this can be the case if a proper well seal has not been demonstrated. It is often due instead to the barometric pumping effect introducing air into the ground (see Fig CS1.3 above).

Conceptual Model

The ground gas conditions at this Case Study site are summarised as follows;

- At the site, the unsaturated sands in the immediate vicinity of the landfill are subject to the migration of low volumes of landfill gas. Boreholes within a few metres of the edge of the waste record up to 54 % v/v methane to be present.
- Once the landfill gas enters the external ground gas regime the dominant mechanism affecting both the movement and composition of the gas is the barometric pumping effect. This is evidenced by the observed fluctuating, positive and negative changes in ground gas pressures and borehole flows (-8 l/hr to +19 l/hr).
- The introduction of air into the ground by the barometric pumping effect facilitates the rapid oxidation of the methane within around 30 metres of the edge of the landfill.
- Further away from the landfill (>60 metres) site a natural ground gas regime exists, unaffected by the presence of the landfill and also dominated by the barometric pumping effect. This ground composition here is characterised by transient periods where the ground gases contain slightly elevated levels of naturally produced carbon dioxide (up to 3.2 % v/v) and low oxygen, followed by periods when the reverse occurs. Gas flow rates from boreholes are similar to those observed closer to the landfill.
- There is a mixing zone between these two regimes where the ground gas does not have any methane present but periodically contains more elevated concentrations of carbon dioxide resulting from the oxidation of methane closer to the landfill.

References: A selection of papers from the scientific literature describing the Barometric Pumping Effect, oxidation of Methane and Carbon Dioxide production in natural soils

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3. Passive landfill gas emission – Influence of atmospheric pressure and implications for the operation of methane-oxidising biofilters; Julia Gebert, Alexander Groengroeft; Waste Management; 2005
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6. Enhancements for Passive Vapour Extraction: The Hanford Study; Michael G Ellerd et al; Groundwater Vol 37, No 3; 1999
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9. Meteorological factors controlling soil gases and indoor CO2 concentration: A permanent risk in degassing areas; Fátima Viveiros et al; Science of the Total Environment 407 (2009) 1362-1372
10. Currie J.A. (1975) Soil respiration; Soil Physical Conditions and Crop Production; MAFF Bulletin 29, pp 461-468.

CASE STUDY 2 with flow and concentration data
The site is a former brick clay quarry infilled with around 1 million cubic metres of domestic, commercial and industrial wastes. It was operational from the late 1990's through to 2003 and was constructed with full engineered containment, the base and sides being lined with a composite CQA'd liner (1 m clay / FML). Since the end of landfilling the site has been capped and fully restored. Leachate levels are well controlled and in-waste pressure monitoring confirms that negative gas pressures are being consistently maintained by the pumped gas / flaring system.

External ground gas monitoring around the site has been carried out since the commencement of landfilling (and in some cases prior to it). Elevated concentrations of carbon dioxide have been found in almost all the boreholes since monitoring commenced and in a few of them, highly elevated levels of methane.

Environmental and Geological Setting
The quarry was excavated up to 18 m into glacial clays, which has sandy units within it up to and in excess of 1 m thick. At the base of the clays there is a lower sand / weathered sandstone unit overlying sandstones of Permo-Triassic age. Carboniferous coal measures strata are present at depth but no mining extends under the site.

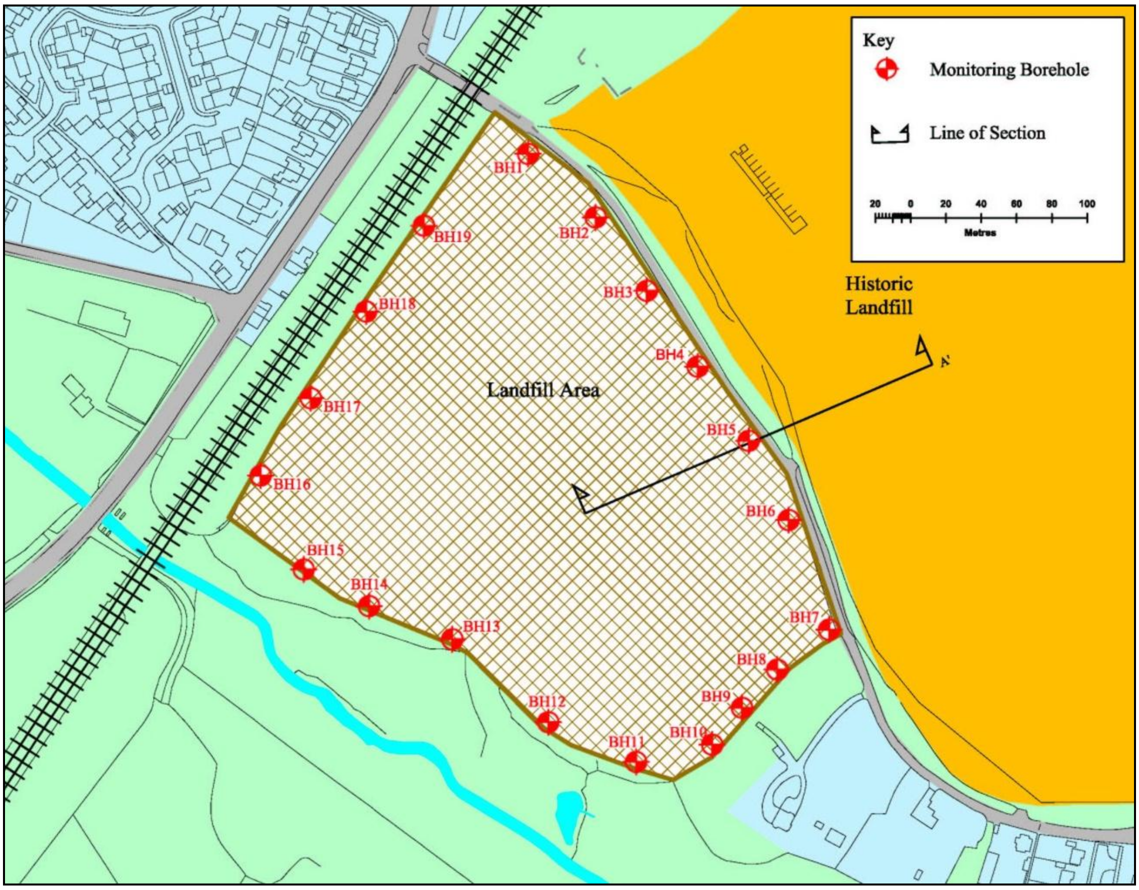

Fig CS2.1. Site plan and borehole locations

Land use in the vicinity is mixed open space, residential and industrial (see Fig CS2.1). Beyond the north-eastern perimeter of the site is a large former local authority landfill which is not lined. A schematic cross section through the site is included as Fig CS2.2.

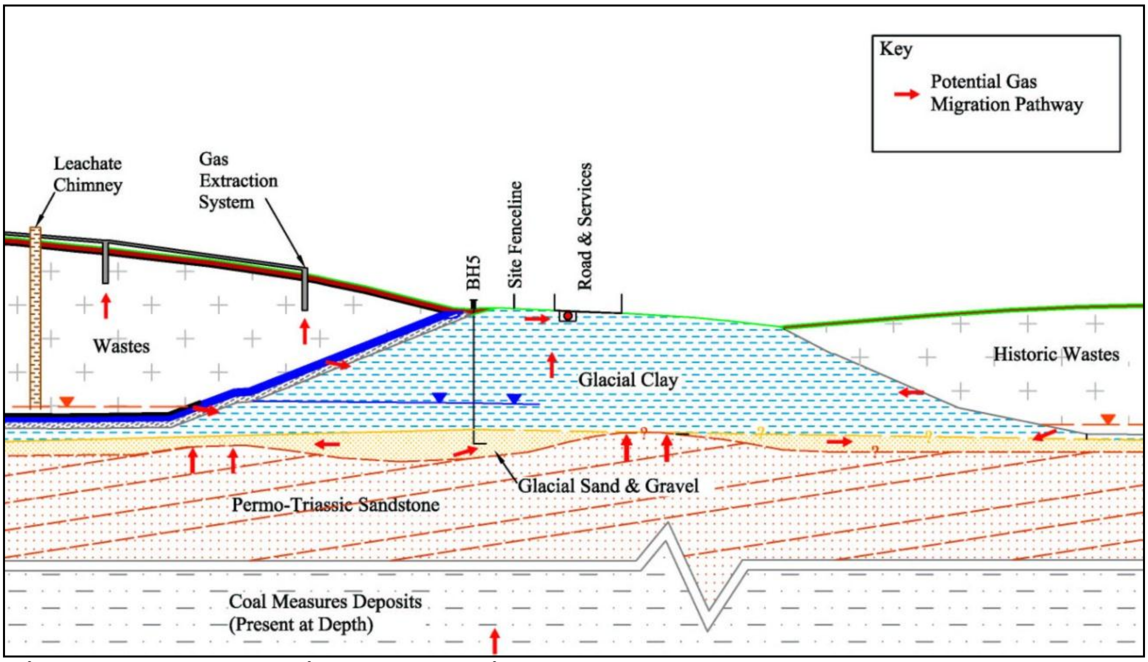

Fig CS2.2 . Schematic cross section and conceptual model

Source Term

Gas production at the site is around 600 m^3/hr with methane concentrations at the flare manifold being maintained in the range 35-55 % v/v (see Fig CS2.3 below).

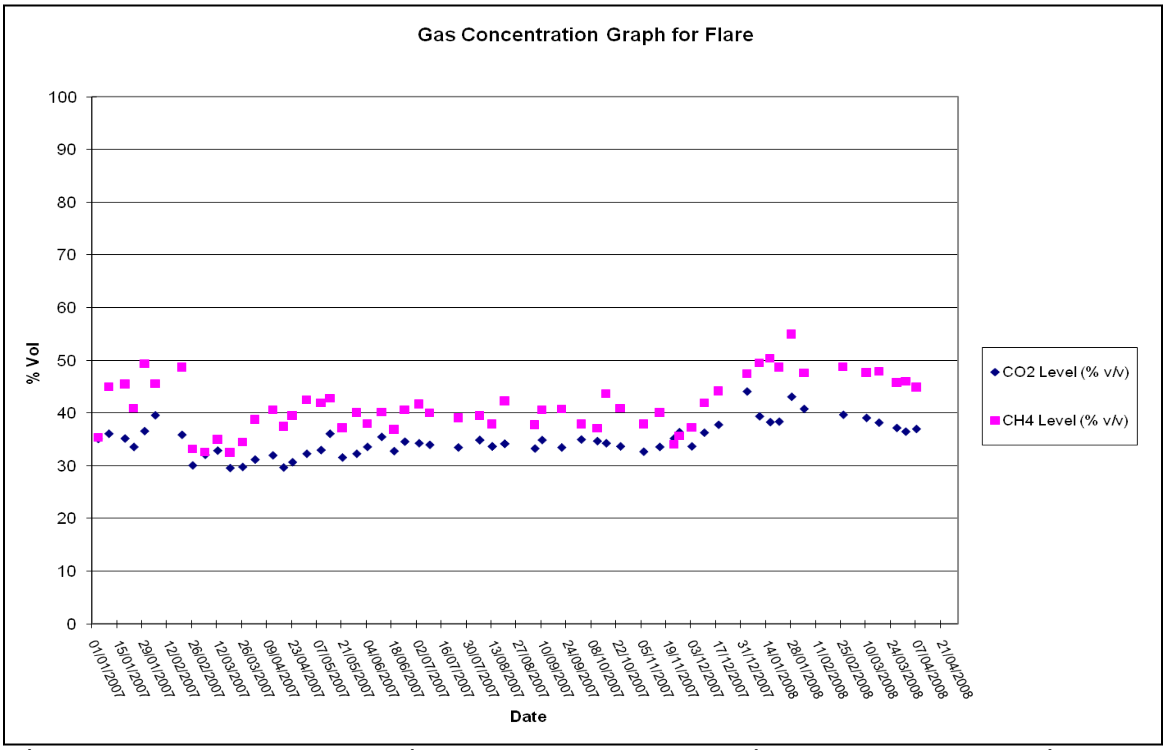

Fig CS2.3 . Gas concentrations at Flare Inlet Manifold - Case Study Site 2

External Ground Gas Conditions
Monitoring of ground gas conditions external to the site has been undertaken weekly since early 1998 via 19 No. monitoring boreholes (see Fig CS2.1 for locations). Some boreholes were monitored prior to landfilling and others before significant landfill gas production commenced. Monitoring of flows from boreholes was carried out from 2006 to 2009.

A summary of some of the main trends is given below.

- Boreholes 1, 7 and 16 were monitored pre-landfilling and recorded elevated carbon dioxide concentrations in excess of 1.5 % v/v but no methane.
- Elevated carbon dioxide levels up to 10 % v/v have been recorded in the majority of boreholes throughout the monitoring period. In some boreholes the carbon dioxide concentrations exhibit a seasonal cyclicity with higher levels being observed during the summer months (see Fig CS2.4 gas concentration graph for BH3).

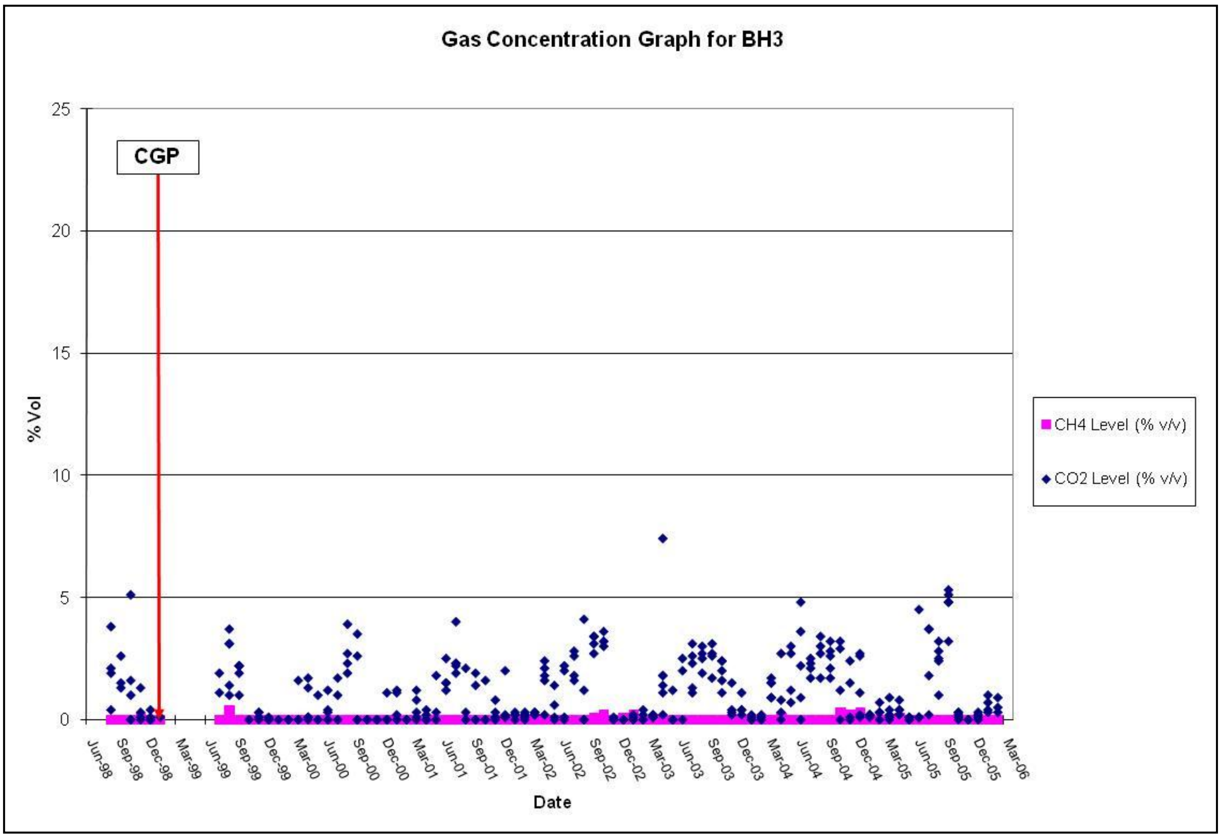

Fig CS2.4 Gas concentration data for BH3

- Many of the external monitoring boreholes recorded elevated concentrations of both methane and carbon dioxide prior to or within six months of the commencement of landfilling, ie before the Critical Gas Production point (CGP) where methanogenesis and significant landfill gas generation occurs. In BH4 and BH12 the methane concentrations reached a maximum of 85.8 % v/v and 48.6 % v/v respectively during this initial period.
- Methane concentrations in BH4 (Fig CS2.5) have been consistently elevated, often exceeding 80 % v/v. In contrast carbon dioxide concentrations in this

borehole have been relatively low with very little fluctuation. Given the close proximity of this borehole to the landfill it is difficult to concieve that the bulk gas trace for this borehole is representative of gas migrating from the landfill. Elevated methane (often in excess of 50 % v/v) has also been recorded routinely in BH12 and BH14. As with BH4, carbon dioxide concentrations have been comparatively low, with only minor fluctuations.

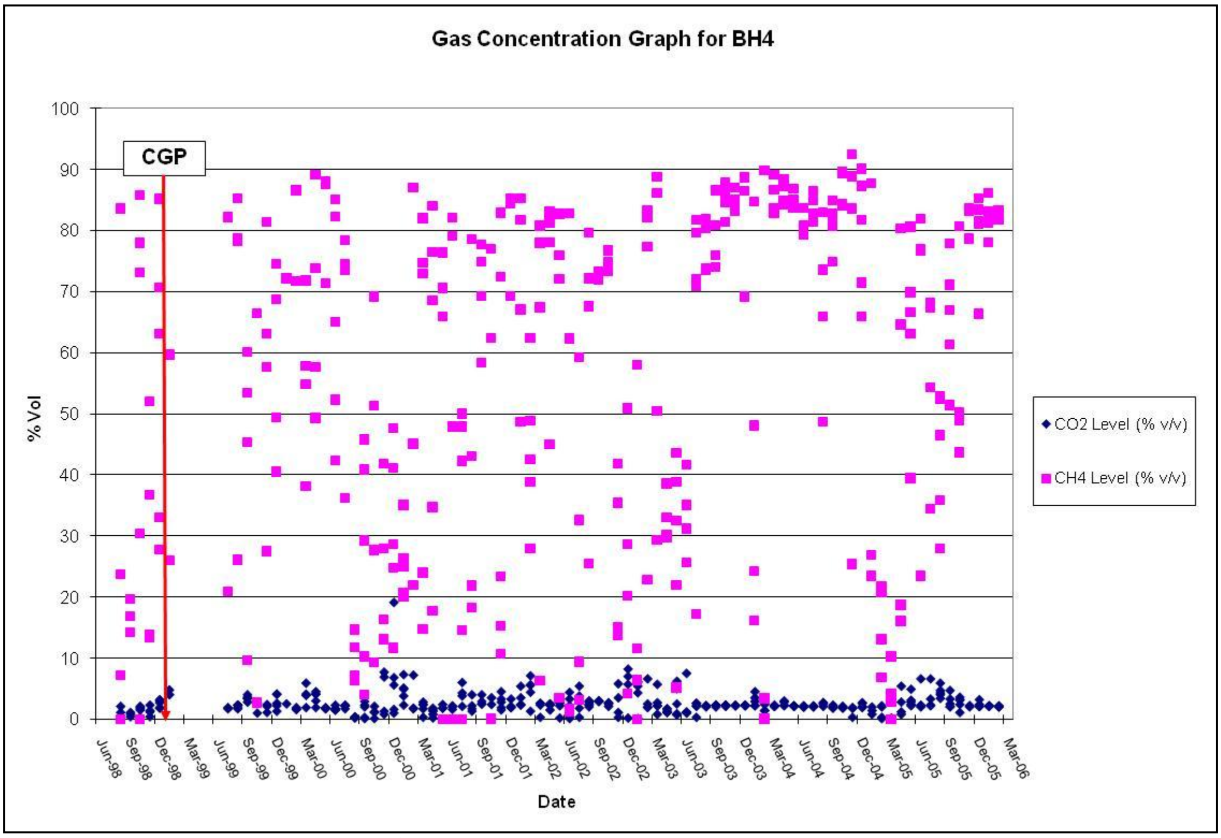

Fig CS2.5 Gas concentration data for BH4

- Trace gas analysis of samples of the methane rich ground gases did not indicate the presence of man made substances (eg chlorinated compounds) which are present in samples of the landfill gas.
- Groundwater sampling indicates that no leakage of leachate is occurring.

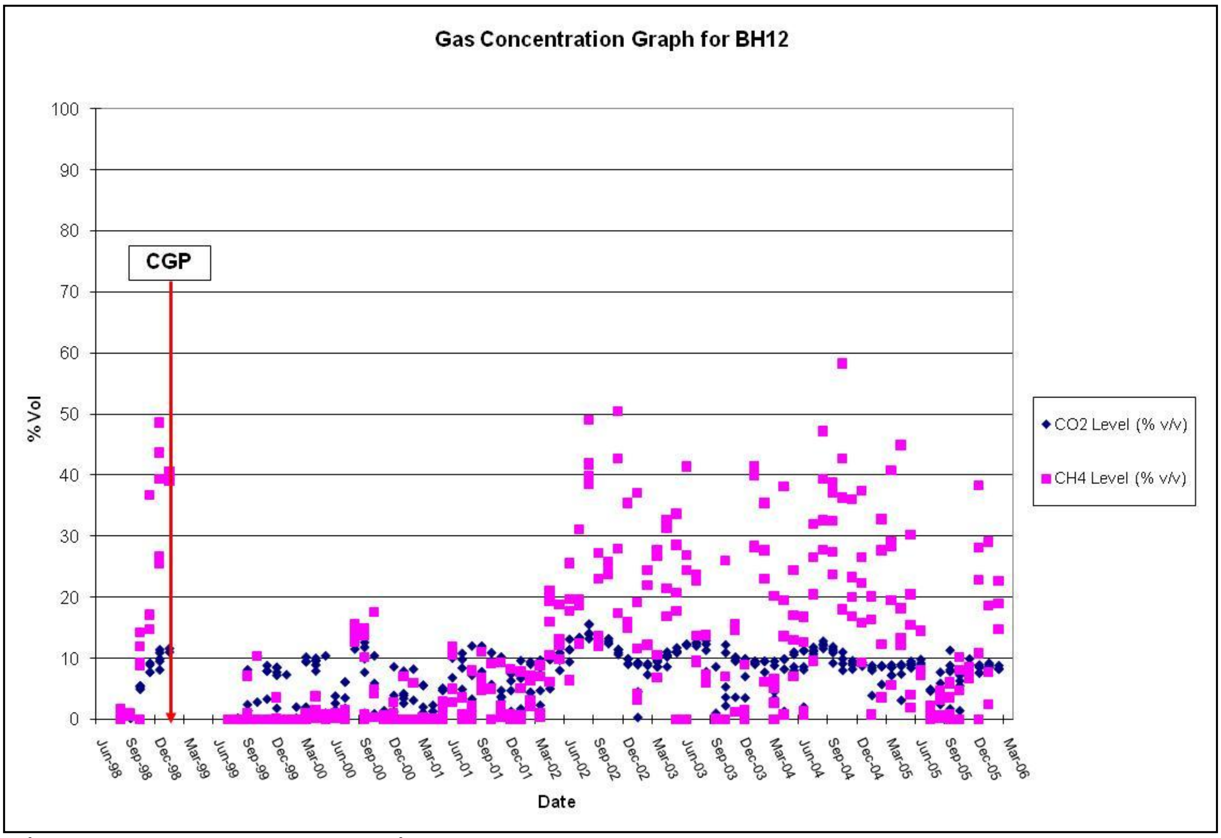

Fig CS2.6 Gas concentration data for BH12

The gas flow data collected during the monitoring period is summarised in Table 1.

Borehole	No. of readings	Average flow rates	
		Max Flow (l/hr)	Min flow (l/hr)
BH1	16	0.7	-0.3
BH2	80	6.6	-4.9
BH3	11	1	-0.5
BH4-4	85	5.1	-4.3
BH5	53	3.5	-1.2
BH6	23	1	<0.1
BH7	30	1.4	-0.7
BH8	69	1.3	-2
BH9	82	1.4	-1.3
BH10	82	1.5	-1.5
BH11	26	1.2	-0.3
BH12	86	1.5	-0.7
BH13	61	3.9	-3.2
BH14	81	>14	-8.1
BH15	73	4.5	-9.8
BH16	45	1.4	-0.6
BH17	18	2.1	-4
BH18	60	1.6	-0.9
BH19	79	1.5	-1

Table CS2/1 Summary of gas flow data collected from perimeter boreholes at Case Study Site 2

As can be seen from the borehole flow data in Table CS2/1, ground gas pressures fluctuate over time with both positive and negative ground gas pressures being observed.

Conceptual Model
A number of lines of evidence indicated that there is a source of methane in the ground gas other than the Case Study 2 landfill site. These include;

i) the presence of methane before gas production from the waste commenced;
ii) the high methane / carbon dioxide ratios in those boreholes where very high concentrations of methane were found (ratios much higher than those measured in the landfill site);
iii) absence of anthropogenic volatile organic compounds in the trace gas fingerprint;
iv) lack of effect of the active gas control system on the external ground gas regime;
v) gas pockets were encountered during the drilling of boreholes into the sands at the base of the clays, indicative of geogenic gases being trapped under the superficial deposits.

Elevated levels of carbon dioxide were also found to be present in those boreholes installed prior to the production of landfill gas from the waste in the Case Study 2 landfill. This was a clear indication that the ground gas regime already contained elevated 'background' concentrations of carbon dioxide. Subsequent monitoring has shown elevated carbon dioxide to be present in most of the boreholes around the site, with concentrations fluctuating on both a seasonal and more frequent basis. Whilst other landfills are present in the vicinity, the absence of methane in most boreholes gives a strong indication that the carbon dioxide is not landfill derived. It is considered that its widespread occurrence in the external ground gases are as a result of natural biogenic activity in combination with the barometric pumping effect.

The conceptual model for the ground gas regime is that there is a geogenic source of very high concentrations of methane which collects in sand units at depth. In respect of carbon dioxide it is considered that there is a non-landfill, natural biogenic source present. It cannot be fully discounted however that there is a minor contribution to the local ground gas regime from the adjacent local authority landfill and/or as result of diffusion through the site's engineered containment lining system.

The movement of gases in the unsaturated zone external to the landfill is influenced in part by the barometric pumping effect. This induces pressure gradients which is evidenced by positive and negative flows from the monitoring boreholes when the sampling valves are opened. At depth, in the saturated zone, the regime is different. The groundwater table (or more correctly the groundwater pressure level) extends into the superficial clays and conditions can best be described as sub-artesian. As a result the geogenic sourced methane is present as pressurised pockets or bubbles of gas trapped under the clays.

Gas Screening Values
Notwithstanding that the conceptual model for the site did not envisage that there was a risk to receptors from landfill gas migration, the concentrations of methane and carbon dioxide present in the ground would be hazardous to humans were the ground gas to migrate into a confined space.

Consideration was therefore given to evaluating the risk to receptors in the locality arising from the ground gas regime as it exists outside the landfill site. To assist this process reference was made to guidance prepared for assessing risks from hazardous ground gases on brownfield land development sites (CIRIA C665, 2007 and BS8485:2007). This guidance proposes the use of GSV's (Gas Screening Values) which takes account of both the concentration and flow of gas from a borehole to give a semi-quantitative means of characterising risk. In BS8485:2007 the concept of hazardous gas flow rate (Q_{hg}) is used which is synonymous with CIRIA's GSV approach.

BH Ref.	Flow (l/h)	CH_4 (% v/v)	GSV - CH_4 (l/hr)	Characteristic Situation	CH_4 Risk Class'	CO_2 (% v/v)	GSV - CO_2 (l/hr)	Characteristic Situation	CO_2 Risk Class'
BH1	0.7	0.1	0.0007	1	Very Low	4.0	0.028	1	Very Low
BH2	6.6	<0.1	0.0066	1	Very Low	15.9	1.0494	3	Moderate
BH3	1.0	<0.1	0.001	1	Very Low	4.3	0.043	1	Very Low
BH4	5.1	<0.1	5.0694	4	Mod to High	7.2	0.3672	2	Low
BH5	3.5	<0.1	0.0035	1	Very Low	5.4	0.189	2	Low
BH6	1	0.1	0.001	1	Very Low	5.6	0.056	1	Very Low
BH7	1.4	<0.1	0.0014	1	Very Low	4.8	0.0672	1	Very Low
BH8	1.3	0.5	0.0065	1	Very Low	17.0	0.221	2	Low
BH9	1.4	0.1	0.0014	1	Very Low	7.4	0.1036	2	Low
BH10	1.5	13.2	0.198	2	Low	13.0	0.195	2	Low
BH11	1.2	0.1	0.0012	1	Very Low	3.4	0.0408	1	Very Low
BH12	1.5	67.9	1.0185	3	Moderate	11.3	0.1695	2	Low
BH13	3.9	<0.1	0.0039	1	Very Low	8.9	0.3471	2	Low
BH14	>14	83.6	>11.704	4 (minimum)	Mod to High	9.1	>1.274	3 (minimum)	Moderate
BH15	4.5	0.1	0.0045	1	Very Low	4.1	0.1845	2	Low
BH16	1.4	0.1	0.0014	1	Very Low	3.6	0.0504	1	Very Low
BH17	2.1	<0.1	0.0021	1	Very Low	3.9	0.0819	1	Very Low
BH18	1.6	3.6	0.0576	1	Very Low	4.4	0.0704	2	Low
BH19	1.5	0.1	0.0015	1	Very Low	5.7	0.0855	2	Low

Table CS2/2. Summary of GSVs generated for Case Study Site 2

GSV's were calculated by taking the worst case gas conditions (concentration and flow) recorded in the previous two years monitoring for both methane and carbon dioxide. The GSV's generated for each borehole are summarised in Table CS2/2 above together with the corresponding Characteristic Situations and Risk Classifications (as given in CIRIA C665, 2007).

From Table CS2/2 it can be seen that the highest risk classifications ('moderate' or more) were associated with BH2, BH4, BH12 and BH14. In none of these boreholes was the gas considered to be originating from a landfill source. Despite this, the generated GSV's were still a useful tool in the risk assessment process as, amongst other things, they provided a simple means of identifying and targeting the areas of greater risk.

Commentary on use of GSV's in landfill site gas risk assessments
The introduction of the use of risk based assessment criteria for evaluation of ground gas monitoring data by CIRIA and in BS8484:2007 is potentially a very useful tool to the landfill gas risk assessor. A GSV value provides a much better understanding of the hazard associated with the presence of the gas in the ground when compared to the historical practise of assessing ground gas concentration data only.

Although ground gas concentration measurements are relatively simple to make there are severe limitations in interpreting such readings in anything but an extremely conservative way. At many sites, the high and variable background concentrations of methane and carbon dioxide in the ground gas environment render impractical the use of concentration based management and regulatory assessment criteria, even if statistical methods are used to interpret the data.

The GSV value better characterises the hazard as it incorporates within it an indication of both its hazardous properties and its ability to migrate in sufficient quantities to realise the hazard.

The CIRIA GSV and BS8485:2007 guidance documents are however prepared mainly for use by the construction industry when considering the risks associated with development on brownfield sites. Whilst these documents do address landfill gas risks some caution is required when attempting to allocate the GSV based risk ratings for brownfield development sites used in these documents, to receptors immediately adjacent to large gassing landfill sites. Indeed the CIRIA guidance notes that it "is not designed to address the issues associated with landfill gas derived from licensed landfills..". However, as a concept the use of GSV's to support landfill gas risk assessments has great potential provided due consideration is given to the conceptual model. For landfill sites, the main source-pathway-receptor characteristics and linkages that are different to those typically considered when redeveloping brownfield sites are summarised as follows;

- significant changes in gas production over the full operational and post closure life of the site;
- the use and operation of active gas control systems;
- other time variable events such as capping of cells and changes in leachate heads
- the pathway(s) are longer and subject to change over time;
- receptors may not just include above ground built development close to the landfill boundary. Other receptors such as underground confined spaces (eg culverts, underground services and soil/vegetation) have to be taken account of in the risk assessment if they are present in the locality.

Taking the above points into consideration however, experience of using the GSV approach to date has shown that some valuable insights can be gained into the risks associated with the presence of methane and carbon dioxide in the ground external to a landfill site. To do this it is necessary to take account of the different characteristics of the landfill environment and make conservative assumptions where uncertainty exists.

It is recommended that the landfill industry commence borehole flow monitoring (and if possible ground gas pressure monitoring) at a range of landfill sites and start to use the GSV approach to support their landfill gas risk assessments. In taking this approach consideration should be given to the following;

- appropriate design and construction of monitoring boreholes which are to be used for flow / pressure monitoring;
- training of monitoring staff and adoption of quality procedures to ensure that high quality data is collected;
- developing an understanding of the background ground gas pressure regime and the effects of natural variations eg due to barometric pumping;
- developing an understanding of how the ground gas flow / pressure regime is incorporated into the conceptual model for the site.

Initially it is recommended that GSV's are used in conjunction with other quantitative and qualitative assessment criteria to evaluate the risks to receptors adjacent to landfill site. It is particularly useful when there is uncertainty as to the source of a particular gas found in a borehole. In these circumstances, if the GSV based risk assessment demonstrates that the risk to receptors is low then it gives the regulator and landfill operator more confidence that a harmful emission to the environment is not occurring.