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Guidance on monitoring landfill gas surface emissions

LFTGN07 v2 2010

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The Environment Agency. Out there, making your environment a better place.

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Foreword

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This second edition of LFTGN07 was the result of a collaborative review involving the Environment Agency, SEPA and representatives of the landfill gas industry forming a sub-group of the Environment Agency and Environmental Services Association Landfill Regulation Group. The authors would like to thank all parties who contributed to this review.

This guidance is one of a series of documents relating to the management of landfill gas. It is intended for use in the assessment of methane emissions from the surface of permitted landfill sites in England and Wales. It is issued by the Environment Agency as best practice guidance and will be used in regulation of landfills.

This guidance is intended for Environment Agency officers to use in regulatory and enforcement activities. It will also be of use to the waste industry and contractors, consultants and local authorities concerned with landfill gas emissions. Any exemption from any of the requirements from other legislation is not implied.

Contents

Executive summary

Landfill operators need to monitor methane emissions through the cap of a landfill as an integral part of demonstrating compliance with the Landfill Directive, and in particular to:

- identify faults in the gas management system at a site and prioritise the remediation required;
- quantify the total emissions of this important greenhouse gas from the areas measured.

This guidance applies to:

- filled and restored phases of an operational or closed landfill with a permanent cap;
- temporarily capped zones of an operational landfill not currently accepting wastes and not expected to do so within three months.

The monitoring of emissions through a landfill cap has two stages.

- Initially, a simple survey demonstrates whether there are inadequacies in the gas containment and collection system. Only when these deficiencies have been located and remedied such that the concentration of gas above the surface is low is it appropriate to begin a quantitative survey of surface flux.
- Subsequently, the flux of methane emitted through the intact cap is measured at a number of representative points using an array of flux boxes. From these individual measurements, we can calculate the average flux from the capped zones. This identifies where the gas flux exceeds an emission standard set by the Environment Agency.

The first stage

The main characteristics of the cap are recorded and mapped in a desk study and a walkover survey is conducted to identify where emissions of methane are high. A sensitive, hand-held gas detector, such as a flame ionisation detector (FID), is used in the walkover to scan the air close to the surface of the cap and thus detect significant concentrations of methane.

The walkover survey should be systematic and give a semi-quantitative ranking of the methane emissions from various features. These faults in the gas management system should then be remediated and the cap resurveyed to identify further features that may need to be rectified.

Monitoring will not normally proceed to the quantitative flux survey until a systematic walkover survey demonstrates that the concentration of methane in the air is:

- less than 100 parts per million by volume (ppmv) immediately above the surface on the main zones of the cap;
- less than 1,000 ppmv close to any discrete feature such as a leachate well or wellhead.

The second stage

A landfill surface should be in a condition suitable for a quantitative flux box survey within one year of capping. Temporary capped areas will also need to be monitored if they have been in place or are intended to be in place for longer than 12 months. Based on the walkover survey, divide the capped area into zones, in which there may be individual features.

- A zone is an extensive area of landfill cap that is generally uniform and homogeneous.
- A feature is a smaller, definable area or installation from which methane emissions are higher than in the adjoining or surrounding zone.

Flux measurements should generally be subject to the following constraints:

- selected geometric patterns applied consistently, with visually obvious emission features assessed separately so that remedial actions can be targeted at them;
- take no measurements immediately after a prolonged period of heavy rainfall or where there are areas of standing surface water;
- barometric pressure must not be very much higher or very much lower than the average for that area and, ideally, should not be rising quickly.

Flux boxes must be sealed on the surface at a number of representative sampling locations within each zone and feature. The rate of change in methane concentration within each box is measured for up to an hour and the flux of methane from that part of the surface is calculated. Calculate an average flux of methane from the zone or feature from the rates measured by individual flux boxes.

Our standards for gas emission from a landfill surface are expressed as the average flux of methane from the surface of the cap in each zone.

The emission standards are:

- permanently capped zone: 0.001 mg/m^2/second
- temporarily capped zone: 0.1 mg/m^2/second.

The assessment is made on the average flux from measurements at an array of several points across the zone. Where a discrete feature within the zone is identified, this is not included in the main flux box array of the zone and the emissions from this feature are calculated separately. The average emission across these identified features must also comply with the standard applying to the associated zone.

The total emission rate of methane from a zone is calculated by multiplying the average flux by the area of the zone. The overall emission rate of methane for the site is the sum of emissions from the surface of each zone and feature. This value may be used in estimating the gas collection efficiency of the site. The annual emission rate may be used in computing or validating the site's Pollution Inventory.

Frequency of monitoring

Survey following cap construction

Undertake the first flux box survey within a year of capping.

If the initial quantitative flux box survey indicates that the zone does not comply with the emission standard, further remedial work must be undertaken and checked by an appropriate survey. You must then undertake a full flux box survey within a year of the initial quantitative survey and then annually until it can be demonstrated that the system is under control and the cap is compliant.

Subsequent surveys

If a capped zone has previously shown compliance with the emission limits and there have been no significant physical changes in the gas management during the year, use a detailed annual walkover survey to demonstrate that the surface emissions are compliant. If these surveys show no change in the pattern of methane emission, the values for flux and total methane emissions measured in the initial survey may be reported and a fresh flux box survey is not necessary.

If the zone remains stable, we will accept the results of these full walkover surveys as part of the submission for the site. In conjunction with this annual walkover, you must undertake regular monitoring of all above ground infrastructure on site. The time interval will be site specific, but must be at least quarterly.

Temporary capped areas

We will only require a flux box survey on areas of temporary cap that have been in place or are intended to be in place for longer than 12 months. Areas of temporary cap less than 12 months old will need to demonstrate compliance with surface concentration limits using regular quarterly walkover surveys.

Remediation plans

If any zone or feature is found to be non-compliant, use the results of the surface emission survey to review the overall gas management plan:

- The plan must prioritise actions to remedy the main emissions and bring the whole capped area of the landfill site within the emission standard.
- It must indicate how you will identify local emission sources, quantify them and, if necessary, remediate.
- If the survey has identified variability in the cap and a high uncertainty in the calculation of flux, the plan must recommend an improved monitoring procedure for subsequent surveys.

This guidance is concerned with minimising the global impact of methane emissions. Sulphur-containing compounds and trace components in landfill gas may cause odour problems even where the surface emission standard is met. You will then need additional controls. Greater control of emissions will be required if a site-specific risk assessment indicates a potential impact on health or amenity at a local receptor.

Reporting to the Environment Agency

You must present the results of the annual emissions survey (whether quantitative or walkover), the remediation plan and any remedial work to reduce emissions to us in a standard format (see Appendix B).

We will assess:

- the appropriateness of monitoring for the particular zones;
- compliance with the emission standards ;
- total methane emission from the zoned areas of site ;
- adequacy of the remedial action plan (where appropriate);
- the timescale for testing after any remedial work.

1 Introduction

1.1 Purpose of this technical guidance

We have produced this document to assist our regulation of methane emissions from the surface of landfills. We recommend a standard set of monitoring methods for collecting emissions data in a valid, transparent and consistent manner such that:

- the gas management system can be assessed regularly;
- annual emissions of methane through the capped areas of the site can be quantified.

The information on the emissions of methane obtained through this surface monitoring is an integral part of demonstrating compliance with your EPR permit for the site, and Article 1 of the Landfill Directive. In particular, we use it to:

- identify faults in the site's gas management system and to prioritise the remediation required;
- quantify the emissions of this important greenhouse gas from capped areas of the site.

The guidance applies to:

- filled and restored phases of an operational or closed landfill with a permanent cap;
- temporarily capped areas of an operational landfill not currently accepting wastes and not expected to do so within three months.

Uncapped operational areas are not included in this guidance on monitoring, but are subject to best practice in gas management (Environment Agency, 2010). This guidance is not written for the measuring of emissions from outside the permanent or temporary capped landfill areas.

This is one of a series of linked documents that support the overarching document Guidance on the management of landfill gas (Environment Agency, 2010). The full series comprises:

- Guidance for monitoring trace components in landfill gas;
- Guidance for monitoring enclosed landfill gas flares;
- Guidance for monitoring landfill gas engine emissions;
- Guidance for monitoring landfill gas surface emissions;
- Guidance on gas treatment technologies for landfill gas engines.

For closed sites where an Environmental Permit remains in force, we will require the operator to produce a landfill gas emissions review. The review will be based on the development of a risk screening/conceptual model of gas management for the site. Where the review identifies unacceptable site-specific risks from landfill gas, an emissions improvement programme should be prepared incorporating the appropriate best practice contained within this guidance. Implement an emissions review according to the site-specific risk and as soon as is practicable.

1.2 Structure of this guidance

This document has four main sections:

- **Context**. Section 2 provides information on the background to this guidance and an overview of emissions assessment.
- **Walkover survey procedures**. Sections 3 and 4 cover the desk study and initial surface scanning, and any remedial actions arising from these tasks.
- **Flux box survey**. Sections 5, 6 and 7 describe the procedures for quantifying surface emissions and processing data.
- **Interpretation and reporting**. Sections 8 and 9 address the interpretation of the data, compliance with emission standards and the assessment of necessary remedial action.

The appendices contain information on the design of a simple flux box, how to calculate the flux, sources of error, report formats and methods of surface scanning.

2 Background

2.1 Regulatory framework

The Landfill Directive 1999/31/EC specifies the technical standards covering aspects of the construction, operation, monitoring, closure and surrender of landfills. The Directive is applied in England and Wales through The Environmental Permitting (England and Wales) 2007 Regulations. In Scotland the requirements of the Directive are applied through the Landfill (Scotland) Regulations 2003.

The Landfill Directive, requires the following gas control measures:

- appropriate measures to control the accumulation and migration of landfill gas;
- landfill gas must be collected from all landfills receiving biodegradable waste and the gas must be treated and, to the extent possible, used;
- the collection, treatment and use of landfill gas in a manner which minimises damage to or deterioration of the environment and risk to human health;
- flare landfill gas that cannot be used to produce energy.

Our strategy for landfill gas control is based on regulating the emissions of landfill gas to minimise environmental impact or harm to human health. A fundamental part of this process is quantifying methane emitted from the surface of landfills. Detailed guidance on the management of landfill gas is available (Environment Agency, 2010).

2.2 Emission of gas through the landfill surface

Landfill gas is produced continuously by microbes acting on buried organic waste. The timely installation of an active landfill gas collection system at modern, engineered landfills minimises the proportion of the raw gas that can escape to the wider environment.

Methane is a major constituent of landfill gas and has a global impact as a greenhouse gas. The gas management systems at a landfill site must minimise the total emissions of methane to the atmosphere. In collaboration with Biffaward and Shanksfirst, we have undertaken work to identify the main emission points of landfill gas and how these can be managed and minimised (Environment Agency, 2003). Frequent monitoring of the site infrastructure ensures continuous control of the landfill gas (Environment Agency, 2010).

This guidance deals with the regular checks necessary to demonstrate active gas management at landfills is minimising the release of untreated gas by achieving the emission standard for methane through the surface of the landfill cap. The guidance describes:

- methods for quantifying the residual flux of methane through the surface covering of the landfill after waste deposits have ceased and temporarily capped zones of an operational landfill not currently accepting wastes and not expected to do so within three months;
- a mechanism for identifying faults in the control of surface emissions;
- a means of quantifying the overall emission of methane through the landfill cap.

Flux box surveys are compliance checks and give no indication of short-term fluctuations in performance. You should use regular walkover surveys to identify areas of high methane emissions and other regularly monitored parameters, such as the total methane extracted by the gas management system to assure performance is maintained between surveys.

This guidance does not address the local impact of odours or trace components of gas; these must be dealt with through a site-specific risk assessment (Environment Agency, 2010) and a gas management plan.

2.3 Surface flux measurement

Landfill gas escapes through any faults in the capping or the gas collection system. If the cap is intact, smaller quantities of gas will still escape through the permeable material that covers deposited waste. Some parts of the capping (such as side slopes) are often more permeable than the main part of the cap. Gas will also be lost laterally into the adjoining ground through any faults in the liner: this guidance does not address losses through lateral migration.

The total emission through the capped surface of the landfill is the sum of emissions from:

- extensive, diffuse sources such as areas of poor quality capping;
- discrete features such as minor fissures/discontinuities in that capping;
- leaking gas wells;
- faulty pipes;
- poorly sealed leachate chambers.

Flux box

A flux box is an effective technique for measuring normal surface emission through a landfill cap (Bogner et al., 1997). We do not recommend other direct methods for measuring methane surface emissions (such as depth/concentration profiling) because they involve assumptions and parameters that can rarely be measured adequately in the field.

A flux box is an enclosed chamber (see Figure 2.1) in which changes of methane concentration above a specific, small area are measured over time in order to quantify the rate of emission at that location. A flux tent is a similar device that covers a larger sample area. However, the tent requires careful use to ensure the large, enclosed volume is mixed adequately and encloses a consistent volume during sampling.

By taking measurements at a number of representative places using a flux box, it is possible to calculate an emission rate for individual zones and hence emissions for the entire capped area of the landfill site. The methodology is simple, quantitative and repeatable at a particular location, and many individual locations can be measured in one day.

Figure 2.1 A typical flux box and methane detector set up for field measurements

The surface flux is calculated directly from the rate of change in methane concentration within the flux chamber. The method gives the actual emission rate from the particular surface over which the flux box is placed. This measurement does not require information on site variables such as soil physical parameters and prevailing meteorological conditions.

The individual flux measurements are easy to calculate, but making the sampling points representative of the zone as a whole requires judgement and is dealt with in detail in this guidance.

Quantifying the total surface emission from the landfill site depends on representative data from several sampling locations which, when aggregated, provide a balanced contribution from the various zones and surface features.

2.4 Zones and features

The physical properties of areas on a landfill surface vary and these will change with time as a site develops. In addition, there will be intrusions through the cap for installations necessary for managing gas and leachate.

For the purposes of monitoring surface emissions, the capped area of the landfill should be divided into a few large zones, in which there may be a number of small features with distinctly different characteristics:

- **A zone** is an extensive area of the landfill site surface that is generally uniform and homogeneous in those factors that affect surface emissions (for example, type of capping, slope, surface integrity). The main types of zone are landfill areas with a permanent cap and those with a temporary cap:
  - Permanently capped zone: an area that will not receive any further waste. It should have final capping in place and a gas control system installed (Environment Agency, 2010).
  - Temporarily capped zone: an covered area that will not receive any further waste for a period of at least three months, but for engineering reasons does not yet have a permanent cap (such as, capping may be temporary until adjacent cells are filled to final levels).
- **A feature** is a smaller, discrete area or an installation from which methane emissions are different from the adjoining or surrounding zone (they are usually higher). It should have visibly different properties from the rest of the zone or be clearly revealed through detection of a relatively high flux at a group of adjacent sampling points.

A feature is the smallest unit over which a surface emission can be reported. The minimum dimension of a feature is the area of a flux box, but to be of use in directing remedial work, the feature must be a definable area with particular characteristics.

Some discrete features (like leachate wells) can be explicitly defined, whereas other features such as a fissured area are less exactly specified. Some may occupy a small area, but have a high emission rate (for example, a well seal), while other features may have a moderate emission rate but cover a wide area (for example, part of a side slope).

Zones and features are detailed further in Section 5.3.

2.5 Emission standards

The emission standards for capped zones are given in Table 2.1. You must monitor identifiable features within a zone separately to avoid obscuring the impact of a definable fault in the average flux for a large zone.

The value for a permanently capped zone given in Table 2.1 reflects the results of monitoring at a series of landfill sites with good, engineered caps and an efficient gas abstraction system (Environment Agency, 1998, 2001). Even with a gas abstraction system in operation, it’s not reasonable to expect the same degree of surface emission control for temporarily capped zones. We have therefore selected a higher emission standard for zones with a temporary or interim cap, but this value is only applicable for the period before this cap is made permanent.
The assessment is made on the average flux from measurements at an array of several points across the zone. The flux at individual monitoring points in the array may thus exceed the standard, but the zone is compliant provided the average flux is below the standard.

Table 2.1 Emission standards for different types of landfill zone

Type of zone	Surface emission standard
Any zone with permanent cap	Methane flux of 0.001 mg/m^2/second
Any zone with temporary or interim cap	Methane flux of 0.1 mg/m^2/second

Where you identify a discrete feature within a zone, exclude it in the main flux box array of the zone. Calculate the emissions from such features separately. The average emission across the feature must also comply with the standard applying to the associated zone.

2.6 Walkover surveys and remedying faults

Surface emissions through the main zones can not be quantified adequately if gas is escaping through major faults in the cap or the gas collection system. Uncontrolled emissions of this type lead to the release harmful gases. These should be at a minimum on a well managed site. It is therefore essential to identify inadequacies in the gas management system and rectify these before attempting to measure the predominantly diffusive flux of gas emitted though the well-capped surface.

Major faults are easy to find using simple hand-held instruments that measure gas concentrations. You can find lesser faults through a systematic walkover survey while using a hand-held instrument for detecting low concentrations of hydrocarbon gas in air.

Remedying the emission of gas through these features on a capped zone must be a short-term action within your overall gas management plan. You must complete remedial work to prevent significant concentrations of gas being found near the surface before beginning a flux box survey.

2.7 Emission assessment procedures

As shown in Figure 2.2, the overall emission assessment procedure has two main stages.

In the first stage, carry out a desk study to determine the main characteristics of the cap. Use this information to then guide a walkover survey of the cap using hand-held gas monitoring equipment to identify where methane emissions are high.

Experience of carrying out flux box surveys, supported by the waste industry's experience has shown that the walkover survey is the most cost effective means of reducing surface emissions through the landfill cap. The ability to undertake the survey at short notice, with limited resources and costs, makes this a suitable method for identifying uncontrolled landfill gas emissions.

In the second stage, use an array of flux boxes to quantify the rate of emission through capped zones and from identifiable features within the cap. You can then assess the average emission from the whole zone against the relevant standard.

You are required to initially quantify the surface emission of methane from permanently capped areas of your site using a flux box survey as part of a 'mass balance' approach to reporting methane emissions and to demonstrate that the permanent cap meets the emission standard.

However providing subsequent annual walkover surveys of that area demonstrate the surface concentration limits in air are less than 100 parts per million by volume (ppmv) immediately above the surface on the main zones of the cap and less than 1,000 ppmv close to any discrete feature, you do not need to carry out subsequent flux box measurements to quantify emissions. Further details of the approach are given in Section 8.7.

If regular walkover surveys show that the emission of gas is increasing, or you make significant changes to the gas extraction in a permanently capped area, then another flux box survey will be required to quantify the emission rate. For example, if the extraction system has deteriorated or you think that gas production in an area has declined to such an extent that extraction is no longer viable you will need to carry out a flux box survey to ensure that the emission standard is still met.

Temporarily capped areas do not need to be quantified using flux box surveys unless the temporary cap will be in place for longer than 12 months (for example on a long term internal flank). For shorter periods of temporary capping, regular walkover surveys should demonstrate compliance with the surface concentration limits in Section 4.6. Use the emission rate limits in Table 2.1 to calculate the annual emissions from temporarily capped areas.

Leachate wells and similar infrastructure are often major sources of methane emissions, but are difficult to quantify using flux boxes. However you must quantify or estimate the emissions from these features and include the results in your reporting.

2.8 Health and safety issues

The Environment Agency does not regulate health and safety at work. We've issued this guidance as advice to those we require to carry out work as part of a site's monitoring activities. The Health and Safety Executive (HSE) deal with any health and safety issues relating to on-site working. In addition to conforming to any site requirements, all work must be undertaken in accordance with all applicable health and safety legislation.

The Dangerous Substances Explosive Atmosphere Regulations 2002 (DSEAR) implement the two European ATEX (explosive atmospheres) Directives; ATEX 94/9/EC and ATEX 1999/92/EC in the UK. This legislation aims to protect workplaces from the risk of fire and explosion from the presence and use of dangerous substances. DSEAR came into effect on 1 July 2003

Landfill gas is flammable, therefore under DSEAR landfill operators must carry out a risk assessment of their sites and identify any areas where an explosive atmosphere could be formed. These areas are then classified as hazardous zones depending on the probability of an explosive atmosphere being formed. DSEAR then restricts the equipment that can be used in these hazardous zones. Only equipment certified to the appropriate ATEX category for the zone classification can be used within a hazardous zone.

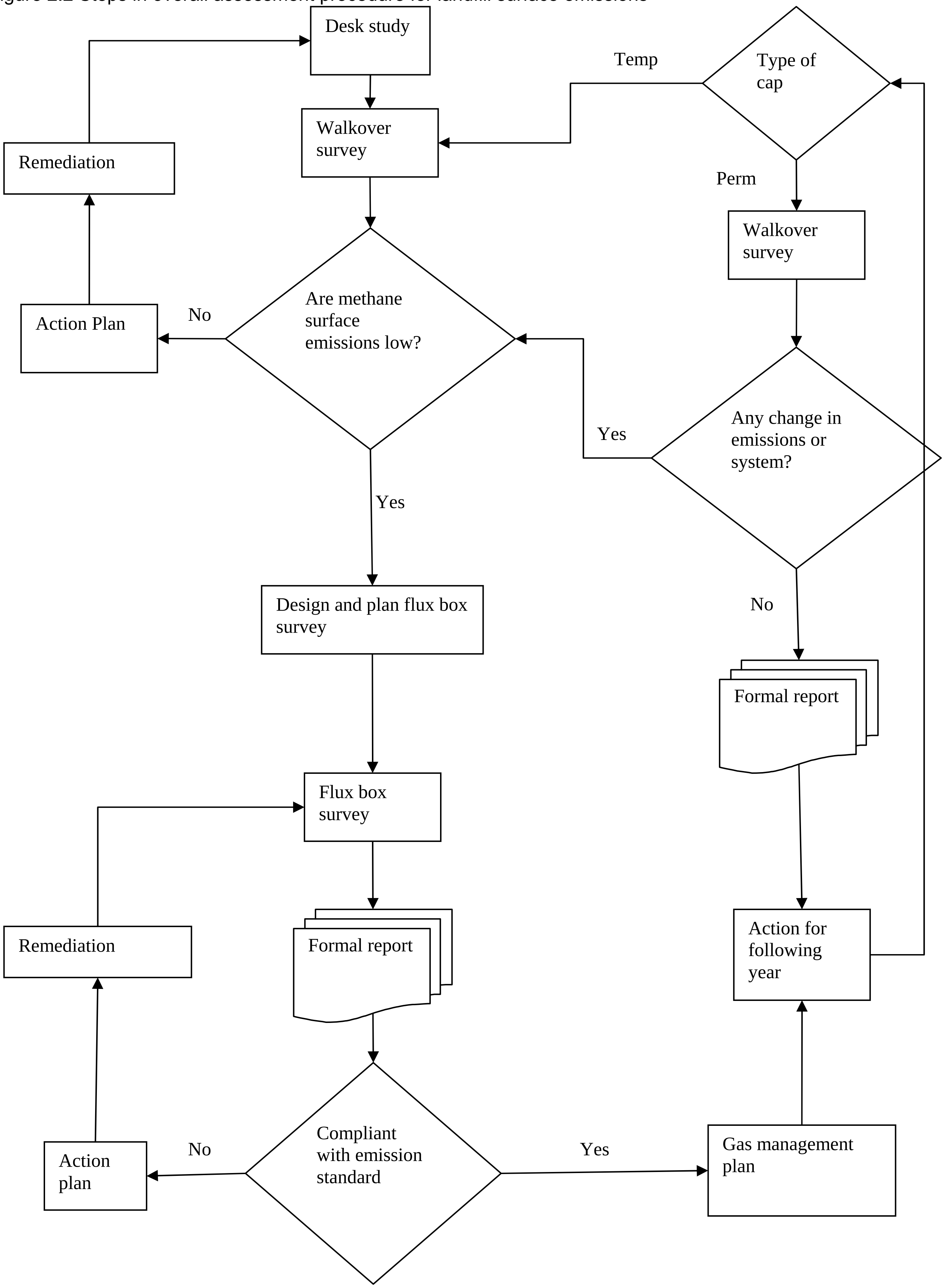
The walkover survey requires the gas concentration close to the surface of the ground should be monitored using a portable landfill gas detector that responds rapidly to hydrocarbons at a 1 ppm level. Flame ionisation detectors (FID) have commonly been used for walkover surveys for many years. Older versions of this type of equipment are not intrinsically safe or ATEX certified and should not be used in DSEAR zones unless an additional risk assessment is undertaken. Alternative ATEX certified instruments, capable of similar performance are becoming increasingly available and should be considered when planning the walkover survey.

You must carry out a site-specific risk assessment before any sampling begins. Use your risk assessment to determine the need for ATEX certified equipment or appropriate control measures to allow the use of non-ATEX certified equipment. Also carry out a COSHH (Control of Substances Hazardous to Health) assessment.

Review and update these assessments, and re-evaluate the physical risks in the light of evolving site conditions in advance of each subsequent visit. Landfill gas is flammable and may contain trace amounts of harmful components. Therefore, your risk assessment must take into account appropriate occupational exposure standards such as those contained in HSE's Guidance Note EH40 (HSE, 2005) and its successor documents.

Sampling and associated work must not disturb the normal safe operation of the site or the gas collection system. Disperse the gas vented during monitoring from discrete features, and minimise staff exposure to undiluted gas. However, the volumes of gas concerned are relatively small compared with those normally emitted from gas management systems, so specific waste disposal arrangements are unlikely to be necessary.

Figure 2.2 Steps in overall assessment procedure for landfill surface emissions



3 Desk study

3.1 Relevance

A comprehensive desk study of site characteristics is the critical starting point in the overall assessment process. As a minimum, the desk study should define:

- the history of the waste management activities;
- the installation of associated capping;
- normal operation of gas control measures.

The example forms in Appendix B set out a comprehensive schedule of potentially relevant parameters. Although some of these are not vital for ultimately assessing whether emission standards are being complied with, the data are necessary for effective definition of any remedial needs.

3.2 Site characteristics

Identify all the site's major characteristics at the outset and record them on a suitable form (an example is given in Appendix B). Such information will aid:

- predicting potential flux rates at the site;
- identifying surface and waste anomalies;
- design of the flux surveys;
- interpreting emissions data.

Typical site parameters are indicated in Table 3.1. Often, this information can be taken directly from your environmental permit and gas management plan.

Table 3.1 Typical site characteristics

Type	**Parameter**
Basic site characteristics	- Containment design (liner and capping) - Planned life and permitted volumes - Waste disposal area
Current site status	- Capped zones: permanent and temporary (percentage of total) - Current filling area (percentage of total)
Waste inputs	- Rate of infilling - Waste stream composition (percentage of monthly totals)
Gas control systems	- Permanent controls: gas abstraction rates, extent and capacity - Temporary controls - Gas monitoring points - Installation of flares and engines
Leachate management systems	- Leachate towers/sumps/risers - Leachate monitoring points - Presence of former co-disposal systems (such as liquid disposal trenches) - Leachate recirculation infrastructure - Leachate heads

A conceptual model of the site should be available as part of the risk assessment for the site and updated using information taken from the gas management plan.

Update your desk study and conceptual model regularly (see Section 9) to account for changes during the operational life of the site.

3.3 Site plan and drawings

A suitable large-scale site plan and specific technical drawings are essential for the overall assessment procedure. These documents help to identify particular construction details or features such as gas abstraction pipelines, wells and capping layer designs.

An annotated site plan should be the primary product of the desk study. This allows you to record key site characteristics in a manner that facilitates later use, both on-site and during the subsequent interpretation of results. Ideally, produce the plan in electronic format so further data (such as, details from the walkover survey and emissions monitoring exercises) can be easily incorporated.

At this stage, the landfill site may be divided into a number of zones. Within each, the cap has particular characteristics. The plan should identify any features that may have different emission characteristics to the larger capped zone within which they lie. Represent the location and extent of all zones and features relevant to the subsequent site-based exercises accurately.

4 Walkover survey and remediation.

4.1 Initial walk over survey

Before carrying out a quantitative survey of surface emissions, you must identify and rectify any major faults in your gas management system. An initial walkover survey with a hand-held gas detection instrument will locate significant emission sources and identify failures in the gas collection system. A quantitative flux box survey will be of little value until the methane concentration in the air is less than 100 parts per million by volume (ppmv) immediately above the surface on the main zones of the cap and less than 1,000 ppmv close to any discrete feature. This will allow you to take immediate action to prevent gas escaping. In addition, the initial site walkover will assist in planning the next stage of the survey using flux boxes.

The complexity of this initial walkover survey will depend on the quality and nature of the cap. Very large faults can be identified by visual inspection and the odour of the escaping gas. You can locate moderate escapes of landfill gas using simple hand-held instruments that measure the concentration of landfill gas in air. Surface scanning techniques may help to map variations in gas concentration over extensive sources of emission.

The main objective of the walkover survey is to:

- identify features through which gas is escaping;
- prioritise the treatment necessary to eliminate all significant sources of surface emission.

This is an iterative process, in which you identify and rectify the major faults first. Secondary faults may need more targeted surveying and repeated treatment and re-monitoring.

4.2 Pre-visit checks

You must address the health and safety issues highlighted in Section 2.8 before any on-site work is undertaken. During the walkover survey, local concentrations of landfill gas may be relatively high around individual features of the cap, you should take particular care to minimise risks associated with exposure to them.

Anyone using gas-monitoring equipment must ensure they are fully conversant with safely and effectively using the equipment. In addition, the following minimum checks must be carried out before each monitoring visit.

Keep a suitable record of all such checks:

- confirm the suitability of the equipment for the tasks envisaged, (for example, detection levels and calibration date);
- check the battery and status of other items that might be depleted;
- check the equipment's calibration date.

4.3 Site walkover survey

The walkover survey establishes the pattern of near-surface gas concentrations in the relevant zones. It must identify features where the emissions are unusually high and mark on the ground where the main failures in the gas management system are located.

4.3.1 Method

Before beginning, the surveyor notes:

- the general weather conditions, (such as, barometric pressure, recent precipitation, wind speed and direction);
- the nature of the areas adjacent to the survey, (that is, activities that may emit gas or lead to gas migration).

You may need to take these observations into account when interpreting the survey results.

The gas concentration close to the surface of the ground should be monitored using a portable landfill gas detector that responds rapidly to hydrocarbons at a 1 ppm level. A flame ionisation detector (FID) is generally the most convenient instrument available for this purpose. However as highlighted in Section 2.8 there may be restrictions on where you can safely use this instrument.

When the sample probe is held as close to the surface as possible (<5 cm), it will take in air containing any localised emissions of gas through the surface. If a specialised surface sampling probe is not fitted, you can attach a small (150 ml) funnel to the simple probe to facilitate sampling immediately above the surface. Because the hold-up volume of the funnel will reduce the responsiveness of the instrument, clear the probe volume for 15 seconds when investigating specific features before sampling for another 15 seconds.

You can distinguish the contribution of emissions from local surface features from those of other features upwind by occasionally sampling the air well above the ground (at head height). If there is a large difference between the airborne reading and the near-ground reading, the main contribution is from the ground close by. Where the readings are similar, the main source is probably upwind or is associated with a high general background at the site.

The zones you identify in the desk study must be traversed in a systematic manner to ensure the whole area is surveyed. However, the walkover survey must be directed by:

- observations of the surface;
- the methane emissions that can be measured with a hand-held instrument;
- secondary factors such as odour.

The intensity of the initial walkover survey will vary depending on the output from your desk study. Large, uniform zones with a quality assured cap warrant less detailed inspection than temporary features or boundaries.

Walkover survey

The initial walkover survey of a zone should be along regular lines or transects. On a permanent cap, these transects are typically 50 metres apart and on a temporary cap typically 25 metres apart. If odour has been an issue at the site, the transects should be closer than 25 meters. The surveyor should begin by walking along predetermined lines, monitoring the gas concentration continuously. Where they detect high concentrations of methane, the survey should deviate to locate the likely source of the emission. This will probably be upwind of the initial detection point. Once located, survey this area on a closely spaced grid to define the extent of the feature. The surveyor then returns to the wider spacing of the general survey grid and continues the transect.

Survey areas where failures in gas containment are more likely on a more intense grid (for example, traversing at 5-metre spacing for smaller features) that has been adapted to avoid obstructions. You should have identified features that may warrant individual attention during your desk study.

The edge of the cap is a potential line of weakness in the containment and can create an emission feature. You should investigate this region of discontinuity during the walkover survey to check whether there is evidence of high concentrations of gas. This area may also be part of your quarterly infrastructure checks.

The walkover will identify other potential features. Particular attention should be given to:

- surface cracking or fissures;
- stressed vegetation (see Figure 4.1);
- interfaces between capped zones;
- landfill edges and side slopes;
- gas wells and monitoring points;
- junctions in gas collection pipework;
- pathways where pipework may be buried in trenches;
- leachate sumps, towers, risers and other monitoring points;
- liquid discharge infrastructure (leachate recirculation techniques or condensate discharge).

Where the walkover identifies locations with particularly high methane emissions, mark these with paint or poles for attention during subsequent remedial work. Relocating specific points on a large, open cap can be difficult and it is helpful to use a simple handheld global positioning system (GPS) unit to fix the location for future investigation. Take colour photographs of both general and particular site features (if safe to do so) as a record of site conditions at the time of the survey. This evidence can be useful in judging changes to areas of vegetation distress or potential features.

Record the results of the survey and use them to update the desk study. The logic you used to assign capping zones and features should be tested and confirmed by the site walkover survey.

4.3.2 Sources of interference and uncertainty

Although the walkover survey is semi-quantitative and aims to rank the potential sources of emission, it is important to consider factors that might obscure locations where gas may be released under normal conditions.

Gas emission through extensive areas of the cap will be affected by weather conditions and barometric pressure; saturated ground will act as a barrier to gas migration and high or rising pressure will also suppress emissions. Air turbulence, topographical features and surface cover can all affect the local gas concentration above the surface. Emissions from point sources may be less affected by atmospheric factors, but any gas released will be diluted more rapidly by air turbulence.

Factors outside the survey may affect the emissions through the cap. The surveyor should note relevant features such as working faces, adjoining operational areas or historic passive gas vents. Although uncapped areas are not within the scope of this guidance, best practice requires that you install adequate gas collection in a timely manner on any part of the site where a significant amount of landfill gas is being generated (Environment Agency, 2010). Similar monitoring techniques can be used on these uncapped or operational areas to identify emission points and to help with the control provided by the temporary gas management systems installed there.

Unconfined spaces

Measuring gas concentrations in an unconfined space only provides an indication of where gas is escaping and identifies the main points of emission. However, this is sufficient to guide initial remedial action. You can make a semi-quantitative estimate of the flux from discrete features by measuring both the gas concentration and the gas flow close to the release point. This may aid prioritising remedial action where there are multiple emission points. You can estimate gas flows using a hot-wire anemometer (see Appendix C). However, this equipment is not ATEX certified so additional risk assessments must be made before using this equipment. The escaping gas may contain significant amounts of trace components, which may have auto-ignition temperatures close to the temperature of the hot wire (ca. 140^{o}C) and so you must use it cautiously. Pitot tubes and micromanometer assemblies are alternative techniques.

4.4 Surface scanning

On large caps with diffuse sources of emissions, it may be helpful to obtain positional information associated with the gas concentration measurements over a substantial area. You can use various surface scanning techniques to inform a preliminary site investigation, and to optimise the subsequent investigation of faults in the gas management system. Hyperspectral scanning and emissions mapping are two such techniques that can be particularly helpful in assessing large or very heterogeneous sites (see Appendix F). Thermal photography can also be useful in identifying areas of higher emissions.

4.5 Action on gas management

If a walkover survey demonstrates the cap is not consistent and there are discrete features emitting substantial amounts of landfill gas, remedial action is required as soon as practically possible.

Large surface fissures in landfill capping do not comply with current best practice for site restoration. Irrespective of the gas concentration close to these features, you should assume some remedial action will be necessary. For example, Figure 4.2 shows a large fissure that should be repaired using conventional engineering techniques.

Consider the site comprehensively. High surface emissions cannot be dealt with solely by repairing faults in the cap or pipework, but will require improvements in the overall management of the gas generated in the landfill (Environment Agency, 2010).

This might include:

- improving the gas collection system, for example by:
  - using a well engineered cap and lining;
  - sealing fissures and gaps;
  - closing inspection points;
  - maintaining the gas pipework.
- reducing the pressure of gas in the landfill through more effective gas extraction, for example by:
  - installing more effective wells;
  - balancing the gas field;
  - matching gas handling capacity to gas output.

Undertake remedial action as part of your overall gas management plan. Actions you take to rectify faults in one zone may affect the gas management elsewhere. Hence, a walkover survey that follows any remedial work should not only monitor gas concentrations around the repaired fault, but should also check the surrounding areas.

4.6 Completion of the initial survey stage

Continue the cycle of walkover surveys followed by remedial action until the gas concentrations your surveys detect are low. The criteria for this will vary depending on local conditions and the scanning procedure you use.

Figure 4.1 Vegetation stress potentially caused by emissions around a gas well

Figure 4.2 Large fissure in a landfill cap (>3 cm wide)

However, as an indication, a quantitative flux box survey will be of little value until the methane concentration in the air is:

- less than 100 parts per million by volume (ppmv) immediately above the surface on the main zones of the cap;
- less than 1,000 ppmv close to any discrete feature.

It is unlikely your site will meet these conditions if a measurable gas flow rate remains from any discrete feature. Where a site has a heterogeneous cap or features over which a flux box cannot be fitted, the methane concentrations will generally need to be lower than those indicated above before you undertake a flux box survey.

You may require several iterations of survey and remedial action to bring all the significant emission sources on a large cap under control. During this work, partial surveys around particular features may be sufficient to direct the remediation work. Ensure you agree the scheduling of your remedial work with us before it commences. Remedial action and re-monitoring of the whole zone by walkover surveys and the first flux box survey must be completed within a year of placing the cap. A limited flux box survey may aid your targeting of some final remediation to control releases above the guidance levels, but quantifying releases is not generally appropriate until you've stopped all major emission sources.

Benefits of the survey

The importance of completing the cycle of walkover survey followed by remedial action is illustrated in Figure 4.3. The targeted walkover survey using a portable instrument (such as, a FID) identifies significant sources of methane emission. The resulting remediation brings the surface flux down to the range where the flux box can be used effectively to quantify surface emissions. On an intact cap, emission rates slightly above the emission standard can not be identified with confidence by the FID alone and so a flux box survey using an array of sampling locations at regular intervals is necessary to measure the average flux from a low flux zone.

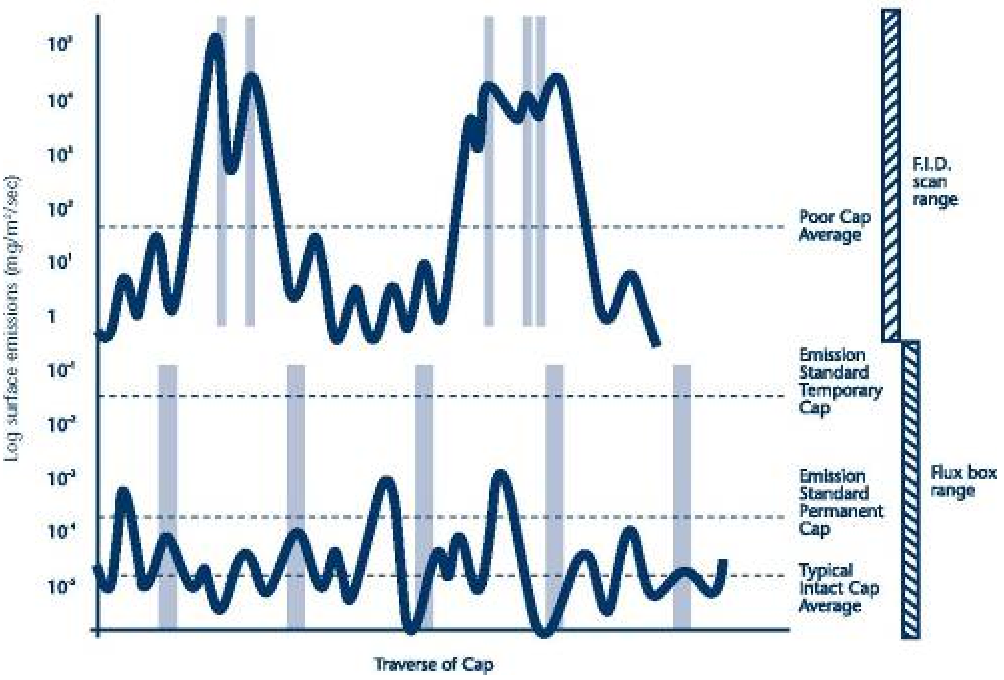


Figure 4.3 Schematic representation of the two stages for surveying methane emissions from the surface of a landfill. In the FID scan (the walkover survey), detailed examination (grey areas) is targeted on high emission features.

In the flux box survey, detailed measurements are made at regular sampling intervals, which are selected independently of the local flux.

4.7 Intermediate Walkover Surveys

Once a zone or area of a landfill has passed the initial walkover survey and flux box test, carry out regular additional walkover surveys to show that there are no gross point source emissions. These walkover surveys focus on any infrastructure such as gas and leachate wells that extend through the cap. Include any areas or features where settlement has occurred to ensure that landfill gas emissions have not increased.

The frequency of these additional surveys will be site specific but we consider that a minimum of a quarterly check around all the infrastructure represents the minimum frequency.

5 Design of flux box surveys

5.1 Survey approach

Do not undertake a flux box survey until the main faults in a gas management system have been rectified. If you can still easily find features that emit methane with a sensitive handheld instrument such as an FID, you should use this instrument to guide further remedial work.
An intact cap is likely to be relatively homogeneous, such that a small number of regularly spaced monitoring points (flux boxes) are representative of the main zones of the cap.

Objective
The objective of a flux box survey is to quantify the total releases of methane from the surveyed area. This may identify locations where the gas flux through the cap exceeds an emission standard and thus will initiate further remedial work.

Design
The design of the flux box survey should ensure that:

- areas with similar characteristics are monitored together;
- zones and features are uniquely identified and measured;
- all zones and features aggregate to the total capped part of the landfill site;
- monitoring locations are representative of the zone or feature.

A representative survey depends on the spatial frequency (see Section 5.5), meteorological context (see Section 5.6) and temporal frequency of the monitoring (see Section 5.8). The criteria used in this document for selecting the total number and location of flux measurements take account of guidance issued by the United States Environmental Protection Agency (USEPA, 1986).

5.2 Selection of survey zones

Before beginning a flux box survey, you should review the information gathered during your desk study and walkover surveys together. The latest walkover survey following remediation will be the most relevant guide to defining zones and features on the cap. The general definition of a zone and a feature is given in Section 2.4. Typical zones and features that can contribute differentially to the overall emissions are identified in Table 5.1 and described in more detail in Section 5.3.

Although most features will lie within or adjacent to a capped zone, they are considered individually because they may have emission rates that differ significantly from the rest of the zone. Remediating these identifiable features is vital in improving the overall surface emission rate.

Table 5.1 Categories of emission zones and features

Designation	Examples
Zones	- Permanently capped areas - Temporarily capped areas
Features	- Surface fissures - Leachate chambers and monitoring points - Gas wells and monitoring points - Pipework leakage - Cap disruptions, such as wells and buried pipelines - Side slopes - Landfill edges or capping junctions - Areas showing affects of gas, such as stressed vegetation

5.3 Typical zones and features

5.3.1 Zone

A zone is an extensive area of the landfill surface over which the average emission can be calculated from a number of representative monitoring points. It will generally be covered uniformly with a single capping system that is intact and has a consistent slope. A zone need not bear any explicit geographical relationship with a landfill cell and thus could cover part of a landfill cell or a series of cells.

You should consider two types of zone:

- a permanently capped zone where no more waste will be accepted;
- a temporarily capped zone that will not be receiving waste for a period of at least three months.

A landfill site may have several zones in each category as the standard of capping may differ across the various cells.

Figure 5.1 shows an example of a temporary cap. Temporary capping may have been installed where placing a permanent cap is delayed until adjacent cells are filled to final levels. Alternatively, there may be plans to import additional wastes to achieve final profiles before constructing the final capping system. You must agree your timetable for replacing the temporary or interim cover with a permanent cap with us.

On more mature sites, agricultural activity may affect measurements of methane at the surface. It is therefore important to record the form of land use at each of the zones.

Figure 5.1 Temporarily capped zone of a landfill

5.3.2 Features

A feature is any discrete area, equipment or infrastructure within a zone where abnormal emissions might be found (these are usually relatively high). Discrete features are easily defined because they are visibly different from the surrounding area (for example, leachate wells). Some features may be visible but have less clearly defined boundaries (such as, a fissured area, see Figure 4.2), whereas others may only be revealed through detecting a high flux at a number of adjacent sampling locations.

Although a feature may be as small as the surface area of a flux box, it must be potentially emitting significant amounts of gas to warrant attention and remediation. Hence, a single elevated flux measurement in an apparently homogeneous zone would not itself warrant designating it as a feature. To be regarded as significant, a feature must show elevated emissions over several traverse lines in the walkover survey or very high releases from a point source.

Visible evidence of a feature might be:

- lack of uniformity in the surface;
- a gap at the interface between the cap and another item;
- signs of vegetation stress around gas wells (see Figure 4.1) indicating gas emissions.

Surface emission scanning should help to determine whether it is necessary to sub-divide the zone to take account of such features. The key issue is that you should identify features so that, if they do not comply with emission standards, they could be readily defined and remediated.

Potential features may have been apparent from the walkover survey. Although the most significant faults in the gas management system should have been remedied before flux box measurements began, the FID may have identified potential points of weakness that can be classified as features.

The main categories of features are detailed below.

Surface fissures
Although large fissures will have been remediated during the initial work, smaller fissures will remain in the surface. These may be individual cracks or an area within which there is a network of finer fissuring. The surface cracking may not accurately reflect the actual permeability of the area to gas since it is difficult to establish the depth and continuity of the fissures. However, during a survey, these areas will normally be treated as features to be monitored separately.

Intrusions
A number of wells, boreholes and posts will penetrate the surface of a landfill. Each of these will be a potential weak point through which there could be a high flux of landfill gas. Because installations such as gas wells penetrate deep into the active area of the landfill, the seal between these and the cap is a crucial barrier that can be damaged or deteriorate. Hence, the survey should class the following as potential features:

- the area around leachate and gas wells;
- the sealing on the inspection covers;
- any associated pipework.

Gas pipelines
These are unlikely to be emission sources during active gas extraction because any pipeline leaks would allow air into the pipes rather than allowing gas to escape. When the pumping system is inactive, however, such leaks can become emission points for gas. Leaks from exposed pipework are easy to identify and the necessary remedial action can be assessed.

The cover soil above any buried transmission pipeline may be less stable than surrounding material and trenching may have disturbed lower levels. Hence, you should establish the line of these pipelines and investigate them as potential features during the survey.

Side slopes
Sloping areas can be affected by differential settlement and it is therefore important to identify places where there is a significantly different gradient as features for particular attention.

Compacted waste with layers of daily cover may have greater permeability to gas in the horizontal plane rather than the vertical plane (that is, it will show anisotropic permeability to gas). This will lead to lateral migration toward the side slope and a higher potential for surface emissions from the slope. The effectiveness of any gas abstraction system is likely to be lower near the landfill edges, with a consequent increase in emission potential.

Junctions in liners or capping material
Where a synthetic membrane has been used as a lining or capping material, unwelded junctions may provide a lower permeability pathway for gas. Although any cover material covering the junction that is, clay or soil will mask this, failures along the line of these junctions may still create an emission feature.

The edge of the cap is a potential line of weakness in the containment and can create an emission feature. Investigate this region of discontinuity during the walkover survey to check whether there is evidence of high concentrations of gas.

5.4 Annotation of site plan to indicate zones and features

Figure 5.2 illustrates the manner in which the different zones and features may be indicated on a site map. The naming convention you use should aid later interpretation and grouping of similar features and zones.

5.5 Number of monitoring locations

The number of monitoring locations you require is a function of the zone size. For the purposes of this guidance, there are two sizes of zone, they are less than 5,000 m^2 and more than 5,000 m^2.

The classification is based on practical rather than scientific considerations in order to provide a pragmatic spatial distribution of the monitoring.

In both classes, the minimum number of monitoring locations in a zone is six (USEPA (1986)). In order to make the survey representative, you should space the monitoring locations regularly within the zone.

Having determined the number of necessary monitoring locations, divide the survey area in the form of a regular grid pattern (see Figure 5.3 at the end of the section).

Reference each grid location uniquely and record it on the site plan. Subsequent surveys on that zone can use the same or an equivalent grid pattern, but you should always uniquely define the monitoring locations.

5.5.1 Zones of area greater than 5,000 m^2

The number of required flux measurements (n) depends on the size of the zone (Z m^2) and, based on USEPA (1986), is calculated as follows:

$$n = 6 + 0.15 \sqrt{Z}$$

Using this equation, Table 5.2 shows the number and average spacing of monitoring locations for zones of particular size. These recommended spacing on extensive areas of a cap are consistent with geostatistical analysis of research data.

Table 5.2 Recommended numbers of sample points and average spacing in large zones

Zone size (m^2)	Number of locations	Average spacing (approx.)
5,000	16	18 metres
10,000	21	22 metres
50,000	40	35 metres
100,000	53	43 metres
200,000	73	52 metres
1,000,000	156	80 metres

Example calculation:

Zone area (Z)	= 205 m x 135 m	= 27,675 m^2
Number of measurements (n)	= 6 + 0.15 $\sqrt{27,675}$	= 31
Average monitoring spacing	= $\sqrt{(27,675 m2/31)}$	= $\sqrt{892.7}$ m^2
		= 29.9 metres

5.5.2 Zones or features of area less than 5,000 m^2

For smaller zones or extensive features, the criterion for determining the number of locations is:

$$n = (\text{zone area}/5{,}000) \times 16$$

subject to a minimum of six locations

Table 5.3 Recommended numbers of sample points in smaller zones or extensive features

Zone size (m^2)	Number of locations
1,000	6
2,000	6
3,000	10
4,000	13
5,000	16

5.6 Meteorological factors

Data quality can be directly influenced by the meteorological conditions prevailing before and during the monitoring period. In particular, surface emission rates can be affected by factors such as rain and changes in barometric pressure.

If surface soils and clay capping are saturated with water, they will be less permeable to gas and this will greatly reduce the surface flux. You should therefore avoid survey work following periods of unusually heavy rainfall. Surveys must never be conducted on areas where there is standing water.

Frost

Frost can similarly reduce the permeability of the cap due to the expansion of the water held in the soil pores of the cap. Conversely, frosty conditions could lead to higher methane emissions due to a reduction in the rate of biological methane oxidation within the soil capping. This makes results ambiguous and may have an impact in zones with a low flux.

The internal pressure of gas in the landfill is generally only marginally above atmospheric pressure. This means that small changes in the weather can alter the observed emissions from the surface.

Barometric pressure

When the barometric pressure is falling or is below the norm for that area, methane fluxes can be higher than normal, and vice versa. Ideally, surveys should be conducted when barometric pressure is at neither extreme. Meteorological effects can be self-cancelling because low barometric pressure is usually accompanied by rainfall, which reduces the permeability of the soil and can reduce surface emissions.

Wind speed

Wind speed can also affect the flux measurements due to the increased potential for air ingress through the base seal of the flux box. Therefore, only carry out routine surveys under Beaufort force 2 conditions or below (that is, <3 metres/second). If the site is normally windy, you may need to undertake measurements when wind speeds are higher than this recommended value. Take particular care when sealing the box to the surface in order to nullify any interference. If wind speeds are high during the survey, note this and take it into consideration during your data interpretation.

5.7 Control station

You can use a flux box positioned at a control station as a reference if you are carrying out a survey over more than one day. Record variation in the flux at the control station alongside atmospheric pressure, rainfall and wind speed data. Assessing the variation at the control station over the survey period will be useful when calculating and appraising the overall site flux. However, you cannot rely on single control stations to provide unambiguous reference data where surveys extend over large areas or prolonged periods.

5.8 Temporal frequency

Because emissions monitoring is periodic, select sampling periods that are representative of normal operation of the gas management system. Check existing data on the routine operation of the system to confirm your monitoring will coincide with normal site conditions. Sampling performed during atypical periods may prove invalid for assessing compliance against emission standards.

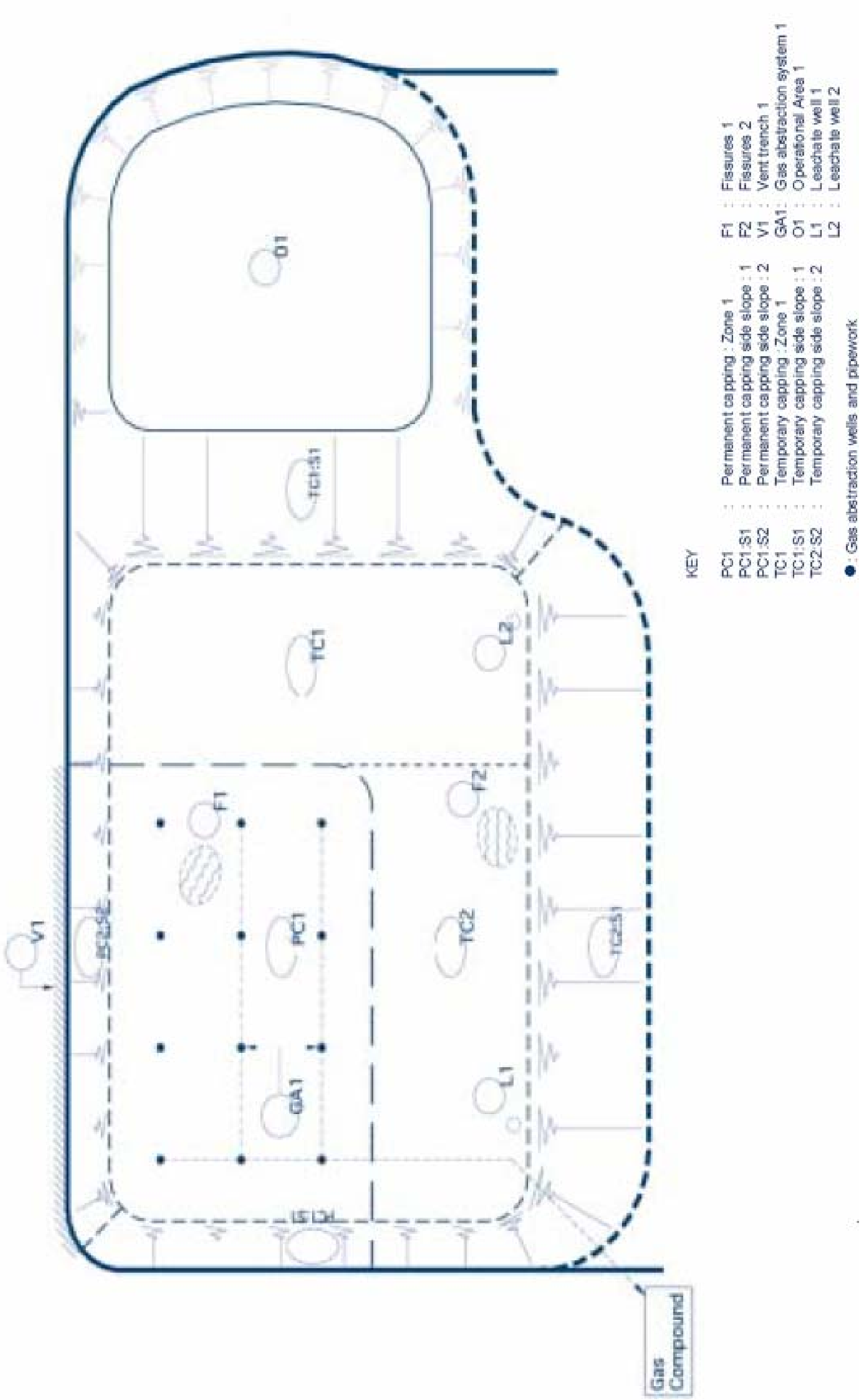


Figure 5.2 Example of landfill site zones/features

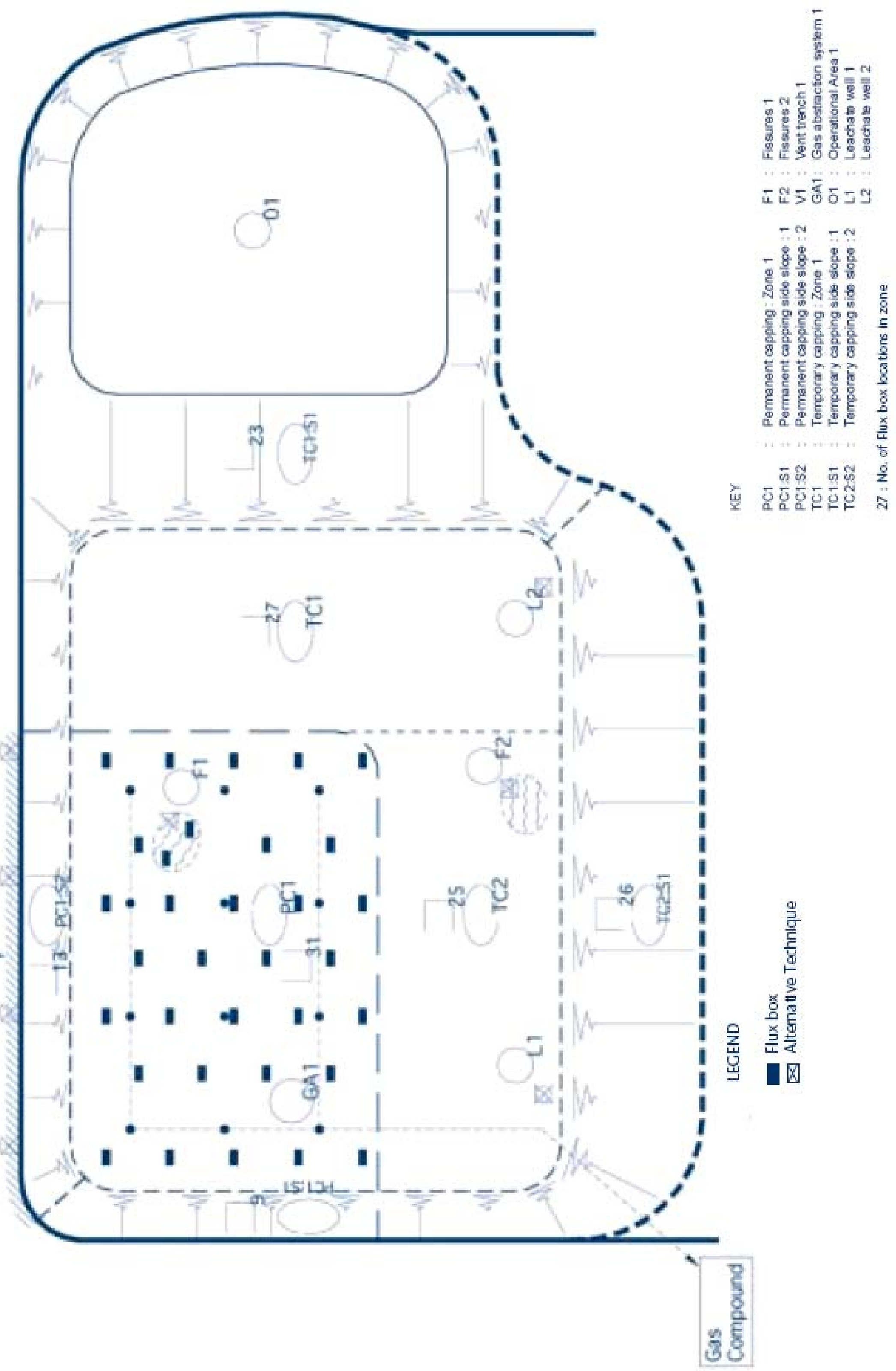


Figure 5.3 Example of emission monitoring – spatial frequency and patterns

6 Measuring emissions using a flux box

6.1 Range of application

The protocols for using the flux box described here are for making individual measurements during an emissions survey. Following the initial stage of a walkover survey and remediation, the cap should be generally intact and uniform. A flux box survey should be designed, as described in Section 5, with regularly spaced sampling points in the various zones and features on the cap. However, you may still encounter some minor anomalies. You will need to make adjustments to the placing of individual boxes. You must record any changes to your original survey design and account for them in your assessment.

Suitability
A flux box is suitable for measuring emissions on relatively smooth landfill caps where the device can be readily sealed against the surface. The device is not suitable for measuring flux where the emission surface can not be enclosed or covered and adequately sealed by the box.

The lower detection limit for a flux box is an emission rate of methane through the surface of 5×10^{-5} mg/m^2/second, which is well below the applicable emission standard (see Section 2.5). The upper limit of effective measurement for the flux box is 5 mg/m^2/second (equivalent to 250 m^3/ha/hour of methane). Hence, a flux box is only suitable for measuring where methane concentrations in the air close to the surface are low.

If the weather deteriorates during a survey such that the conditions outlined in Section 5.6 are no longer met, cease taking measurements with flux boxes till conditions improve.

6.2 Flux box method for capped zones

6.2.1 Basic principles of a flux box

The flux box is a container, open at the base, with a sampling line connected to gas monitoring equipment. The device described in this guidance is a passive flux box, which is inexpensive to construct; for example, the flux box shown in Figure 2.1 is adapted from a plasterer's bath (see Appendix A for details of its construction). It consists of an enclosure of known volume, with two ports fitted at the top. The inlet port is used for pressure equilibration and the outlet port leads to the gas monitoring equipment.

FID detector
An FID detector is generally most suitable for measuring the methane concentrations encountered in surface emissions monitoring on landfills (see Appendix A for details). An FID will actually respond to a range of hydrocarbons, but methane is the predominant hydrocarbon in most landfill gas. For the purposes of surface emission measurement, the FID reading is an adequate measurement of methane.

Siting
The box is placed with the open face downwards and the bottom edge is temporarily sealed onto the ground during the monitoring. The equipment should be painted white to minimise any thermal effects caused by heating of the wall of the box by sunshine.

You can use a flux tent as an alternative to a flux box, but use of flux tents is not covered by this guidance. The tent covers a larger area and, if well designed, is easier to seal on uneven ground. However, to assure representative sampling, you must demonstrate that:

- the large enclosed volume of air and gas is mixed adequately;
- the volume enclosed by the flexible material is consistent under operational conditions at the site.

Method

The flux box monitoring procedure, which is described in detail in Section 6.2.3, involves the following steps at each sampling location:

- sealing the flux box against the ground surface on the capped area;
- measuring the methane concentration within the box at short time intervals over a period of up to an hour;
- plotting the concentration of methane (in mg/m^3) versus time on a graph and applying a 'best-fit slope' as the rate of change in methane;
- calculating the methane flux (in mg/m^2/second) by multiplying the rate of change of concentration by the internal volume of the flux box chamber, and dividing this value by the box's 'footprint' area.

This procedure converts a series of time-based measurements of a single value of flux for each location. The result only applies to the particular area of ground on which the flux box stands. To calculate the total flux of the zone under investigation, you must aggregate the readings from a number of flux box measurements. You must take these at locations that are representative of this whole zone.

The flux box will perturb the normal emissions from an area, but this effect will be insignificant over the sampling timescales. Factors such as changes in the biological oxidation of methane due to reduced access to air will also be insignificant over the monitoring period.

6.2.2 Sealing against landfill surface

An effective seal between the flux box and the site surface will depend on ground smoothness. A good seal with the ground is essential to allow accurate measurement of the emitted gas. This is particularly important in windy conditions, when the system is most vulnerable to air ingress.

Carefully consolidating the ground on which the box edge will sit can establish a basic seal. It is important to ensure the soil permeability within the box footprint is not affected by this tamping to consolidate the edges.

A template placed on the proposed monitoring location can help define both the need for any particular preparation and the nature of that preparation.

Procedures

The following simple procedures may improve the seal:

- If there is no established vegetation on the landfill capping; use a spade to create the necessary plane of contact for the edges only. However, this should not involve excavating the ground to sink the edges of the box because this will affect the pathway of gas through the soil pores.
- Placing a weight on the box can help to improve the ground sealing process.
- Moist, plastic clayey materials from the site can facilitate the sealing of the box to the ground. Where these materials are not available low permeability (rubber) tubing filled with sand or low permeability (rubber) skirts sealed to the box should be used. The use of wet sand alone or wet sand in permeable bags or stockings is not acceptable.
- Areas of long grass or other more substantial vegetation should be cut down so that they do not interfere with sealing or mixing within the flux box. The area should be left vacant for a few minutes to allow dispersion of the small amounts of volatile organic compounds (VOCs) that may arise from freshly damaged plants.

A container without a bottom lip will have a sharp edge you can push directly into the capping soil. Although this could be an ideal sealing method on many soil surfaces, the absence of a lip may make a plastic box less robust and durable. A metal container is inherently more stable, but is much heavier for surveyors to carry and may conduct solar heating into the enclosed chamber (thus affecting the gas measurement).

Some sealing imperfections will stem from the heterogeneity of the surface profiles at the sampling locations. If no other suitable locations are available, monitoring should proceed but you should record any reservations about the effectiveness of sealing so that the greater uncertainty in these data can be taken into account during the assessment.

6.2.3 Using the flux box

Equipment requirements:

- set of flux boxes with appropriate fittings (see Appendix A);
- tools to clear the surface;
- tape measure or GPS device for recording the flux box position;
- trowel/shovel for flux box sealing;
- FID (or similar device) gas measuring equipment for each active box (one FID can be moved from box to box);
- stopwatch;
- unique ID markers for each location.

Step 1: Location confirmation

- Inspect the proposed sampling locations to ensure practicality and safety.
- Modify the exact positions as necessary, taking care not to distort the survey by avoiding locations that appear to have high rates of emission or over-representing areas of low emission rate.
- Optimise the deployment of the available flux boxes based on the information collected during the walkover survey.
- Assess the likely time needed to acquire the necessary data at each location.
- Assign a unique ID to each location and mark it on the site plan.

Step 2: Monitoring conditions

- Record the weather, wind, temperature and local ground conditions on site record sheet (see Appendix B). Include details of the recent barometric trends and weather conditions and record the source of all meteorological information.
- Record the operational status of the relevant parts of gas management system on the record sheet.

Step 3: Instrument preparation

- Start the FID in a safe area following the procedures described in the manufacturer's operating manual. (The instrument should not be switched on in areas where flammable gases could have accumulated such as an office.) We recommend using an intrinsically safe FID or similar device.
- Allow the FID to stabilise while placing the upturned flux boxes near the selected positions for analysis. Do not attempt to seal the boxes until you've made all preparations for taking concentration measurements, otherwise the gas environment in the flux box may have a 'false zero'.
- Zero and calibrate the FID with a certified calibration gas. Calibration is normally valid for the remainder of the monitoring period.
- During monitoring, record the time and methane concentration at each successive reading. This can be either done manually or via a data logger. If the latter is used, make a back-up paper copy in the field.

Step 4: Initial gas concentration reading

- Seal the flux box on the site cap and complete the flux box assembly with sampling T-bar and inlet filter.
- Only connect the gas analyser to the flux chamber for the minimum required period before each reading because gas analysers withdraw significant volumes of gas that can affect the measurements. A sampling period of 30 seconds is usually required to obtain a stable reading. Note that in the design shown in Appendix A, it takes approximately 15 seconds for the gas sample to reach the analyser. Table 6.2 gives examples of gas extraction rates for commonly encountered gas analysers.
- A data logger can be set up to take ten readings over a 20-second interval and will calculate the mean of these ten values. For manual measurements, take the reading typically as an average over a 15-second period.

Step 5: Measurements during first five minutes of monitoring

- Take initial measurements at regular intervals of not more than **one minute**.
- Following this, the interval can be increased to a maximum of **five minutes**, depending on the observed rate of change in gas concentration (see first two items in Step 6).
- You can monitor flux boxes in groups, that is, following the initial period of frequent monitoring at the first flux box, measurement can then be started at the second box (repeating Steps 4–6), and so on. However, allow sufficient time for moving to the next box, sealing it, taking measurements at the necessary intervals, and returning to the previous flux box. To achieve this, place flux boxes on the ground in the order in which they will be monitored.

Table 6.2 Typical gas sampling rates for commonly available gas analysers

Instrument	**Flow rate (ml/minute)**
Gas-Tec	900
Autofim I	625
Autofim II	650

Step 6: Measurements of rates over sampling period

- **Locations with very low flux**. A minimum concentration change of 5 ppmv over a maximum of 30-minutes monitoring time is necessary to give an acceptable error on the measurement. If no positive concentration change is detected after 30 minutes, report this as less than the 'lower detection limit value', namely 5×10^{-5} mg/m^2/second for a flux box of comparable dimensions to that described in Appendix A.
- **Locations with moderate flux**: In areas with a moderate flux, there are larger changes in concentration resulting in better monitoring accuracy over a particular period. Typically, 10–20 measurement points taken over a period of up to 30 minutes will be sufficient to allow you calculate a rate of change in concentration. At emission rates close to the standard, it may be necessary to take measurements over a period of an hour to achieve adequate levels of confidence in the measurement of the rate.
- **Locations with high flux**: Where the flux is high, the concentration within the flux box can change rapidly. Therefore, take measurements:
    - until a continuous set of rising readings has been taken over a 15-minute period, or;
    - the concentration within the flux box has stabilised or has decreased after five consecutive rising fluxes.

  The time interval between successive measurements and the total length of time over which to take measurements can both be much shorter than at locations with a low flux.
- **Locations with very high flux**: Where the upper detection limit of an FID (that is, one per cent v/v methane) is exceeded in the flux box in less than **five minutes**, assume the flux exceeds the emission standard. The feature will therefore require remedial action.

Deciding the number of boxes to use

The number of boxes you can monitor simultaneously will depend on the rates of change in concentrations observed in the individual flux boxes. Thus, for high fluxing zones, the time taken to complete monitoring at each location will be shorter but the number of simultaneous activities will be fewer. It is generally not practical to monitor more than 20 flux boxes/locations in a day.

Record the monitoring data from each location as indicated in Appendix B. All site data sheets should have an individual reference that defines the following uniquely:

- landfill site name
- zone or feature being monitored
- monitoring position number
- date and time of monitoring.

Include these sheet references in your site monitoring record (see Appendix B2), which must also include details of the prevailing and preceding weather conditions.

6.2.4 Monitoring small features

It may be physically impossible to use a flux box to contain small features that stand proud of the surface. In these circumstances, we recommend you check the gas concentration alone.

If the local concentration of methane in air is less than 100 ppmv and there is no measurable gas flow using a hot-wire anemometer, you may assume that a small feature is not contributing substantially to overall methane emissions. If these conditions are not met, either remedial work will be required or you will need to modify your monitoring method in order to quantify the flux.

Address point source emissions of gases other than methane, which may have a local impact on health or odour, through your site-specific risk assessment.

6.3 Monitoring anomalies in the cap

Discrete features are potential anomalies in any capped zone and require particular attention. Such features, which are examined in more detail below, fall into four main classes:

- fissures or cracks in the capping material;
- intrusions, such as gas wellheads and pipework leaks;
- intrusions, such as leachate wells/chambers and monitoring points;
- engineering faults such as side slopes, joins, edges and buried pipework.

6.3.1 Fissures

Some surface fissures do not extend to the base of the capping. The scale of gas leakage can therefore vary greatly between apparently similar fissures.

- **Large fissures**. These are defined as generally more than 30 mm wide (at the surface) and more than 5 metres long (see Figure 4.2). It is unlikely that large fissures will remain after completion of the walkover survey stage and remediation.
- **Medium fissures**. These are defined as generally less than 30 mm wide (at the surface) and less than 5 metres long. Good practice is to remediate any medium fissures found in the walkover survey. However, where these have formed, monitor the emissions as follows:
    - determine total area of all medium fissures on the site;
    - carry out flux box measurements at a minimum of six randomly selected measurement locations from the sum of all medium fissures/fissured areas that make up the feature.

  You need to take particular care to seal the box where the fissure underlies the edge.

- **Small-fissure areas**. These are features where the surface is ‘crazed’ (for example, clayey surfaces with no vegetation cover). They may therefore have emission characteristics that are not typical of the general capping system. Monitor these areas as per the normal flux box guidance with a spatial frequency equivalent to at least one per 100 m^2.

6.3.2 Gas wellheads and pipework leaks

If a gas abstraction system is in operation, any gaps in the capping around the wellhead could allow air into the waste rather than allow gas to escape (see Figure 6.1). You must repair these leaks to avoid the risk of fires and the dilution of extracted gas by air.

Where you have any doubts about the quality of the seal around the wellhead, you should check the air in the vicinity carefully with an FID. If the local methane concentration is more than 100 ppmv, you should treat the wellhead area as a discrete feature and assess it separately.

It may be possible in some instances to place the flux box directly on top of the wellhead. However, it is normally necessary to improvise by taking flux box measurements on the ground surrounding the well, targeting the areas at which the FID detected high methane concentrations. If this is impractical, assess the wellhead as a small feature (see Section 6.2.4).

Faults in the pipework are likely to allow gas to escape during operation. There is significant risk associated with working on these. Monitoring and remediation should be carried out on a case-by-case basis.

6.3.3 Leachate wells/chambers and monitoring points

Any intrusions that are not sealed will have high emission rates. You will normally identify and remedy this type of feature during your walkover survey before the flux box survey begins.

Where you have doubts about the quality of the seal on the chamber cover (see Figure 6.1), check the air in the vicinity with an FID. If the local methane concentration is more than 100 ppmv, treat the emission point as a discrete feature as described above for a wellhead.

6.3.4 Side slopes, joins, edges and buried pipework

High permeability features can develop during engineering work done after capping or due to waste settlement.

The number of measurements required will depend on the scale of the feature. In all cases, the minimum number of measurements required is normally six, or one per 100 m^2.

For large areas of greater than 3,500 m^2, take measurements on the grid spacing recommended for a normal capped zone.

Where the gradients of side slopes are no more than 1:2, it should be possible to carefully place a flux box safely on such slopes. Ensure you perform appropriate risk assessments for such tasks.

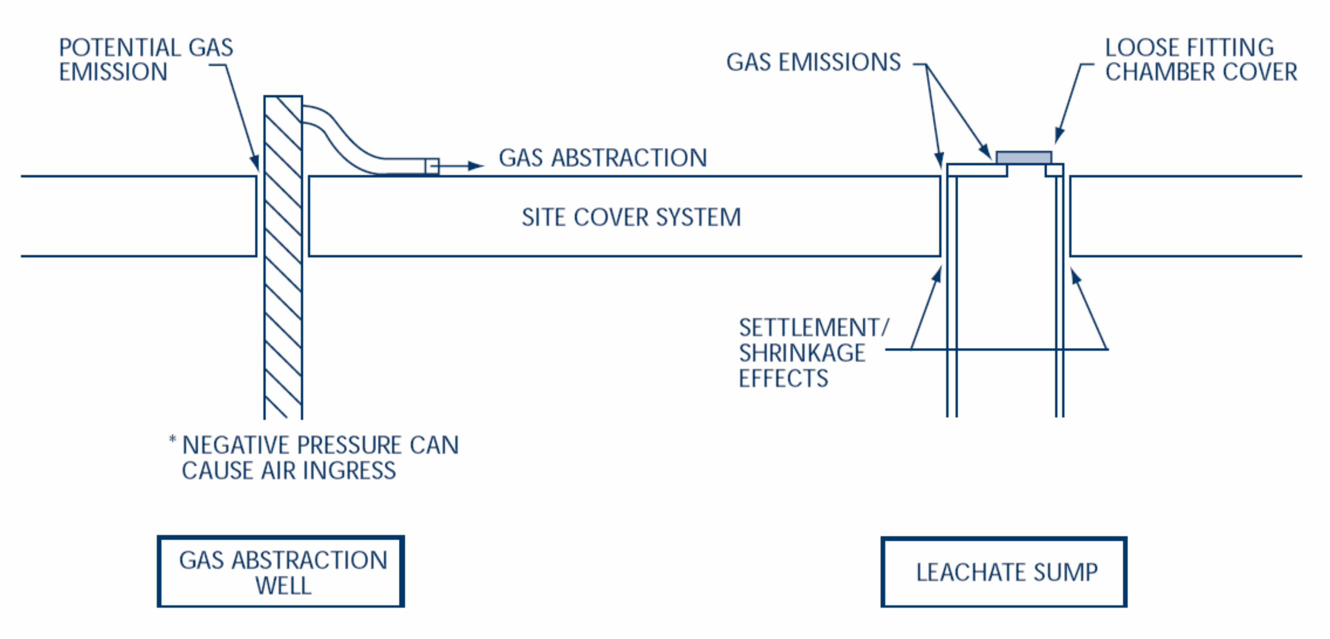


Figure 6.1 Gas leakage from gas abstraction wells and leachate sump.

7 Data Processing

7.1 Flux measurement

The monitoring data from the flux box locations are used to calculate emissions for the individual zones and features. These values are then aggregated for the whole site or the part subject to this guidance.

The basic principles of the calculation process are described below. Appendix C gives examples of detailed calculations.

Since most portable gas detectors such as the FID measure concentrations in ppmv, you will need to convert these volumetric concentrations to mg/m^3 (that is, mass units) at standard temperature and pressure (STP - 273K and 101.3 kPa) using the following calculation:

$$\text{Concentration (c) } [mg/m^3] = \frac{c\,[ppmv] \times \text{Molecular weight of methane}}{\text{Molecular volume of methane}}$$

$$= \frac{c\,[ppmv] \times 16 \times 10^3\,[mg/mole]}{22.4 \times 10^3\,[mole/m^3]}$$

$$= c\,[ppmv] \times 0.7143$$

The small correction factors from ambient temperature and pressure to STP are negligible relative to other larger errors that are accepted parts of the measurement technique (such as, the correction factor for temperature would be in the range 273/283 to 273/298).

7.2 Calculating flux in individual flux boxes

You can calculate the flux for each flux box location using the following equation.

$$Q = \frac{V}{A} \times (dc/dt)$$

where:
Q = flux density of the gas (in mg/m^2/second)
V = flux box volume (in m^3)
A = flux box footprint (in m^2)
dc/dt = rate of change of gas concentration in the chamber with time (in mg/m^3/second)

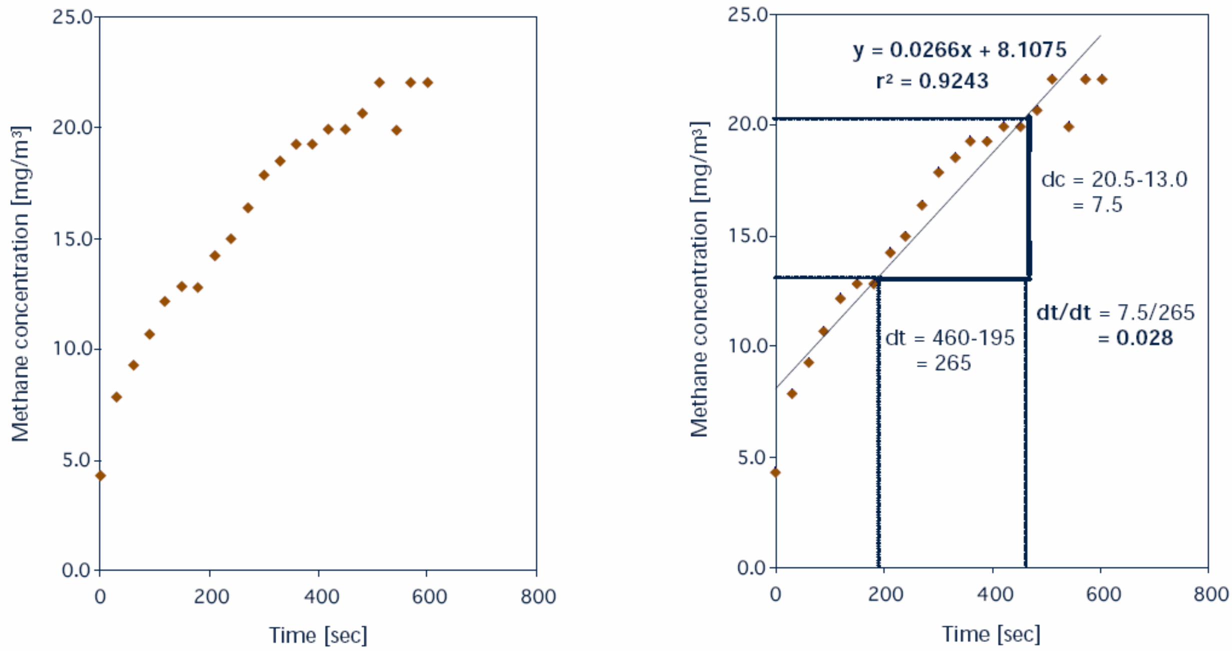
The rate of change of the gas concentration (dc/dt) is determined by plotting the data on charts with the x-axis representing time (in seconds) and the y-axis representing the mass concentrations (in mg/m^3).

Analysing monitoring data

Typical monitoring data from flux boxes at locations with a low and a high flux are plotted in Figures 7.1 and 7.2, respectively. These data show that, after a certain period of time, the concentration of methane within the flux box stabilises or can fall. This may be due to factors such as methane saturation in the flux box, back diffusion into the ground, or the effects of methane oxidation.

In other cases, the first few minutes of monitoring may be characterised by steady or even slightly decreasing methane concentration instead of the expected increase. This phenomenon can be the result of wind effects in the period before the box is fully sealed or the effect of the gas abstraction system.

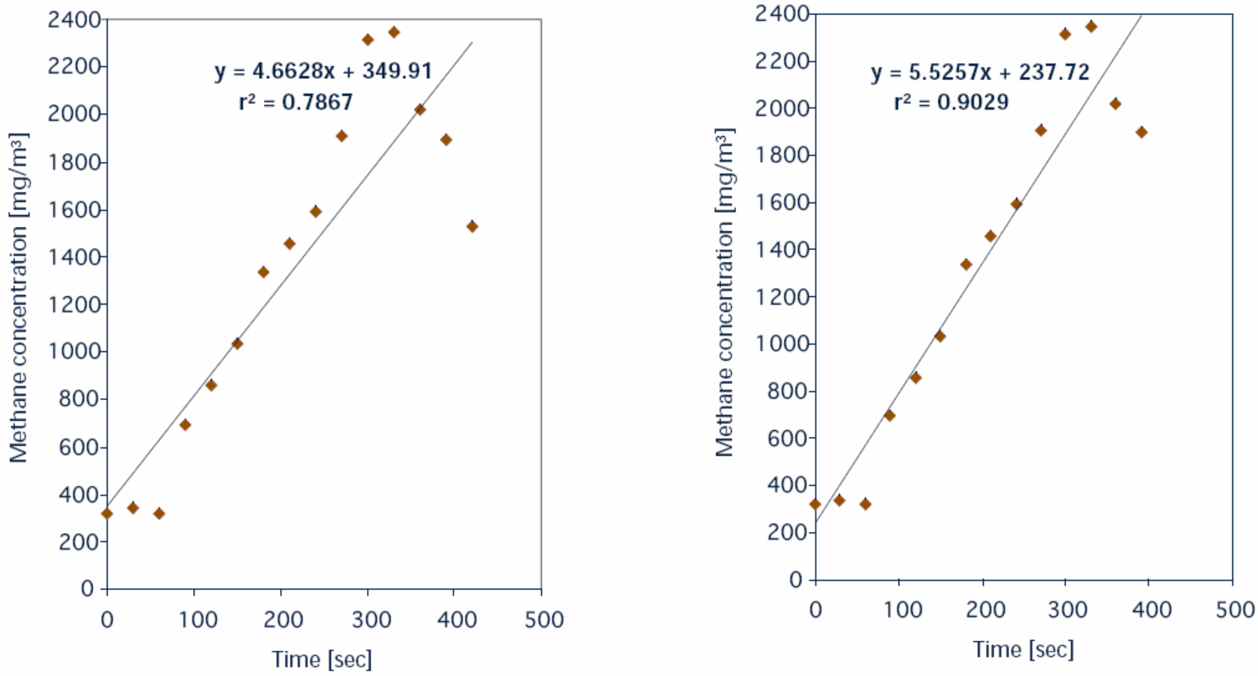
To eliminate these effects, individual data points are removed from the ends of the dataset – first from the last data collected and then the initial readings, until a correlation coefficient (r^2) >0.8 is obtained. The data will then show a correlation coefficient illustrating a high degree of association between time (t) and concentration (c).



(a) Concentration profile*

(b) Best-fit line trendline*
* After manipulation of data

Figure 7.1 Typical low flux scenario



(a) Concentration profile*

(b) Best-fit line trendline*
* After manipulation of data

Figure 7.2 Typical high flux scenario

We consider the data acceptable if the following criteria are achieved:

- r^2 >0.8
- the graph has more than five data points
- the change in concentration is greater than zero.

The initial rate of change is the most representative of the flux in the absence of the enclosure. Therefore, you should give least priority to later samples if eliminating data points.

If these criteria are not satisfied, you must report the methane flux as being at the lower detection limit of the method (5 x 10^{-5} mg/m^2/second or the limit of detection of the flux box used).

7.2.1 Emissions from narrow features

When a flux box is placed over a relatively narrow feature such as a fissure, the total flux is that from fissures and from the area of unfissured capping covered by the flux box.

In practice however, the flux from the capped zone surrounding the fissure is probably insignificant and the measured emission can be regarded as that of the feature alone.

7.3 Quantification of flux from zones and discrete features

Flux from a homogeneous zone or a discrete feature where flux boxes have been used can be calculated using a simple spreadsheet.

The average flux (in mg/m^2/second) of a zone or feature is the sum of all the flux measurements from the individual flux boxes divided by the number of monitoring points used on the zone or feature.

You can also use more sophisticated approaches (including geostatistics, Thiessen polygons or other spatial interpolation techniques), but these are generally not warranted for routine monitoring and lie outside the scope of this guidance.

7.4 Calculation of emissions from overall site

Table 7.1 gives an example of how a series of emissions from different zones and features are calculated and compared. These hypothetical data, which are based on the landfill site shown in Figure 5.2, show the wide variation in the flux and the mass flow from different site elements.

Table 7.1 Example calculation of total site emissions

Zone/feature[1]	Average flux ($mg/m^2/second$)	Number of measurements	Surface area (m^2)	Mass emission rate (mg/second)
Permanent capping[2] (PC1)	0.0005	31	27,675	14
Temporary capping				
Zone 1 (TC1)	0.789	27	19,425	15,326
Zone 2 (TC2)	0.095	25	16,400	1,558
Side slopes				
PC slopes (PC1:S1)	0.0032	9	2,800	9
PC slopes (PC1:S2)	0.0018	13	4,000	7
TC slopes (TC1:S1)	1.174	23	13,500	15,849
TC slopes (TC2:S1)	0.56	26	18,000	10,080
Fissures/fissure zones				
Fissures 1 (F1)	75	3[3]	400	30,000
Fissures 2 (F2)	23	3[3]	350	8,050
Leachate wells				
Well 1 (L1)	6,600 (mg/second)		Included	6,600
Well 2 (L2)	33,000 (mg/second)		Included	33,000[5]
Net landfill area = 102,550 m^2	**Total surface emission rate = 120,493 mg/second**			
Vent trench (V1)[4]	2.23	6[3]	250	558

1 As in Figure 5.2.
2 Net of fissures
3 Minimum number
4 These measurements were not included in the site surface emission assessment.
5 This feature should have been picked up in the walkover survey so may be a recent fault.

Mass emission rate

The mass emission rate for each zone and feature is obtained by multiplying the average flux per unit area by the area of the zone or feature. The sum of all these mass emission rates gives the total emission rate of methane from the site areas monitored. It may be more convenient for you to convert the total mass emission rate to units of tonnes/year for use in reporting the annual emission for your pollution inventory. To convert from mg/second to tonnes/year, multiply the emission rate by 0.031536.

If you wish to compare the magnitude of surface emissions with other emission sources, it is convenient to convert the flux measurements to m^3/hour – the units generally used to describe the capacity of landfill gas flares and engines.

The scale of local emissions may best be appreciated in volumetric terms as a rate in litres/m^2/hour. Table 7.2 shows the relationship between data expressed in four sets of units.

Table 7.2 Comparison of measurements expressed in different units

Measured flux in $mg/m^2/second$	Equivalent flux for methane in $m^3/ha/hour$	Equivalent flux for landfill gas in $m^3/ha/hour^†$	Equivalent flux for landfill gas in $litres/m^2/hour^†$
10	500	1000	100
1	50	100	10
0.1*	5	10	1
0.01	0.5	1	0.1
0.001**	0.05	0.1	0.01

* Emission standard for a temporarily capped zone
** Emission standard for a permanently capped zone
† Assuming methane @ 50 per cent v/v.

7.5 Potential sources of error or uncertainty

Uncertainty in quantifying the overall emission from a zone or feature can arise from three sources:

- the precision and accuracy of individual measurements made at the sampling locations;
- the selection of sampling locations;
- linking the individual measurements to the overall value.

These factors are considered in detail in Appendix D.

7.5.1 Ranking errors

The errors associated with a flux box survey fall into three categories:

- errors at individual monitoring points such as temperature variations, poor sampling or instrumental errors;
- uncertainty due to the timing of the survey or failure to locate the individual box appropriately;
- factors likely to make the measurement invalid such as interference from other sources of methane or unrepresentative sampling locations in the zones.

7.5.2 Overall errors and uncertainty

Instrumental errors in individual measurements can be managed and minimised by following the guidance given here. Similarly, the errors arising from local environmental factors and seasonal effects will be small if you follow this guidance.

Errors associated with identifying appropriate sampling locations will also be low provided you follow good sampling practice.

Homogenous cap

The greatest uncertainty will arise from calculating the total emission from individual emission measurements made at the representative sample locations. On a homogeneous cap, the difference in emissions at the various locations will be small, and so the uncertainty in the overall emission will be similarly low.

Heterogeneous cover

However, on a site with heterogeneous cover and variable surface composition, this uncertainty can be as high as one order of magnitude. Inspecting individual flux measurements and their spatial relationship may identify features that were not apparent on the site but could be treated separately. However, you should not do this without confirming the 'feature' can be distinguished physically and delineated on the site.

Variability

It is important your reporting of the overall emission rate takes account of the variability in the individual measurements and the number of different zones or feature that have been aggregated to give this value.

- If the surface of the site is demonstrably homogeneous, you may report an average value for total surface emissions with evidence of why this is representative (for example, the individual readings are similar).
- If the surface of the site is heterogeneous and there are large differences in the emission rate at individual monitoring points within a zone, a range of emissions must be reported (typically the maximum, minimum and most probable values).

It is likely that such zones will be subject to remedial action to deal with the higher flux features. Any remediation plan should include actions that will reduce the uncertainty in the overall emission. This is likely to involve work on the high emission areas. Your gas management plan must also indicate how subsequent surveys will reduce uncertainty either by refining the extent of the features and zones and/or by increasing the number of sampling locations in the variable regions.

8 Assessing emissions

8.1 Assessment procedure

Assess the monitoring data so as to:

- identify clearly all the main zones and any features that have different methane emissions;
- use the recommended procedure to calculate flux of methane through the surface and take into account uncertainty in the values;
- report the average flux for each zone, the flux from any individual features in that zone and the overall methane emission of the site area monitored;
- determine whether the average flux from each zone and feature is less than the relevant emission standard given in Section 2.5;
- prepare a prioritised remediation plan for those zones or features that do not comply (and which will bring them into compliance);
- identify any modification required in subsequent monitoring to reduce uncertainty in the measurements from zones with variable emissions.

8.2 Assessing compliance with emission standards

Make sure that your assessment considers the individual measurements, their distribution and the relationship of the various zones and features. Base it on:

- the plans drawn up in the desk study;
- the identification of zones and features from the walkover survey;
- the design and results of the flux box survey.

The emission standard applies to each zone and to each discrete surface feature within a zone. Emissions will vary across each zone or feature and your assessment should be based on the average emission for the part under consideration. Figure 4.3 illustrates typical variability in the emissions and shows that some individual measurements may be above the emission standard, despite the average being within the standard.

On a uniform intact cap, points of relatively high emission will be detected randomly and do not invalidate the general compliance of a zone with an average emission within the standard. However, if a number of adjacent sampling points have emissions above the standard, you will normally need to classify this as a feature for separate consideration.

Features

A feature (as specified in Section 2.4) must be definable, emitting significant amounts of methane and be amenable to targeted remediation. If a single measurement above the standard is from a visible fault or a very high measurement is associated with a known weak point in the engineering, these should be treated as features.

Figure 8.1 illustrates three circumstances that may occur during your assessment.

The central portion of the zone has a few randomly distributed points where the emissions are above the standard, but the average for this zone is within the standard and thus would be compliant were there no features. However, the emissions measured through the linear feature within this zone are generally higher than the standard and the average emission is also higher than the standard. Hence, the feature is non-compliant and remedial action is required.

Side slope

The side slope has an average emission below the standard and most of this feature has a random distribution of higher emission points. However, one corner has a series of adjacent monitoring locations with emissions above the standard. Although this can occur by chance, investigate the area to determine whether there is a discrete feature within the overall side slope area. If any of these adjacent measurements are very high or there are visible differences between this area and the surrounding surface, treat this corner as a separate feature. This new feature is likely to be non-compliant and require targeted remediation.

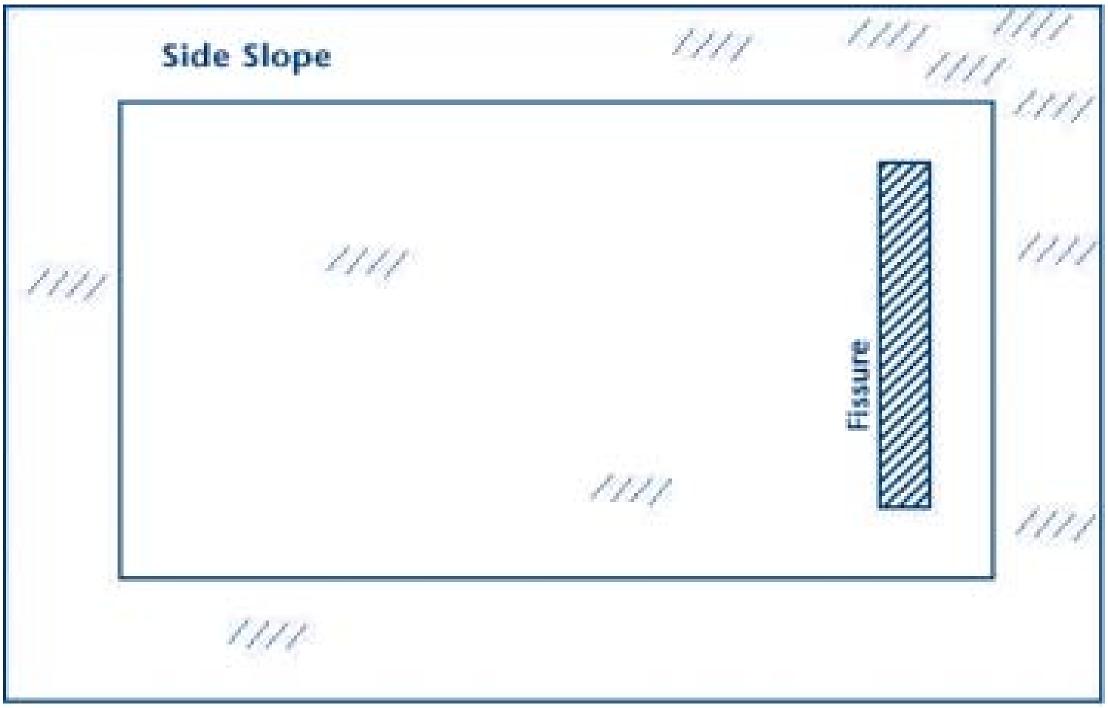


Figure 8.1 Schematic representation of the emissions measured in a zone with two types of feature. The hatched areas show locations where the measured emission is above the standard.

8.3 Summarising the assessment

Table 7.1 contains an example calculation of the flux from individual zones on a site and the aggregation of these to produce a value for the total surface emission from the site. The summary report and comments given in Box 8.1 complete the overall assessment process for compliance with relevant emission standards. This includes an overview of the landfill as a whole as well as consideration of the individual zones.

Different emission standards apply to the various zones but comparing the relative contribution made by each is important in prioritising the remediation plan. The typical assessment in Box 8.1 comments on the results, discusses the priorities for reducing or minimising the emissions, and outlines the methods that might be adopted for achieving compliance as a landfill progresses towards completion. Use this report to review the conceptual model of the site and the gas management plan as a whole.

Identifying non-compliant zones

Identifying non-compliant zones or features does not depend solely on the results of a monitoring exercise. Visual and other observations, together with experience, should highlight places where significant emission of methane is occurring. However, a detailed monitoring exercise will ensure the physical limits of non-compliant zones or features are determined properly, and appropriate remedial actions are prescribed.

Periodic emission survey

A periodic emission survey is unlikely to measure the worst case of emission from a site, that is, it will not capture short-term increases in emissions due to equipment failure or unusual periods of drought that affect the permeability of the cap. We have set the emission standards to indicate best practice in gas management so that identifiable faults can be rectified and the annual emission of methane from the capped area of the site can be quantified.

Site-specific risk assessment of the impact of odours and trace components in the landfill gas emission may require more detailed monitoring than the surveys undertaken here to measure methane emissions.

Box 8.1 Assessment summary and comments on surface emissions for a landfill site (based on the data given in Table 7.1).

Overall assessment

The permanently capped zone (PC1) appears fully compliant with the relevant emission standard. However, the overall site flux is dominated by excessive emissions from five zones/features:

- temporarily capped zone 1 (TC1)
- the temporary capping to the side slopes (TC1:S1 and TC2:S1)
- one fissured area (F1)
- one of the two leachate wells (L2), both of which are badly capped.

Two of these non-compliant features (F1 and L2) could be remediated with relatively little effort, and together they account for virtually 50 per cent of the total site flux. By also addressing two other features, that is, fissures 2 (F2) and leachate well 1 (L1), emissions could be reduced by over 60 per cent.

Temporarily capped zone 1 (TC1) and the associated side slope temporary capping (TC:S1) are less easily improved. However, data for temporarily capped zone 2 (TC2) suggest that quite a different quality capping has been applied to this – possibly because it is adjacent to an operating cell and so may seen as having a short-term function. In addition, the relatively high flux from fissure 1 in the permanently capped zone (PC1) suggests that the gas abstraction system is not operating effectively (as well as affecting the nearby side slope emissions).

Priority action 1

Capping the leachate wells properly would achieve the following:

Revision 1: Flux reduction at L1 and L2 ≈ 39,600 mg/second or about 33 per cent lower site flux.

Priority action 2

The permanently capped zone (PC1) appears compliant, but the area fissures 1 (F1) within this has emissions over the emission limit and so is non-compliant The fissured area therefore causes the whole zone to fail, but remediating FI would make it relatively easy to achieve compliance.

Revisions 1 and 2: Flux reduction at L1, L2 and F1 ≈ 69,600 mg/second or nearly 60 per cent reduction.

This action would also make permanently capped zone (PC1) fully compliant with the emission standard, and the principal residual actions would relate to the temporarily capped zones.

Priority action 3

The next actions would involve much more comprehensive engineering works. While fissures 2 (F2) produce significant emissions, it would not seem sensible to address these in isolation from the work necessary for the wider temporary capping in that area (that is, TC2). For practical reasons, it is appropriate to assess the scheduled life for TC1 since it might emerge that the zone is scheduled to be upgraded to ‘permanent’ status as soon as operational area 1 (O1) is complete and winter has ended (that is, when earthworks are more practicable). At the same time, the side slope TC1:S1 will become covered by the rising wastes in O1. Thus, while non-compliant at present, it may be best to ensure that the causes of the non-compliance are not repeated in future temporarily capped zones.

The non-compliance of TC2 and the associated side slope TC2:S1 cannot be addressed with the same pragmatism due to both the scale of the problem and the potential period over which it could continue. The solution, however, might largely lie in extending the active gas abstraction system into TC2. Indeed, the relatively ‘good’ temporarily capped in TC2 could well be the reason for high emission rates on the associated side slope.

Additional actions

The permanently capped side slopes (PC1: S1 and S2) are marginally non-compliant and it would be necessary to examine the individual data for those zones to assess the possible cause(s), which could be to surface erosion effects or differential settlement. Further monitoring could also be appropriate before any remedial actions are sanctioned or demanded.

The temporarily capped slopes (that is, TC1 and 2: S1) are one to two orders above the corresponding emission standard but it is likely that, by extending the gas abstraction into the temporarily capped zones, both the capped zones and the side slopes could become compliant.

8.4 Remedial action plans

Your report on surface emission flux will form the basis for proposals on remediation through your gas management plan. Remedial measures can range from major engineering (such as, extending the gas abstraction system) to a number of small improvements such as rectifying fissures and sealing leachate sumps.

More complex potential actions include improving a poorly designed and/or constructed permanent capping system. Such actions can compromise existing gas collection networks and, in the extreme, affect the agreed final levels and surface gradients. In addition, the optimum period for such works is usually weather-dependent. Your plan must take account of such issues. You are responsible for identifying the most appropriate remedial actions and agreeing these with us.

The critical factor in all cases is identifying priority actions and particularly those where large improvements can result from relatively modest and easily implemented actions. Identifying necessary actions need not depend completely on the results of a monitoring exercise because visual observations and experience will highlight essential actions in most cases.

Purpose

A remediation plan should:

- prioritise actions to deal with the main emissions and bring the monitored areas of the site within the emission standard;
- indicate how any local emission sources are to be identified, quantified and, if necessary remediated, so that, irrespective of whether a flux can be monitored, no spot measurements of over 100 ppmv methane are observed consistently on the capped zone;
- recommend an improved monitoring procedure for subsequent surveys on areas where the current survey has shown variability in the cap and uncertainty in the value for the flux.

This guidance is primarily concerned with minimising global emissions of methane. However, high concentrations of sulphur-containing compounds and other trace components in the gas may cause odours at fluxes below the emission standard and additional controls may be needed to deal with these. The emission of landfill gases from some point sources may have a impact on local health and amenity. We may need to implement a lower threshold for action on the gas concentration around discrete features if your site-specific risk assessment indicates there are sensitive receptors close to this source.

8.5 Timescale for remediation

Carry out all remedial actions necessary for achieving compliance as soon as is practical. However, site-specific conditions and the scale of non-compliance will influence the most appropriate timetable. There are circumstances where you can and should take immediate action, while you can programme others on a longer timescale. However, the onus is on you to justify the timescale necessary to achieve compliance. An important factor is whether there is an immediate environmental impact (such as, an odour) as a result of the non-compliance.

When you complete the remedial actions, undertake a new surface emissions survey to confirm the adequacy of the work. The survey type will depend on the magnitude of any change. However, since most parts of gas management systems are interdependent, a comprehensive walkover re-survey will usually be needed to confirm there are no major changes in adjoining areas. A partial flux box survey covering the affected area may be sufficient.

8.6 Continued compliance

To ensure continued compliance between annual surveys, your gas management plan should identify other features of gas management you can monitor more regularly or continuously to assure the performance of the overall system is maintained between surveys. Such features include:

- total methane extracted into the gas utilisation system, including normal extraction rate and normal suction on the field;
- balanced flow from the main sectors of the gas field;
- the presence of nitrogen or oxygen in the gas.

These parameters are often already measured and recorded as part of the active management of gas from a landfill. You can infer continued compliance with the surface emission standard from stability of the overall gas management on your site. Investigate any major excursion from normal operating values as part of your gas management action plan, which should include considering potential changes in surface emissions.

You must not ignore any indications of abnormal emissions of landfill gas between annual surveys. Odour problems or the detection of gas during a site walkover can indicate elevated surface emissions and that action is required to remedy this.

8.7 Frequency of flux box survey

An initial flux box survey is required within a year of the permanent cap being installed on an area. You will only proceed to the second stage of flux box measurement once your walkover survey has confirmed you've met the surface concentration above the cap and there are no substantial faults in the gas management system. This initial flux box survey demonstrates that the cap meets the emission standard and quantifies the emission of methane through the cap.

If this initial quantitative flux box survey indicates the zone does not comply with the emission standard, you must undertake further remedial work followed by an appropriate survey. You must then carry out a subsequent full flux box survey within a year, and thereafter **annually** until you can demonstrate the system is under control and the cap complies with surface emission standards.

Permanently capped areas

Permanently capped, closed areas progressively achieve a reliable degree of gas control. If you have previously shown a permanently capped zone to be compliant and there have been no significant physical changes in the gas management during the year, you can use an annual detailed walkover survey to demonstrate the surface emissions are under control. If these surveys show no change in the pattern of methane emissions, report the values for flux and total methane emissions measured from the previous compliant survey. If the zone remains stable, we will accept the results of full walkover surveys as the site report and not require a further quantitative flux box survey of the stable permanently capped zones. In conjunction with this annual walkover, regular monitoring of all above ground infrastructure on site must be undertaken. The time interval will be site specific, but should be no less frequent than quarterly.

Where a walkover survey shows a potential increase in emissions compared to the previously compliant results or surface concentrations are above **100 ppm** then you may require a limited flux box survey of the affected area to demonstrate compliance and to quantify the increased emission. Where you are able to do so we expect you to undertake actions to investigate and remediate these emissions.

Temporary capping

We will require a flux box survey on areas of temporary capping where you intend this capping to be in place for longer than 12 months, or on an area that has had a temporary cap in place for 12 months. An example would be where the phasing of site operations means that final waste contours cannot be achieved or an internal flank of a cell will be exposed until an adjacent cell is filled. Once you demonstrate this temporary cap meets the emission standard you will need to demonstrate continued compliance using quarterly walkover surveys.

Where the temporary cap is intended to be in place for less than 12 months you do not need a flux box survey however you will need to demonstrate that methane emissions meet the surface concentrations by quarterly walkover surveys.

8.8 Long-term changes

Surface emission monitoring should begin before your site is fully filled as progressive restoration of the site takes place. The gas management will change as the site progresses through various stages making regular re-assessment of the surface emissions necessary.

Whenever you've made substantial changes to the engineering or the gas collection system, you should monitor any impact on the existing capped zones through an assessment of the walkover survey data. This data must also highlight any deterioration in older gas management systems. We anticipate that, over time, remediation work will be needed on areas that have previously met the emission standard.

If you make significant changes to the gas management system, carry out any remediation on the permanent cap, or where you cease to extract landfill gas then you will need to carry out a further flux box survey to demonstrate that the emission standard is being met. Once you have demonstrated the area complies with the emission standard, you will need to demonstrate continued compliance through regular walkover surveys.

8.9 Overall emissions of methane

You can use the flux data to calculate the two reportable characteristics for a site:

- the collection efficiency of the gas management system;
- the annual methane emissions to the atmosphere.

The collection efficiency of a gas management system is defined as the amount of gas collected as a percentage of the gas generated. Guidance on the management of landfill gas (Environment Agency, 2010) shows how you can use the quantity of gas emitted through the cap per unit time in estimating collection efficiency.

On most sites, the main loss of gas to atmosphere falls under the category of surface emissions. You may report the annual methane emission calculated from the flux box survey as the methane component for your site's pollution inventory. In conjunction with the monitoring data on trace component composition, you can use the annual methane emission in calculating the annual emissions of other gaseous emissions required in your pollution inventory report.

9 Reporting

9.1 Initial monitoring stage

The results of walkover surveys and any surface scanning should form the basis of your plans for immediate remediation work. You should provide us with a written report that specifies:

- the survey conclusions
- the proposed remediation
- the plans for subsequent re-monitoring.

Revise your gas management action plan to take account of any changes. Since this stage is an event-driven, iterative process, reporting will differ depending on your site's circumstances.

9.2 First flux box measurement report

Complete the walkover surveys and any arising remedial actions within one year of capping so you can undertake a full flux box survey. It is your responsibility to report your monitoring results and associated interpretation to us.

Your initial flux box survey report to us (see Appendix E1) will set out the key characteristics of your site prevailing at that time (see the example form in Appendix B). Make sure you clearly link this data to a suitably large site plan, provided in the following groups:

- **General site data**
  -basic design parameters and permitted waste inputs;
  -gas control and utilisation systems installed (and proposed);
  -time since waste disposal commenced and expected completion date;
  -gas abstraction data.

- **Specific data**
  -gas monitoring results and conclusions;
  -proposed remedial actions and their timetable;
  -further gas monitoring proposals.

Where your site doesn't meet an emission standard, you should identify necessary remedial actions (and their location) and the your proposed timescales for their implementation (see Appendix E).

Where you consider that the collected data do not adequately reflect emission conditions and that remedial actions are not necessary, state this in your report along with your proposals for repeating or expanding the monitoring and assessment exercise.

Where the cap is heterogeneous and the maximum emission rate above the standard even though the most probable rate is below the standard, your report should explain how you intend to reduce uncertainty in future surveys, for example by reducing the spacing between sampling locations.

Your report must include a timetable for replacing any temporary or interim capping with a permanent cap.

9.3 Remedial actions and reporting

Appendix E3 contains a summary form for describing remedial actions necessary to achieve compliance with the relevant emission standard. This schedule addresses the key zones and features on a site, identifies the range of appropriate actions and sets out an action programme. This forms the basis of the remediation plan you will need to agree with us. You will need to regularly update this plan in the light of subsequent activities and monitoring data.

When you have carried out remedial actions, monitor those works as soon as possible after completion to check compliance. Again, report the results of this to us in the format recommended for subsequent reports (see Appendix E2).

9.4 Assessment by the Environment Agency

We will assess of the data you provide.

This assessment will cover:

- the results of the annual emissions survey;
- the remediation plan;
- reports of any remedial work undertaken to reduce emissions;
- the appropriateness of monitoring carried out for the particular zones;
- compliance with emission standards;
- the site's total methane emissions for the zones monitored;
- the adequacy of the remedial action plan (where appropriate);
- the timescale for testing after any remedial work.

Our assessment will take account of the potential impact of the gas emissions on local receptors.

9.5 Second and subsequent reports

Second and subsequent regular reports (see Appendix E2) should include a summary of any key changes to your general site data. Present the new monitoring data and your interpretation in full and, where relevant, compared with the results of previous monitoring exercises and related to the conceptual model of your site.

For a stable zone where a walkover survey is reported rather than a full flux box survey, you must state your reasons for assuming the results of the previous flux box survey are still valid. Report your progress towards replacing any temporary capping with a permanent cap. These statements are necessary to allow us, as well as you, to see the overall pattern of operations and emissions from your site since monitoring began.

Potential changes

Gas management is dynamic and some changes will occur over a period of years. The fact that a zone has historically complied with the surface emission standard does not mean it will necessarily continue to do so as the landfill matures and site operations change. Your reports form part of your regular review of the gas management plan for your site.

Over a period of years, a body of information will build up on the long-term emission pattern from zones and features on your landfill site. On a stable site, you may use this information to target a more limited flux box survey towards features that have historically been potential weaknesses in the gas management system.

Appendix A: Flux box construction

A1 Flux box characteristics

A passive flux box consists of an enclosure of known volume, with two ports fitted to the top. The inlet port is used for pressure equilibration and the outlet port for removing samples. This arrangement facilitates the sampling of gases without disturbing the pressure within the box.

We analyse the methane concentration inside the box using a portable gas detector such as a flame ionisation detector (FID) or an instrument with a similar sensitivity and response time.

The device described in this guidance is made of materials that are readily available commercially. The main features of its design are:

- a simple enclosure with a level, open base that can cover an area of approximately 0.33–1 m^2 ;
- two controlled openings on the top face of the box;
- a sampling line;
- a gas detector with an optional data logger.

The equipment shown in Figure A1 is a plasterer's bath, which is made of plastic and is about 150 mm high. It has a lip to give it rigidity.

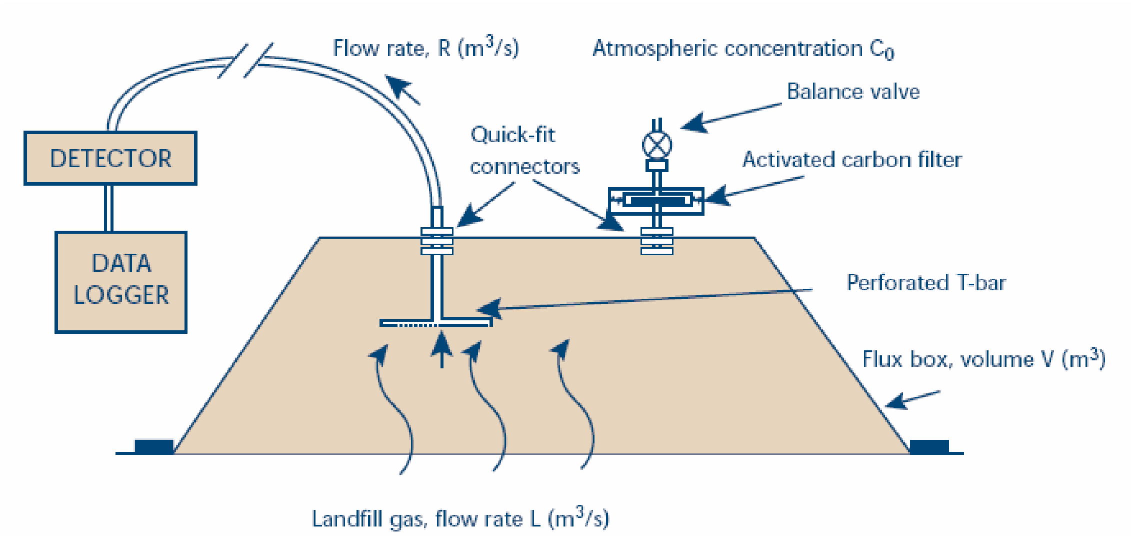


Figure A1 Schematic of a passive flux box

Table A1 lists the essential items needed to construct this device and potential sources of these components.

A manual or battery operated 'paddle' may be fitted within the box to promote gas mixing. The need for this additional device will depend on the dimensions of the flux box and the rate of surface flux; for example, low flux rates take longer to diffuse within the box. A large footprint with a small volume will integrate the emissions over a larger area, but there will be poor mixing within the container. A pyramidal design represents the optimum theoretical shape for a flux box.

Flux boxes typically have a footprint of less than 1 m^2; the design shown in Figure 2.1 is a reasonable compromise between footprint area, volume to footprint ratio, ease of construction and practicability on site.

Alternative designs for a flux box include the use of a box without a lip made from more rigid and durable material or a two-part box with a detachable base. In the latter case, the sealing process could be achieved in two steps.

First, the rigid basal section could be set on the ground and sealed without regard to the time taken to prepare the seal, that is, gas will not be able to accumulate. Then, the box top could be placed over the basal section, with the application of a grease (or similar) coating to affect an improved seal between the two components.

Flux tents are larger containers that cover a larger area with a pyramidal framework covered in a gas impermeable membrane. However, the gas in the enclosed space may not be homogeneous and it is essential that adequate mixing of the gas is demonstrated and that the device is sufficiently rigid to enclose a consistent volume before these devices are employed.

The sample must be withdrawn from the bath at a point where the gas is representative of the mixture in the flux box. The volume withdrawn must not be so great as to cause significant dilution of the remaining gas.

A2 Gas sampling and analysis equipment

The analytical equipment used for methane measurements must have the following characteristics:

- portability
- low detection limit (0.5–1 ppmv)
- high sensitivity (resolution <1 ppmv)
- wide detection range: (0.5 ppmv to 10,000 ppmv)
- fast response time
- weather resistance.

Because most instruments only have a direct readout facility with measurement in ppmv, it will generally be necessary to convert the results to mg/m^2 (the units required in the calculations).

The gas analyser used should be capable of resolving small changes in methane concentrations over a period of a few seconds during an overall monitoring period of several hours.

Flame ionisation detector

A portable instrument such as a flame ionisation detector (FID) with a range over five orders of magnitude from 0.5–1,000 ppmv is the minimum requirement. Because a FID actually responds to a number of hydrocarbon gases, it will tend to overestimate the methane concentration. However, the dominant hydrocarbon in landfill gas is generally methane and so the FID reading can be regarded an adequate measurement of the change in methane concentration. The most important feature is the ability to assess the rate of concentration change with precision (that is, repeatability) rather than absolute concentration accuracy. It is particularly important that the response of the instrument is linear over the designated range. ‘Zeroing’ to a set point is desirable, but less critical than linearity over the usable range.

Reading measurements

A digital scale for reading output is easier to use for flux box measurements than an analogue scale. Digital instruments for use in the field are now available with in-built data loggers. However, a paper log of the measurements taken in the field is essential for checking the quality of the digitally recorded data and as protection against data loss (for example as a result of battery failure).

A3 Flux box assembly instructions

As well as the items listed in Table A1, you will also need thread tape and some white paint. The main steps in the assembly of a passive flux box are:

- Determine the centre of the top of the bath or similar container. Drill a hole to fit 5/16 inch quick-fit connectors at two locations about 20 cm from centre (along box length).
- Fit quick-fit connectors into the drilled holes and secure with a nut from inside. Thread tape should be used to improve seal between connector and nut.
- Connect the filter assembly and the balance valve (this is fitted by the supplier with quick-fit plug on one side) to one of the quick-fit connector sockets. Screw the balance valve into the threaded hole of the filter assembly.
- Assemble the perforated T-bar by connecting both perforated pipes into the three-way connector with open ends facing the inside of the connector. The pipes should form a straight line (that is, the cross bar of the 'T'). Fit the Teflon tube into the connector at 90^o to the perforated pipes. Connect one end of the Teflon tube to the threaded tube connector. Screw assembly from the inside the box as for filter assembly.
- Paint the outside of box white or similar.

The box is ready for use when an effective basal seal is achieved on-site and the methane detector is connected, together with a data logger (if required).

Table A1 Schedule of flux box components and potential sources

Item	Size	No.	Example sources
Plasterer's bath or similar plastic container	Volume: 0.15 m^3 Footprint: 0.61 m^2	1	Builders' merchants
Quick-fit connectors (including nuts to fix connectors)	5/16 inch outside thread and 3/16 inch inside thread (both at the rear end)	2	Stuart Well Services Ltd[1]
Balance valve	3/16 inch thread connection	1	Stuart Well Services Ltd Telegan Gas Monitoring Ltd[2]
Activated carbon filter	As per standard size	1	Telegan Gas Monitoring
Perforated T-bar consisting of: -two perforated pipes blocked off at one end -one PTFE three-way connector -Teflon tubing and threaded tube connector (3/16 inch outside thread to fit inside quick-fit connectors)	 -180 mm long x 4 mm diameter (approx.). -4 mm inner diameter -25 cm long x 4 mm outer diameter	1 2 1 1	Stuart Well Services Ltd Telegan Gas Monitoring
FID or gas detector with similar sensitivity and responsiveness		1	Telegan Gas Monitoring Geotechnical Instruments[4] GMI Ltd[5]
Data logger*		1	Digitron Instruments[3] Telegan Gas Monitoring

1 Stuart Well Services Ltd, Stuart House, Crows Hall Lane, Attleborough, Norfolk NR17 1AD
2 Telegan Gas Monitoring Ltd, The Fleming Centre, Fleming Way, Crawley, West Sussex RH10 2NN
3 Digitron Instruments Limited, Mead Lane, Hertford SG13 7AW
4 Geotechnical Instruments, Sovereign House, Queensway, Leamington Spa, Warwickshire CV31 3JR
5 GMI Ltd, Inchinnan Business Park Renfrew, PA4 9RG.
* Not essential. Data may be recorded manually, but some FID analysers are already fitted with an internal data logger.

Appendix B: Example forms

This appendix contains examples forms for:

- site characterisation
- recording site monitoring data.

B1 Example form: site characterisation

It is important to establish a site's key characteristics before carrying out any survey or monitoring. This also facilitates the subsequent interpretation of data and the preparation of reports for the Environment Agency, as well as enhancing your records. You should summarise your site's key characteristics in a consistent format on the example form.

During the course of the overall monitoring regime, several site characteristics might vary in the light of operational or other changes, for example, introducing or shutting-down an active gas abstraction systems.

Date and amend your site's characterisation details in line with the actual site conditions.

B2 Example form: site monitoring record

Recording the concentrations of methane at particular time intervals is central to the surface flux assessment process. Use the example form to ensure a clear audit trail for the collected data.

B1 Example form: site characterisation

SITE CHARACTERISATION SUMMARY

Site name/address: .... Licence/permit no: .... Report no: ....

....

Licence/permit holder: .... Issued: .... Date: ....

Period since commencement of waste disposal: ....

Residual operational life (permitted): .... Drawing nos.*: ....

Site plan: ....

*Showing locations of key features/activities addressed below

Basic Skills characteristics	● Waste disposal area ● Primary engineering measures/designs (drawing numbers)	● Net site area ● Permitted volume ● No. of cells ● Planned life ● Liner design ● Permanent capping design ● Final surface side slope characteristics
Current site status	● Waste/capping and filling	● Permanently capped zone and number of gas wells/other gas extraction methods ● Temporarily capped zone and number os gas wells/other gas extraction methods ● Current filling area and nature of gas extraction ● Period since commencement of cell filling ● Expected period before capping
Waste inputs	● Permitted ● Actual ● Filled cell details	● Gross volume ● Rate of infill ● Waste composition (percentages) ● Volume received to date ● Composition (if different) ● Cell no - Volume - Age (average) - Depth
Active environmental controls	● Gas management system(s) ● Normal condition of system	*Permanent controls* ● Capped area (percentage of site) ● Gas abstraction: extent/capacity *Temporary controls* ● Number of engines and flares ● Normal gas abstraction rate ● Normal suction on the field ● Settings on gas balancing system ● Normal oxygen content of gas

Comments:

B2 Example form: site monitoring record

SITE MONITORING RECORD

Site name/address: .... Report no: . ...

....

Date(s) of monitoring: .... Report Date: ....

Weather	Atmospheric Pressure	Rising/falling	Temperature	Description (wet/dry/sunny/windy .)
Day of monitoring				
Week before (generally)				

Continuous monitoring data traces are desirable for one week before if available.

Site Conditions	
● Current gas abstraction rate ● Current suction on the field ● Settings on gas balancing system ● Methane content of extracted gas ● Current oxygen content of extracted gas Location of pipework and leachate wells General nature of cap (for example, open, grass cover, post-closure use)	

Zones	Number of flux box positions	Area	Ref. no. raw data Monitoring sheets*	Comments
Permanently capped zones				
Temporarily capped zones				
Features				
Fissures				
Gas wellheads, monitoring and pipework				
Leachate wells and monitoring points				
Side slopes, junctions, edges and buried pipework				
Other features				

* Provide a data recording sheet for individual flux box locations with date/time, grid co-ordinates (from global positioning system if possible), gas concentration over time, and so on.

General Comments:

Appendix C: Calculating rates of emissions

C1 Example calculation of methane flux (Q)

$$Q = \frac{V \text{ x } (\text{dc/dt})}{A}$$

Internal flux box volume (V) = 0.15 m^3
Flux box footprint (A) = 0.61 m^2

dc/dt = gradient of graph of methane concentration (mg/m^3) versus time (seconds)

= 0.5 mg/m^3/second (say) (see below)

$$Methaneflux(Q) = \frac{0.15m^3 \text{ x } (0.5 \text{ mg/m}^3\text{/second})}{0.61m^2}$$

= 0.12 mg/m^2/second

C2 Calculation of correlation coefficient

The manual calculation below illustrates how the correlation coefficient is calculated. Electronic spreadsheets will calculate r^2 automatically and are recommended.

$$r^2 = \frac{n\Sigma t \text{ x } c - (\Sigma t)\ (\Sigma c)\ ^2}{\sqrt{}\{[n\Sigma t^2 - (\Sigma t)^2][\ n\Sigma c^2 - (\Sigma c)^2\}}$$

where:
n = number of measurements
t = individual time measurements
c = individual concentration measurements.

Table C1 below shows the data used to plot the graph shown in Figure 7.1a. In this example of a low flux area, n = 21.

Table C1 Data used to plot the graph shown in Figure 7.1a

t (seconds)	c (mg/m^3)	t (seconds)	c (mg/m^3)
0	4.3	330	18.6
30	7.9	360	19.3
60	9.3	390	19.3
90	10.7	420	20.0
120	12.1	450	20.0
150	12.9	480	20.7
180	12.9	510	22.1
210	14.3	540	20.0
240	15.0	570	22.1
270	16.4	600	22.1
300	17.9		

Substitution in the equation gives r^2= $(0.961)^2$ = 0.923.

C3 Calculation of dc/dt

Below is an example for the calculation of the slope using the data from an area with low flux shown in Figure 7.1a. Figure 7.1b shows the best-fit trendline after manipulation in accordance with the data acceptance criteria; the best-fit trendline or slope (gradient) represents the quotient dc/dt. These gradients (or slopes) can be determined graphically by determining the difference between the intercepting lines on the x-axis (dc) and dividing this by the difference between the intercepting lines on the y-axis (dt). The graph slopes can also be calculated using the equation below or electronically using simple spreadsheets. These two latter methods provide more accurate results.

$$dc/dt = \frac{n\Sigma t \times c - (\Sigma t)(\Sigma c)}{n\Sigma t^2 - (\Sigma t)^2}$$

Using the data from Table C1 from Figure 7.1a, dc/dt = 0.0266.

C4 Calculation of methane emission from flow rate

In cases where a flux box will not physically fit over a feature, the flux can be quantified by measuring the methane concentration and the flow rate. Multiplying these two values together gives the mass flow per second. Measuring the area from which this gas escapes allows a flux to be calculated. This will only give a semi-quantitative value, but may be helpful in ranking the magnitude of the emission from a discrete feature.

A hot-wire anemometer is recommended for measuring the velocity of the gas flow. However, this equipment is not ATEX certified so additional risk assessments must be made before using this equipment. The escaping gas may contain significant amounts of trace components, which may have auto-ignition temperatures close to the temperature of the hot wire (ca. 140^{o}C) and so you must use it cautiously. Readings from a hot-wire anemometer depend on the thermal conductivity of the gases being measured; for example, a methane-rich gas will show a different reading from an identical flow of carbon dioxide-rich gas.

Example calculation using a hot-wire anemometer and a gas analyser
The **landfill gas velocity** (in metres/second) as measured with the anemometer is converted to a **landfill gas flow rate** (that is, to litres/second) by multiplying the cross-sectional area of the feature (in m^2) by 1,000 (that is, litres/m^3).

Example

Landfill gas velocity = 0.1 metres/second
Pipe diameter = 300mm
Landfill gas flow rate = 0.1 metres/second x 0.0755 m^2 x 1,000 litres/m^3 = 7.5 litres/second

Calculate the **methane flow rate** by multiplying the landfill gas flow rate by the methane concentration (per cent v/v) – as measured with the gas analyser.

Methane concentration = 45 per cent v/v
Methane flow rate = 7.5 litres/second x 45 per cent v/v = 3.4 litres/second
The **methane mass flow** is calculated by multiplying the methane flow rate (litres/second) by the molecular weight of methane (16 g/mole) and dividing by the molecular volume of methane (22.4 litres/mole).

$$\text{Methane mass flow} = \frac{3.4 \text{ litres/second} \times 16 \text{ g/mole}}{22.4 \text{ litres/mole}}$$

= 2.43 g/second or 2,430 mg/second

This represents the emission rate from the whole feature. Dividing this rate by the area of the feature will give an estimate of the flux in mg/m^2/second.

Appendix D: Managing errors and uncertainty

D1 Potential sources of error or uncertainty

Uncertainty in the overall emission from a zone or feature can arise:

- from the precision and accuracy of individual measurements made at the sampling locations;
- from the selection of sampling locations;
- when linking the individual measurements to the overall value.

D1.1 Errors at the monitoring location

Potential errors at the sampling location are of two main types:

- instrumental
- local environmental factors.

Instrumental errors

Errors introduced during measurements are easier to identify. The guidance given in this document outlines procedures that will minimise these by:

- preventing leakage around the seal;
- avoiding solar warming;
- minimising cooling by wind chill;
- taking the sample from a well mixed, representative part of the flux box;
- only taking a small portion of the collected gas as a sample;
- taking account of instrumental drift.

Leakage around the seal is probably the most significant source of instrumental error in a well-designed flux box.

Local environmental factors

Factors that can affect the validity of the measurements include:

- high ambient air concentrations of flammable gases;
- discrete features and surface conditions which can impact on emissions at the point of measurement.

If there is a significant concentration of methane in the ambient air, the background or starting concentration in a flux box will be high. This reduces sensitivity and makes it difficult to measure low fluxes near the emission standard. Ambient methane concentration may be high close to or downwind of working areas, or where engineering work is in progress. The effect of this can be partially overcome by ensuring the inlet to the pressure balancing port is fitted with an activated carbon filter to prevent ambient flammable gases (such as diesel fumes) being sucked into the box during sampling.

Any discrete features with significant emissions identified during the walkover survey should normally be remediated or eliminated before undertaking a full flux box survey.

The importance of noting atmospheric conditions before and during the surveys cannot be over emphasised, as these are major influences on the measured flux. Waterlogged ground after heavy rain, sudden changes in atmospheric pressure, frost or high wind speeds can all change the measured flux by at least an order of magnitude. Carry out surveys under stable or gently falling atmospheric pressure, with a moderate to low wind speed, and not within **two days** of heavy rain.

The size of the potential error at monitoring locations
Monitoring errors fall into three categories:

- Errors likely to involve small variations (±100 per cent of the measured value), including:
  -solar warming
  -wind chill
  -poor mixing or sample withdrawal
  -instrumental drift.
- Uncertainty likely to involve order of magnitude variations, including:
  -diurnal and seasonal variations
  -rainfall
  -poor seals.

Factors likely to make the measurement invalid. These include fluctuating ambient air concentrations due to:

-high methane from operational/uncapped zones;
-diesel-engine vehicles operating in the vicinity of the survey (landfill machinery or road traffic);
-upwind sources of pollution (for example, from industrial processes).

D1.2 Selecting representative locations

Calculating the overall emission rate of a zone using measurements from a series of flux boxes can give rise to considerable uncertainty.

The main sources of this uncertainty are:

- inappropriate selection of sampling locations;
- inadequate interpretation of the aggregated data.

The potential error will be greatest on sites that have a number of zones with very different characteristics. It will be particularly high if the zones are ill-defined, vary in size and are heterogeneously distributed.

Representative locations
Selecting locations that will be representative of the whole zone requires careful judgement of:

- the locations in each zone;
- the pattern in which these sampling locations are laid out.

Any grid survey – regular or random – will miss some anomalies. This is particularly true for flux box surveys that need to cover a very large zone and so will typically use a low-density grid (see Section 5.5) The results of the walkover survey will have a strong influence on flux box sample locations, as these will be at a much higher sampling density (usually 5 m transects).

It is important to design a sample grid pattern that has a high probability of identifying all anomalous areas. Simple rectangular grid patterns give a relatively poor probability of finding all the features unless the grid spacing is very small.

Research has shown that a herringbone grid is the best design for locating anomalous features within a survey area (for example, Ferguson and Abbachi, 1993; DoE, 1994). If the suspected area is of a known size then a triangular grid can be used (Smith 2005). Table D1 shows the relationship between a herringbone grid spacing and the probability of detection of a circular 25 m^2 feature – typical of a surface fracturing or less well-engineered cap.

The probability is significantly less if the feature is elliptical or the grid pattern is regular.

It is unlikely that flux box surveys alone – even using a herringbone grid pattern – will identify all the anomalies. A detailed walkover survey must be carried out first to identify features and zones, before deciding where to place the flux boxes.

Table D1 Relationship between a grid spacing and probability of detecting a circular 25m^2 feature using a herring bone layout

Grid spacing (metres)	Size of grid cell (m^2)	Target area (m^2)/grid cell (m^2)	Probability of detection (%)
5	25	1.00	90
10	100	0.25	25
15	225	0.11	10
20	400	0.06	6
30	900	0.03	3

Combining measurements

Linking the individual measurements to the overall value requires judgement. Calculation of the average and total flux from a zone based on discrete sampling point measurements will depend on the relative weighting given to each point. There are several methods of dealing with this.

If a regular grid or herringbone grid is used, there is no need to weight the contribution for the area associated with each flux measurement. However, it is difficult to achieve a regular grid and this method is likely to overestimate emissions from discrete sources that have been intercepted by a single flux box.

A more statistically valid approach is termed ‘kriging’ (Webster and Oliver, 1990). Kriging gives weighted averages for points at varying sampling distances and is usually computer-generated. This method is particularly appropriate where irregular grids are used and/or where ‘hotspot’ zones have been delineated by additional flux boxes at a reduced spacing around the anomaly.

Magnitude of total uncertainty

The potential error due to aggregating the measurements at several locations is indicated below.

Assigning different radii of influence to sampling points has a profound effect on the average value for a zone. The change in the average value will be greatest when the variation between individual adjacent values is greatest. When adjacent sampling locations have very different flux rates, the precise area over which any particular measurement is representative is difficult to quantify. However, the maximum and minimum values can normally be determined with more confidence.

By way of illustration, three approaches to estimating the flux of methane are considered below using typical site data. In this example, the walkover survey identified a high emission zone within a larger, low emission zone.

The three estimates of methane emission are:

- the crude average of all the values within the zone (0.08 mg/m^2/second);
- assuming a 20 m^2 area of influence around each sample point (0.036 mg/m^2/second);
- assuming the area of a flux box itself placed on each of the surface points within the zone which gave a measurable surface emission reading during the walkover survey; that is, no zone of influence around each sampling point (0.0067 mg/m^2/second).

The values calculated from the three approaches span an order of magnitude difference. On a heterogeneous site, therefore, the data should be reported as a maximum, a minimum and a most likely value. This range is likely to be the greatest source of uncertainty in the flux from a site with a heterogeneous or variable surface.

Appendix E: Reporting surface emissions to the Environment Agency

This appendix contains information on the contents of:

- initial report in the initial report to us;
- subsequent reports;
- remedial action schedule (summary).

E1 Initial surface flux report

Table E1 lists the main items that should be included

Table E1 Items for initial report to the Environment Agency

Item	**Relevant section of this guidance**
Executive summary	Remedial action schedule (Appendix E3)
Summary of desk study information	Appendix B Form Section 3
Summary of site walkover and surface scanning exercise	Appendix C1 Form Section 4
Design logic used for monitoring survey	Section 5
Summary of emissions data	Appendix C2 Form Sections 6 and 7
Compliance assessment and consequent remedial actions	Sections 8 and 9
Date of proposed next report	Section 5
Enclosures/appendices: • site plan(s) with: - defined zones and features; - monitoring locations. • monitoring data; • site photographs of: - general features; - key features. • detailed calculations of emission rates; • detailed specifications and programme for any remedial actions.	

E2 Subsequent surface flux report

Second and subsequent reports to the Environment Agency should be as brief as possible. The report should emphasise any key changes in site conditions whether in respect of emissions, new environmental control systems (for example, temporary or permanent capping) or critical surface changes (such as settlement).

Structure subsequent reports as shown in Table E2.

Table E2 Items for subsequent reports to the Environment Agency

Item	**Relevant section of this guidance**
Executive summary	Remedial action schedule (Appendix E3)
Key site changes since previous survey	
Summary of monitoring strategy	
Summary of emissions data	
Summary of emissions data	
Compliance assessment and consequent remedial actions	
Date of proposed next report	
Enclosures/appendices: • site plan(s) with: - defined zones and features (if revised from previous report); - monitoring locations. • monitoring data (flux box or walkover survey); • site photographs (as relevant to any material changes); • detailed calculations of emission rates or justification for basing current annual emission on previous flux box survey; • detailed specifications and programme for any remedial actions.	

E3 Remedial action schedule

SURFACE FLUX REPORT

REMEDIAL ACTION SCHEDULE (Summary)

Site name/address: .... Site permit/licence holder: ....

....

Date: .... Schedule no.: ....

Zones/features	**Survey date Point sources**	**Compliant?**	**Proposed action**	**Programme**	**Post-action compliance testing**	**Date of testing**	**Further actions**
Permanent capping zones (PC)							
Temporary capping zones (TC)							
Fissures (F)							
Gas wellheads (G)							
Leachate chambers (L)							
Side slopes (SS)							
Point sources							
Other features							

Appendix F: Surface scanning techniques

F1 Surface scanning

Before making a detailed map of a large area, it can be helpful to screen the surface of the landfill to facilitate preliminary zoning. Scanning the surface with a semi-quantitative monitoring method linked to positional information allows mapping of areas with very high and very low emissions, and helps to identify the extent of areas with similar surface emissions.

Two approaches are described here:

- hyperspectral scanning
- emissions mapping.

F2 Hyperspectral scanning

A large area of landfill can be screened in a single operation using an optical scanning technique. The equipment is fitted in an aircraft, which overflies the landfill or zone of interest.

Hyperspectral scanning responds specifically to methane/carbon dioxide and can indicate the principal areas of methane and carbon dioxide gas emission activity, and their relative scales. This allows the survey team to focus more efficiently on the relevant portions of the landfill surface and is particularly valuable on large sites.

The technique is not yet widely available and is expensive, and so cannot be seen as a routine element in the assessment process. Moreover, the method only produces qualitative data and thus needs to be calibrated for quantitative assessment.

Figure F1 shows an example of hyperspectral scanning performed at a municipal solid waste (MSW) landfill. The trapezoidal area on the left has a one metre cap with gas wells at a 50 metre spacing. The area on the right is provided only with a 30 cm temporary soil cover. Note the high flux edge feature where new fill (1999) abuts Victorian river embankment engineering, and several high flux 'hotspots' within the temporary capped zone. Each pixel represents five metres by five metres: the sensor is aircraft mounted and flown at 6,000 feet. (Personal communication from Dr Gavin Hunt, Hunt Spectral Consultancy, Faringdon, Oxfordshire, UK)

F3 Emissions mapping

High quality GPS can be linked to simple monitoring devices to provide surface mapping profiles of particular characteristics. Survey packages integrate a lightweight GPS unit to a general-purpose hand-held gas monitor using a computer data logger.

For emissions of landfill gas, a flame ionisation detector (FID) or a photoionisation detector (PID) may be used. A walkover or drive-over survey on a raster pattern will give mapping resolution down to the metre level. The output is presented as a site map with the concentrations of gas detected by the monitor displayed semi-quantitatively as coloured zones (that is, a similar presentation to that illustrated for hyperspectral scanning).

This technique provides more comprehensive mapping than can normally be achieved by a simple walkover survey. You can use the spatial information in the preliminary survey to identify and relocate features with high surface emissions. During planning of the flux box survey, you can apply the scanning data to delineate zones with a similar flux over an extensive and heterogeneous area, and so facilitates the selection of representative sampling locations.

These surveys are available commercially under proprietary names (for example, Groundhog).

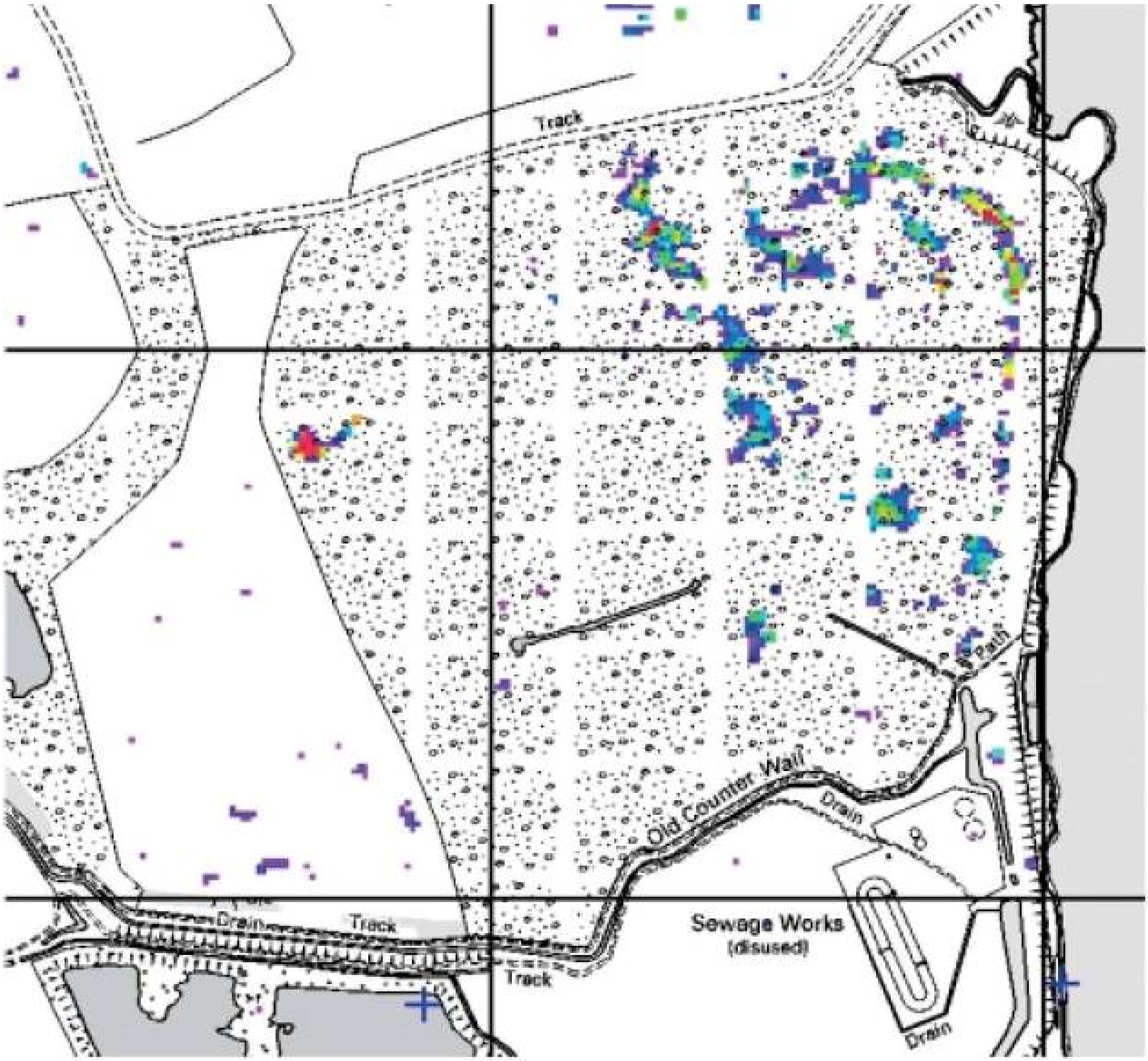


Figure F1 Hyperspectral scanning image illustrating areas of high methane concentrations at the surface of a MSW landfill (Note: higher methane concentrations are shown by the ‘red end’ of the spectrum colours)

Glossary

Feature
A discrete, definable area or installation that may emit gas at a higher rate than the surrounding zone.

FID
Flame ionisation detector. Can measure total flammable gas [usually 98 per cent methane in a landfill context] concentrations in parts per million by volume (ppmv).

Fissure/fissured area
A feature, or series of features within a specific area, where the site surface is cracked such that it is likely to have a greater permeability to gas than the surrounding surface.

Flux box
A chamber that, when sealed against a landfill surface, allows surface emissions to enter by diffusion as a result of the concentration gradient between the landfill surface and atmosphere.

GPS
Global positioning system

Hyperspectral scan
An airborne sensor that detects methane and carbon dioxide by virtue of the degree of absorbance of reflected light at gas specific frequencies.

Kriging
A computer-based statistical technique for estimating the contribution of adjacent monitoring points.

Landfill gas
All the gases generated from the landfilled waste.

Landfill site
A waste disposal site for the deposit of the waste onto or into land under licence or permit.

Monitoring
A continuous or regular periodic check to determine the ongoing nature of a potential hazard, conditions along environmental pathways and the environmental impacts of landfill operations to ensure the landfill is performing according to design. The general definition of monitoring includes measurements undertaken for compliance purposes and those undertaken to assess landfill performance.

Operational area
Part of landfill site still receiving wastes and which has not been capped temporarily or permanently.

per cent v/v
Percentage composition of a gas on a volume basis.

Permanently capped zone
A filled, capped area that will not receive any further waste for disposal within the period of the current permit. This cap may not yet be the final capping.

ppmv
parts per million by volume, an expression of concentration. 10,000 ppm v/v equates to 1 per cent v/v gas at STP by volume.

STP
Standard temperature and pressure. Used to normalise gas data to 273K (0ºC) and 101.3 kPa (1 atmosphere)

Temporarily capped zone
Area of landfill that, according to the current site operational plan, has not reached its final profile but is scheduled to receive no further waste for disposal during a period of at least 3 months, and which has been covered with an interim capping material.

Zone
An extensive area of the landfill surface that is generally uniform and homogeneous in those factors that will affect surface emissions (for example, capping/completion quality, slope).

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