

Landfill gas fugitive emissions monitoring guideline



Environment
Protection
Authority Victoria

Publication 1684, February 2018

Guideline

Contents

1. Introduction.....	2
1.1 Document history.....	2
1.2 Scope and purpose.....	2
1.3 Application of this guideline	2
1.4 Legal status of this guideline.....	2
1.5 Health and safety precautions	2
2. Objectives of landfill gas fugitive emissions monitoring.....	3
2.1 Notification to EPA where BPEM landfill gas action levels are exceeded.....	3
3. Key factors that influence the monitoring of landfill gas.....	3
4. Instruments.....	4
4.1 Extractive landfill gas analysers (category 1).....	4
4.2 Low-concentration methane detectors (category 2).....	4
5. Landfill final cap and intermediate cover areas – surface emissions of methane	5
5.1 Instrument.....	5
5.2 Purpose	5
5.3 Monitoring locations.....	5
5.4 Method.....	6
5.5 Monitoring frequency	7
5.6 Notification to EPA where surface emissions action levels are exceeded	7
6. Subsurface geology – landfill gas concentrations, relative pressure and gas flow rate	8
6.1 Instrument.....	8
6.2 Purpose	8
6.3 Monitoring locations.....	8
6.4 Method.....	8
7. Methane monitoring in subsurface services	11
7.1 Instrument.....	11
7.2 Purpose	11
7.3 Monitoring locations.....	11
7.4 Method.....	11
8. Methane monitoring in buildings and structures	12
8.1 Instrument.....	12
8.2 Purpose	12
8.3 Monitoring locations.....	12
8.4 Method.....	12
Glossary.....	14
References.....	15
Appendix A: General quality control considerations.....	16
Appendix B: Example perimeter gas bore monitoring sheet	18
Appendix C: Guidance for determining background ground gas concentrations.....	19
Appendix D: Method for methane surface emissions quantification using a flux box (not for compliance purposes)	21

Landfill gas fugitive emissions monitoring guideline

1. Introduction

1.1 Document history

Following consultation in 2011, EPA published a draft landfill gas fugitive emissions monitoring guideline. The addition of mandatory landfill gas fugitive emissions monitoring conditions in all landfill licences and post closure pollution abatement notices (PC PANs) (for the ongoing management of closed landfills) meant that consistent monitoring methodologies were required. Since publication of the draft guideline, the key landfill management document in Victoria: *Best Practice Environmental Management; Siting, Design, Operation and Rehabilitation of Landfills* (EPA publication 788 (as amended) known as the 'Landfill BPEM') has been updated, hence the need to update and finalise this guideline. As with any kind of monitoring, consistent methods must be used to ensure that decisions made based on the interpretation of the monitoring results are appropriate. This guideline should be used and followed by trained and experienced personnel when undertaking landfill gas fugitive emissions monitoring.

1.2 Scope and purpose

A consistent approach is needed for landfill gas fugitive emissions monitoring across the state. This guideline establishes procedures for the collection of landfill gas fugitive emissions data. This guideline standardises the steps involved in monitoring and methods to use when collecting representative, quality data for compliance reporting to EPA, providing data to EPA-appointed environmental auditors and remediating the landfill cap and infrastructure – including optimising landfill gas collection systems.

The landfill gas fugitive emissions data collected using this guideline can be relied upon to determine whether the gas action levels in Table 6.4 of the BPEM are being met or exceeded.

1.3 Application of this guideline

EPA Victoria is committed to raising environmental performance standards of landfills across the state and providing appropriate guidance to enable all stakeholders to understand what is expected. This guideline is designed to support the approach to landfill management described in the BPEM; it is important that both documents are read in conjunction.

Interpretation of the collected data is not within the remit of this guideline but should always be undertaken by a suitably qualified professional. The intent of this guideline is to provide such a professional with confidence that the data presented to them is of a suitable quality to make appropriate interpretations.

1.4 Legal status of this guideline

This guideline is advisory in nature. Technical details in this guideline are suggested measures for meeting the requirements of the *Environment Protection Act 1970*.

1.5 Health and safety precautions

The risks associated with landfill gas monitoring must be carefully assessed before starting work. Appropriate risk management measures must be in place and all site safety procedures should be followed. Risks may arise from a range of hazards associated with monitoring and from the prevailing physical conditions. Some of the hazards include:

- exposure to explosive concentrations of methane
- exposure to asphyxiating conditions (lack of oxygen)
- exposure to a range of volatile organic compounds (VOCs) and trace gases
- other general hazards related to landfills.

Landfill gas fugitive emissions monitoring guideline

2. Objectives of landfill gas fugitive emissions monitoring

The objective of this guideline is to set standard methods for the monitoring of landfill gas fugitive emissions and to:

- determine if emissions of landfill gas exceed the gas action levels in the BPEM
- enable a landfill gas risk assessment to be undertaken by determining the concentration, relative pressure and flow of landfill gas in the environment – or entering the environment – from a specific source
- assess the effectiveness of landfill gas control measures, such as the operation of a landfill gas collection system or landfill liner and cap integrity
- provide data for emissions inventories
- provide some of the data required for assessing the collection efficiency of the gas collection system.

It is critical to use appropriate monitoring methods and equipment correctly, so that results are representative of conditions at the site and can be used to achieve the monitoring objectives.

2.1 Notification to EPA where BPEM landfill gas action levels are exceeded

The action levels for landfill gas at different monitoring locations are set out in Table 6.4 of BPEM. When monitoring shows these action levels are exceeded, the landfill operator or owner must notify EPA within 24 hours, except where surface emissions exceedances are rectified within 24 hours. Licence condition LI_G2 and PC PAN requirement LC14 state that landfill operators or owners must immediately notify EPA of non-compliance with any licence condition or PC PAN requirement, by calling 1300 EPA VIC (1300 372 842), sending an email to contact@epa.vic.gov.au, or by using the EPA Interaction Portal (licensed sites only). Further information on this notification requirement for operating and closed landfills is given in Section 6.7.1 of the BPEM.

3. Key factors that influence the monitoring of landfill gas

It is important to review the conceptual site model prior to undertaking any monitoring. To ensure representative results are obtained, the following factors should be considered when monitoring landfill gas:

- site features, including:
 - landfill size, layout, design and age
 - types of wastes accepted
 - geology and hydrogeology
 - the location of intermediate cover and final caps
 - location of sensitive receptors
 - leachate management
 - bore design, installation and location
 - training and experience of personnel undertaking the monitoring
 - topography
- meteorological and environmental conditions (refer to Appendix A), including:
 - atmospheric pressure
 - rainfall
 - wind
 - frost
 - excessive vegetation
- the type of landfill gas monitoring being conducted:
 - landfill surface final cap and penetrations through the final cap
 - landfill surface intermediate cover and penetrations through the intermediate cover
 - subsurface geology (via appropriately designed, installed and sealed landfill gas monitoring bores)
 - subsurface services
 - buildings and structures.

Refer to Appendix A for general quality control considerations.

Landfill gas fugitive emissions monitoring guideline

4. Instruments

The applicable field instruments generally fall into two categories;

- **Category 1 (for landfill gas monitoring bores)**
Extractive landfill gas analysers that measure volumetric concentrations (% v/v) of methane, carbon dioxide, oxygen and, depending on the configuration selected, the trace gases carbon monoxide, hydrogen sulphide, ammonia and hydrogen in parts per million (ppm). These analysers must also measure bore relative pressure (mb or hPa) and gas flow (L/Hr). Gas flow is included as a parameter to be measured due to its importance in landfill gas risk assessment.
- **Category 2 (for other monitoring locations)**
Low-concentration methane detectors that measure methane in parts per million (ppm) are generally used for monitoring emissions of methane from: the surface of the landfill and penetrations through it; subsurface services; and buildings and structures.

It is essential the correct instrument is selected for the monitoring task, and the instrument is calibrated, operated and maintained in accordance with the manufacturer's instructions.

Instruments should meet the minimum performance criteria listed in Tables 1 and 2 below.

4.1 Extractive landfill gas analysers (category 1)

Extractive landfill gas analysers must be specifically designed for the purpose of monitoring landfill gas. Examples are Geotechnical Instruments GA 5000, GEM 5000 and GEM 2000+, Gas Data GFM430 and GFM436 and Elkins Earthworks Envision Gas Analyser*.

Table 1: Minimum performance specification for extractive landfill gas analysers (category 1)

Sensors	Methane and carbon dioxide: dual-wavelength infra-red cell O ₂ , CO: electrochemical sensor. H ₂ S and H ₂ sensors are optional.
Accuracy	Methane and carbon dioxide: +/- 0.5% v/v across 0.0 to 5.0% v/v range, +/- 1.0% v/v across 5.0 to 15.0% v/v range and +/- 3.0% v/v across 15.0% v/v to full scale of instrument oxygen: +/- 1.0% v/v across full scale of instrument
Range	Methane: 0–70% v/v Carbon dioxide: 0–40% v/v Oxygen: 0–25% v/v
Pump flow rate	300–600 mL/min typical in free air
Relative pressure**	Accuracy: +/- 4 mb typically up to +/- 15 mb maximum
Bore flow measurement**	Flow range: - 10 L/Hr to +15 L/Hr (+/- 0.3 L/Hr accuracy preferred, 0.5 L/Hr acceptable)

* EPA does not endorse one detector or analyser over any other, examples are provided for guidance only and are typical examples found in Australia.

** A standalone instrument may be used.

4.2 Low-concentration methane detectors (category 2)

There are two types of these detectors suitable for landfill gas monitoring, a Flame Ionisation Detector (FID) and a Laser Spectrometer. Examples are the Geotech TDL-500 laser spectrometer, Huberg Laser One, Thermofisher Scientific TVA-1000B FID and Photovac MicroFID II*.

FIDs do not exclusively detect methane but respond to a wide range of flammable gases and volatile organic compounds (VOCs). The total mixture of flammable gases present is reported on the FID in ppm, the gases are not speciated. As methane typically comprises 98–99% v/v of the flammable content** of landfill gas, the use of an FID for measuring emissions of methane in landfill gas from the surface of a landfill is acceptable when the instrument is calibrated using methane.

The TDL-500 laser spectrometer responds only to methane as it uses the wavelength of infrared light absorbed by methane. In addition to monitoring emissions of methane from the surface of a landfill, the instrument is also useful for in-building methane monitoring where flammable gases other than methane (for example hydrocarbon propellants from air fresheners) may be encountered and give false positives for methane on an FID. At the time of writing, the TDL-500 is the only available portable laser spectrometer specific to methane available in Australia.

Landfill gas fugitive emissions monitoring guideline

Photoionisation detectors (PIDs) are not capable of measuring methane. The ionisation energy of methane is sufficiently high that it will absorb the photons from the PID's UV lamp without creating an ion current, that is, the UV lamp will not generate sufficient energy to remove an electron from the methane molecule to generate a current which in turn generates a gas concentration reading. This causes a PID to not report methane concentrations.

* EPA does not endorse one detector or analyser over any other, examples are provided for guidance only and are typical examples found in Australia. Other suitable detectors are likely to become available.

**The flammable content of landfill gas is comprised of methane and trace gases, as the trace gases comprise up to 2% of the volume, methane therefore comprises a minimum of 98% of the flammable content.

Table 2: Minimum performance specification for low-concentration methane detectors (category 2)

Accuracy	<u>Preferred:</u> +/- 10% of reading or +/- 1 ppm, whichever is greater. <u>Acceptable:</u> +/- 25% of reading or +/- 2.5 ppm, whichever is greater. Listed accuracies achieved using methane in the range of 100 to 500 ppm.
Repeatability	+/- 5% across 1 to 10,000 ppm methane range
Response time	Less than 6.5 seconds for 90% of full scale response
Detection limit	1 ppm methane

5. Landfill final cap and intermediate cover areas – surface emissions of methane

5.1 Instrument

Use a low-concentration methane detector (category 2) with an extendable probe, capable of achieving the minimum performance specification outlined in Table 2.

5.2 Purpose

The purpose of this method is to measure the methane surface emissions from intermediate covers and final caps against the gas action levels in Table 6.4 of BPEM. Note that areas covered only with daily cover in the active cell do not have any gas action levels and should not be subject to surface emissions monitoring. The methane surface emissions monitoring results should be compared with the gas action levels in BPEM, with reference to condition LI_L5 of EPA waste discharge licences for landfills or requirement LC8 of landfill PC PANs. The monitoring method is commonly known as a walkover survey and is completed by walking transects over the landfill surface monitoring methane concentrations in air present above the cap/intermediate cover. The walkover survey will be able to identify defects in the cap or intermediate cover and landfill infrastructure that are allowing emissions of landfill gas.

5.3 Monitoring locations

Monitoring should take place at the following locations:

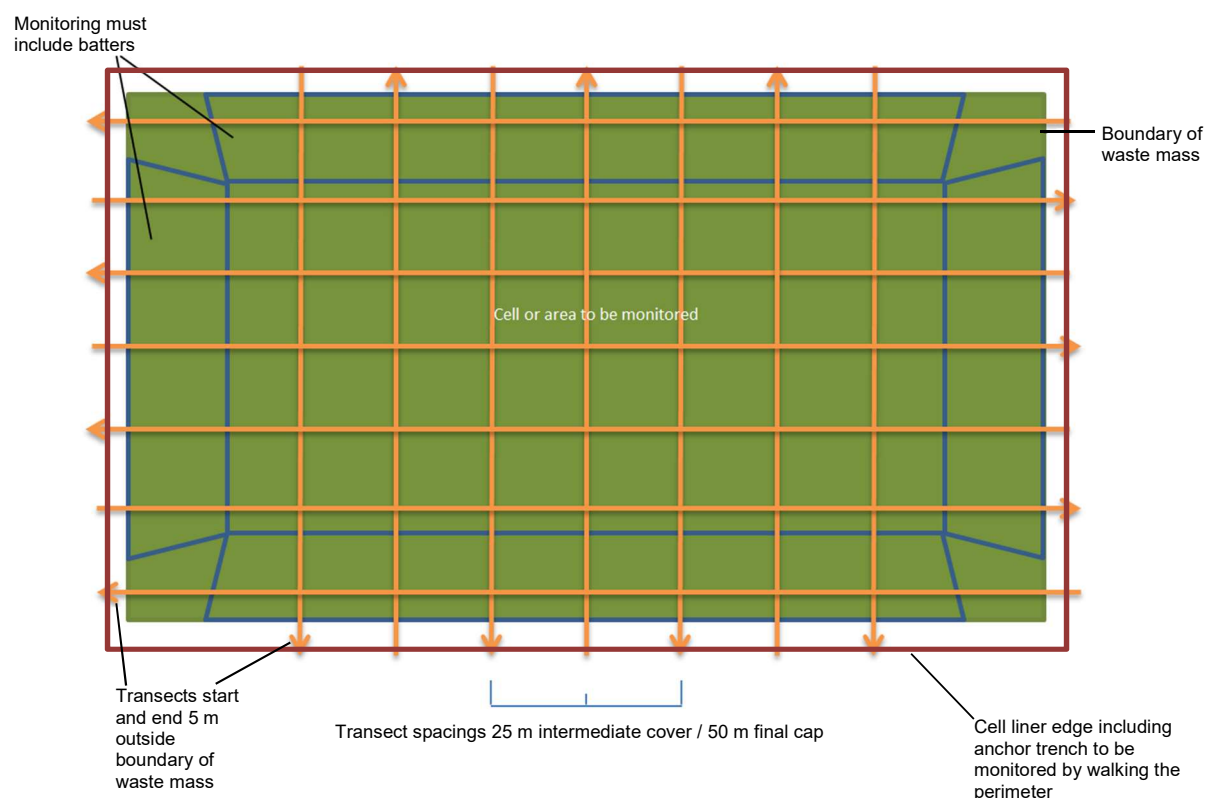
- final capped cells and areas
- cells and areas with intermediate cover
- the edges of the cell liner including any anchor trenches
- penetrations through final caps/intermediate cover i.e. gas wells, gas manifolds, leachate sumps, J-traps, large vegetation
- cracks, gaps, depressions, erosion gullies and areas of vegetation die back in final caps/intermediate cover.

Landfill gas fugitive emissions monitoring guideline

5.4 Method

1. A brief desktop review of the area to be monitored should be conducted prior to commencing monitoring. This should provide an understanding of the number and location of transects to be monitored, and confirm the size of the area, the likely time required to complete the monitoring and the location of any known or likely point sources of emissions or penetrations through the intermediate cover or final cap.
2. Before starting monitoring, note background information including: site identification, start time of the monitoring, date, atmospheric pressure, prevailing weather and recent weather conditions, current ground conditions, instruments used and serial numbers, person completing monitoring etc.
3. The instrument should be calibrated at intervals set by the manufacturer and bump checked with a certified gas mixture. Bump checks/field calibrations should be performed in accordance with the manufacturer's instructions.
4. Surface emissions should be monitored continuously along each transect at a height of approximately 50 mm above the surface of each cell of the landfill. Data should be logged regularly i.e. every few seconds. Where equipment has an automatic data logging capability, this should be used. The transects should be spaced at 25 m intervals for intermediate cover and 50 m intervals for final caps.
5. Monitor at normal walking speed along the transects parallel to the landfill boundary. Typically, two sets of transects should be started from two boundaries at right angles to each other so the transects cross in a grid pattern (see figure 1). Each transect should start and finish approximately five metres beyond the waste boundary.

Figure 1: Transect diagram for undertaking a walkover survey



6. Where observations (including landfill gas odours or bubbling through ponded water) suggest that significant landfill gas emissions are likely to lie off the transect being monitored, divert from the transect to investigate these possible point sources. Note any significant changes in weather during monitoring. Measure wind speed every 15 minutes, approximately 50 mm above the ground using a portable anemometer (see Appendix A).
7. Divert from the nominated transect to monitor around known or newly identified penetrations through the cap or intermediate cover. The monitoring of these locations should take place within 50 mm of the penetrations, features or defects on all sides. Any obvious defects identified (for example, missing well caps, failed bentonite seals) should be noted. Typical penetrations, features or defects around which landfill gas monitoring should be completed include:

Landfill gas fugitive emissions monitoring guideline

- landfill edges and side slopes – these should be particularly focused upon as lower compaction rates occur at the landfill edge, the waste is therefore less resistant to gas movement
 - anchor trenches
 - surface cracking, fissures and/or depressions
 - stressed vegetation
 - interfaces between intermediate cover or final cap on adjoining cells
 - 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 or condensate discharges).
8. Return to the transect and continue monitoring (divert again as required — see 6, 7).
 9. Results should be recorded, and locations of non-compliance marked on a plan, ideally with GPS coordinates. Non-compliant locations should be marked on the ground (for example, with a stake or spray paint) and photographed, for easy relocation, remediation and re-monitoring.
 10. Once monitoring is complete, note the finish time and any identified issues which may have prevented representative data being obtained.
 11. Results should be provided to the site operator, along with a plan showing the approximate locations of the monitored transects and penetrations through the intermediate cover or final cap. Monitoring results exceeding the landfill gas action levels in Table 6.4 of BPEM must be reported, and the relevant locations must be remediated and re-monitored as per the requirements set out in BPEM.

5.5 Monitoring frequency

EPA recommends the frequency of monitoring surface emissions of methane is quarterly, so effects of seasonal variability are accounted for. However, EPA accepts frequency is determined by an environmental auditor based on the landfill gas risk assessment. Site operators must consider the audit frequency, and obtaining and responding to monitoring results in the intervening times between audits, particularly if the audit frequency is greater than annual.

Monitoring results should be obtained in between audits at a frequency which is sufficient to allow management of the site to be adjusted for continued compliance with the EPA waste discharge licence or PC PAN.

The monitoring frequency should be increased or decreased based on the results obtained, or in response to particular issues identified at the site. For example, if quarterly monitoring shows little variation, the frequency could be decreased, or if recurring significant desiccation of the cap is observed, the frequency should be increased. This dynamic response is principally to allow problems to be identified and rectified, with the compliance reporting occurring after rectification works as per section 5.6.

5.6 Notification to EPA where surface emissions action levels are exceeded

If non-compliances with the methane surface emissions gas action level are found, corrective action should be taken, and the walkover survey repeated at the non-compliant locations. Whether compliant or not, after corrective actions have been taken, this second walkover survey must be used for compliance purposes either through your APS or supplied to the operations auditor for inclusion in the data reviewed for the next audit. Any non-compliance reporting to EPA after the second survey should be in accordance with landfill gas Section 6.7.1 and the required outcomes of BPEM.

EPA will accept an average of the surface emissions data to be used for reporting compliance where the maximum concentration below is not exceeded:

- Intermediate cover – a mean of 200 ppm with no individual result exceeding 500 ppm, except at 50 mm from penetrations where the 1000 ppm gas action level must be met.
- Final cap – a mean of 100 ppm with no individual result exceeding 200 ppm.

For the average surface emissions data to be accepted by EPA for compliance reporting, you must have followed the walkover survey method in section 5.4 of this guideline and used an instrument as described in section 4.2 of this guideline. Any corrective action taken should focus on achieving compliance with the mean and maximum methane concentrations above.

Landfill gas fugitive emissions monitoring guideline

6. Subsurface geology – landfill gas concentrations, relative pressure and gas flow rate

6.1 Instrument

Use an extractive landfill gas analyser (category 1) capable of achieving the minimum performance specification outlined in Table 1.

6.2 Purpose

There are two primary purposes for monitoring landfill gas in the sub-surface geology. The first is to measure the methane and carbon dioxide concentrations against the gas action levels (in Table 6.4 of BPEM) in assessing compliance with condition LI_L5 of EPA waste discharge licences for landfills or requirement LC8 of landfill PC PANs. The second is to obtain landfill gas concentration, relative pressure and flow data for undertaking a landfill gas risk assessment. Oxygen, balance, relative pressure and gas flow do not have gas action levels in the BPEM, however EPA recommends these are measured in assessing compliance with licence condition LI_L5 or PC PAN requirement LC8, as this data provides critical information on the behaviour and source magnitude of any landfill gas present. In undertaking a landfill gas risk assessment, oxygen, balance, relative pressure and gas flow are critical data in addition to methane and carbon dioxide.

6.3 Monitoring locations

Sub surface geology is monitored for landfill gas using dedicated landfill gas monitoring bores designed and installed in accordance with Tables B.2 and B.3 of BPEM.

Groundwater monitoring bores should not be used for landfill gas monitoring as these are typically screened only within an aquifer and not across unsaturated strata through which gas moves. In some cases, a small amount of the groundwater bore screen may be within unsaturated strata or the part of the bore screen may become unsaturated due to groundwater level changes. As a result, groundwater monitoring bores will return either false negatives or unrepresentative landfill gas readings.

6.4 Method

1. A desktop review of the area to be monitored should be conducted prior to commencing monitoring, including the number and location of bores, their construction, post-installation leak testing and bore logs.
2. The instrument should be calibrated at intervals set by the manufacturer and bump checked with a certified gas mixture prior to use. Bump checks/field calibrations should be performed in accordance with the manufacturer's instructions.
3. Before starting monitoring, attach the inert sample tubing (maximum 1 m in length) and turn the instrument on in a location unlikely to be affected by landfill gas (or other air contaminants). Confirm the instrument is reading gas concentrations indicative of the prevailing background conditions (generally <0.1% v/v methane, <0.1% v/v carbon dioxide, 21.0% v/v oxygen, 79% v/v balance (not measured directly, represents nitrogen and argon)). The pressure sensors should be zeroed, and care must be taken the tubing is shielded from the wind to prevent the Venturi effect impacting the zeroing.
4. Also note background information, including: site identification, bore location (including distance from the waste mass), start time of the monitoring round, date, prevailing weather and recent weather conditions (see Appendix A), current ground conditions, instruments used (including serial numbers) and person completing the monitoring. Changes in any of the above should be noted as should the finish time.
5. Visually inspect the bore and, without breaking the gas-tight seal, note any issues or deficiencies that may prevent representative data being obtained (such as landfill gas odours, unsealed bores, screened sections of pipework above ground level, failed bentonite seal or an open gas tap). Note whether the bore is locked and secure. Any leaks in a bore not visually apparent should be able to be seen in the gas balance, pressure and flow monitoring data. Alternatively, an FID or laser spectrometer (category 2 instrument) could be used to find methane leaks, noting this is only useful if the strata the bore is installed in has landfill gas in it.
6. Connect the sample tubing to the bore and record the relative pressure, including whether the pressure is positive (+) or negative (-). This must be done in a manner that prevents the pressure in the bore being altered prior to measurement. If the bore is fitted with a gas sampling tap, connect the sample tubing to the instrument and the gas sampling tap prior to opening the tap. If the bore is fitted with a quick-connect coupling (ex-cap type or similar), connect the sample tubing to the instrument before being fitted to the bore quick-connect fitting. Record the relative pressure before starting the instrument pump or measuring gas concentrations.
7. If you need to measure the gas flow rate from the bore (for landfill gas risk assessment purposes) you must obtain this reading before you take the gas concentration readings. This is because the gas flow must be measured under conditions which are as representative as possible of undisturbed ground conditions. If the

Landfill gas fugitive emissions monitoring guideline

gas flow rate is measured after the gas concentration readings the effect of gas analyser pump on the bore will alter the undisturbed ground gas conditions.

8. To obtain gas concentration readings turn on the pump and record the peak and stabilised concentrations of methane and carbon dioxide (see Table 3), the minimum and stabilised concentration of oxygen and the balance gas concentration. Appendix B gives an example gas bore monitoring sheet.
9. If the monitored gas concentrations have not reached a stabilised concentration after three minutes* of continuous sampling, record the gas concentrations at three minutes, along with the direction and rate of change in concentration (increase or decrease in % v/v over a regular time period such as 30 seconds), and note them as non-stabilised final readings.
10. If very high landfill gas concentrations are recorded on the instrument (>30% v/v methane and/or 30% v/v carbon dioxide), then monitoring of the bore should be extended beyond three minutes to try to further determine the persistence of the gas detected within the bore. A flow reading is helpful in these situations as it gives information on magnitude and mobility of the gas source.
11. Once the peak and stabilised concentrations have been recorded, fully close the gas sampling tap (if applicable) and disconnect the sample tubing from the bore. Keep the instrument pump turned on away from the bore and other sources of gas or contaminants until any residual gas present in the instrument has been purged from the instrument and sample tubing. The gas concentrations reported by the instrument should resemble those likely to be indicative of the prevailing background conditions (generally <0.1% v/v methane, <0.1% v/v carbon dioxide, 21.0% v/v oxygen, 79% v/v balance (not measured directly, represents nitrogen and argon)) prior to being used at the next monitoring location. Where the conceptual site model indicates the potential for groundwater to be covering all or part of the gas monitoring well screen, the well should be dipped after gas monitoring to check the water level against the screen level range. If the screen is completely or mostly flooded, results should be disregarded.

* - Leading ground gas researchers have advised that a sampling period of 10 minutes is sometimes required to obtain representative gas concentration and gas flow readings.

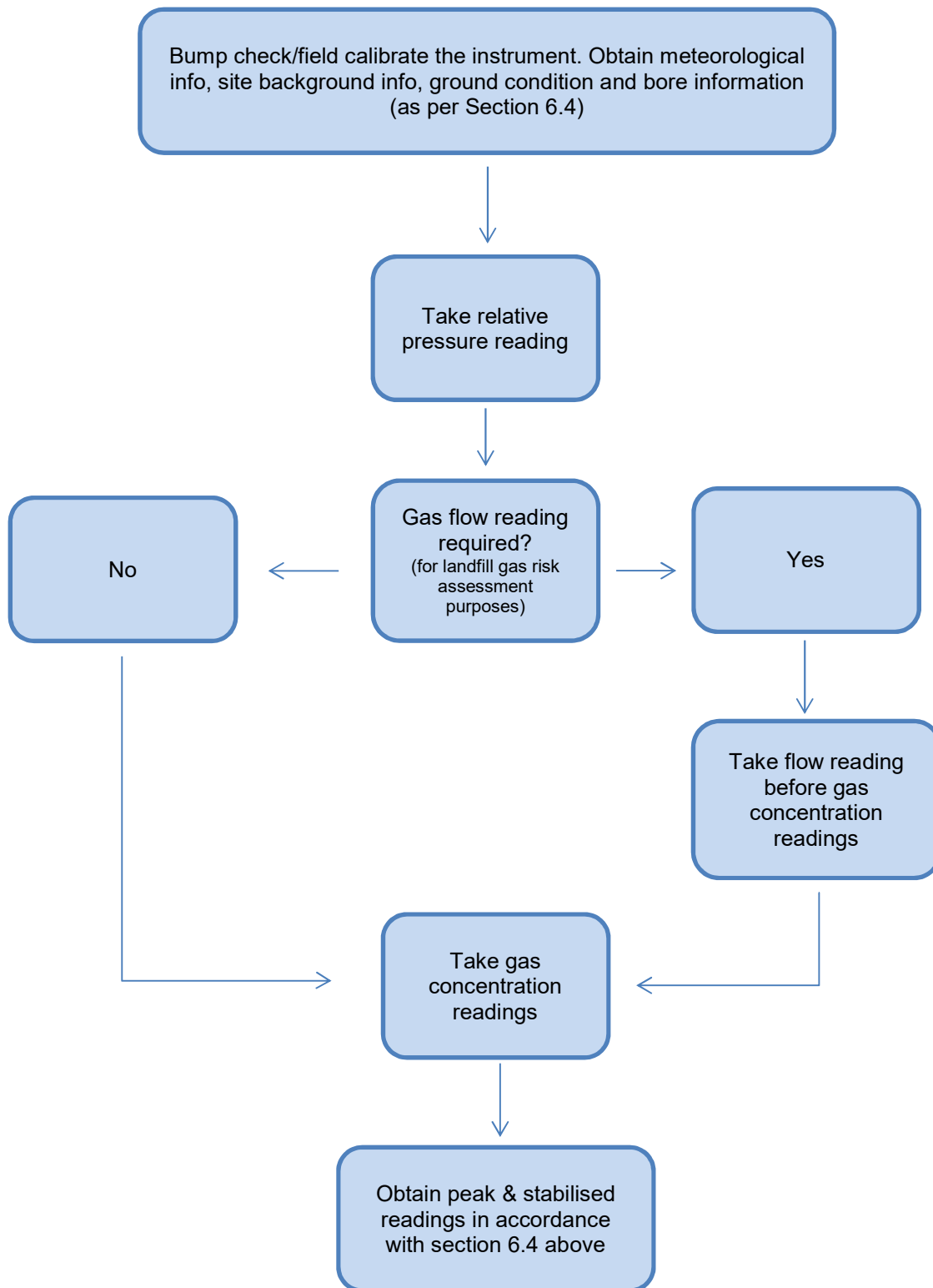
A simple flow diagram for undertaking this monitoring is provided in Figure 2.

Table 3: Peak and stabilised definitions

Term	Definition
<i>peak</i>	Maximum gas concentration detected.
<i>stabilised</i>	Stable gas concentration ($\pm 0.3\%$ v/v) after monitoring for a short period (up to three minutes). If readings haven't stabilised at three minutes, follow 10 in section 6.4 above.
<i>balance</i>	The non-analysed volume of gas taken from the bore into the analyser. Comprised of nitrogen and argon.

Landfill gas fugitive emissions monitoring guideline

Figure 2: Flow diagram for landfill gas monitoring in sub-surface geology



Landfill gas fugitive emissions monitoring guideline

7. Methane monitoring in subsurface services

7.1 Instrument

Use a low-concentration methane detector (category 2) with an extendable probe, capable of achieving the minimum performance specification outlined in Table 2.

7.2 Purpose

The purpose of monitoring subsurface services is to ascertain if landfill gas is moving through the ground via these structures. It is important to note these structures are not designed or ideal for monitoring landfill gas. This is due to the requirement for them to be open to atmosphere, or physically opened up to allow monitoring. While not a replacement for properly designed and installed landfill gas monitoring bores, these structures can provide an indication of a significant gas migration problem, particularly when the structure is quite well-sealed against the ground and persistent gas concentrations are detected.

7.3 Monitoring locations

Subsurface services may include drains, fire hydrant pits and conduits, communications pits, gas and electricity service conduits adjacent to the perimeter of the site.

7.4 Method

1. Prior to arrival at the site, monitoring personnel should complete a brief desktop review of the locations to be monitored to develop an understanding of the number and types of locations to be monitored and the likely time required to complete the monitoring. The instrument should also be checked for calibration information and bump checked with a certified gas mixture.
2. Before starting monitoring, turn the instrument on in a location unlikely to be affected by landfill gas (or other air contaminants where possible). Confirm the instrument is giving readings considered likely for the conditions. Note that the global background methane concentration is ~ 1.8 ppm (Myhre et al, 2013). If using an FID, it is likely to be influenced by emissions from vehicles and industry/commerce. If a busy road or active industrial or commercial emissions are observed nearby, note their effect on the readings of the FID before commencing monitoring of the subsurface services.
3. Note background information, including: site identification, start time of the monitoring round, date, atmospheric pressure, prevailing weather and recent weather conditions (see Appendix A), current ground conditions, instruments used (calibration and serial numbers), person completing monitoring and so on. During monitoring any observations of significance (like changes in weather) should be noted.
4. Record the type and location of the first monitoring location. It is often useful to record the address (street number and name) of the monitoring location and/or GPS coordinates.
5. Visually inspect the location and note any issues or deficiencies with the location that may prevent representative landfill gas monitoring data being obtained (this might include landfill gas odours, unsealed service or inaccessible service).
6. Due to the diverse nature of subsurface services, it is not possible to provide a universal, step-by-step field monitoring procedure for all locations. The following steps may need to be modified, depending on the exact nature of the service. Factors that may influence the method of monitoring, and that may be useful to record, include:
 - dimensions of the subsurface service
 - sealing of the subsurface service
 - accessibility of the subsurface service
 - any known landfill gas dissipation measures
 - weight of access panels or covers into subsurface services
 - locking mechanisms on access panels or covers (if applicable).
7. Turn on the instrument and insert the probe into the subsurface service. This should be done in a way that minimises the ingress of air to the subsurface service. Attempt to monitor across the lateral and vertical profile of the service to account for the differing densities of landfill gas which may be encountered due to its variable composition.
8. Record the highest concentration of methane and approximately stable concentration should this occur. Due to the resolution of the instrument used and the mixing of gases in the sub-surface services with air, the ppm readings rarely stabilise to a set number but will tend to stay within a range, this range should be recorded. If the monitored

Landfill gas fugitive emissions monitoring guideline

gas concentrations have not reached a stabilised range after three minutes of sampling, record the final gas concentration range, along with the direction and rate of change in concentration (rapidly or slowly increasing or decreasing) and note them as non-stabilised final readings.

9. After taking the readings, remove the probe from the subsurface service. The instrument pump should remain turned on away from the service and other sources of gas or contaminants until any residual gas present within the instrument has been purged. The methane concentration reported by the instrument should resemble that likely to be indicative of the prevailing background conditions before monitoring starts at the next location.
10. After monitoring is completed, replace the subsurface service access panel or cover (if removed for monitoring) and confirm it is properly fitted before moving to the next monitoring location.
11. When monitoring has been completed, monitoring personnel should note the finish time and any issues that may have prevented representative data being obtained.

8. Methane monitoring in buildings and structures

8.1 Instrument

It is recommended that monitoring for methane inside buildings and structures, on and adjacent to the landfill site, is completed using a laser spectrometer (category 2). An FID will respond to a wide range of flammable gases which are commonly found in buildings (particularly residences) and can cause false positives for methane to be recorded. If using an FID is the only option, any uses or contents of the building/structure which could affect the monitoring results (for example, smoking, painting, presence of hydrocarbons, household cleaning products) should be recorded. It is highly recommended the owner/occupier of the building/structure is given sufficient notice so all sources of gases which could affect the monitoring results are removed or contained prior to the monitoring being undertaken.

8.2 Purpose

To ascertain if landfill gas (methane is monitored to indicate the presence of methane, carbon dioxide and trace gases) is entering buildings and structures on or adjacent to the landfill.

8.3 Monitoring locations

EPA recommends the following locations within each building/structure are monitored. This list is not definitive and other locations may need to be monitored depending on the design and construction of the building/structure:

- around service ingress points, such as pipework
- inside electricity meter/fuse box
- inside cabinets within bathrooms, kitchens, laundries and other rooms
- around cracks and penetrations through floors
- along skirting boards and joins between floors and walls
- within floor voids (underneath floors)
- within wall cavities (access permitting)
- within any other identified confined spaces or possible entry points for landfill gas.

8.4 Method

1. Prior to arrival at the site, monitoring personnel should complete a brief desktop review of the locations to be monitored, to develop an understanding of the number and types of locations to be monitored and the likely time required to complete the monitoring.
2. Before starting monitoring, turn the instrument on in a location unlikely to be affected by landfill gas. Confirm the instrument is giving readings considered likely for the conditions. Note the average global background methane concentration is ~ 1.8 ppm (Myhre et al, 2013).
3. Note background information, including: site identification, start time of the monitoring round, the date, atmospheric pressure, prevailing weather and recent weather conditions (see Appendix A), current ground conditions, instruments used (and serial numbers), person completing monitoring and so on. During monitoring, any observations of significance (such as changes in weather) should be noted.
4. Due to the diverse nature of buildings, it is not possible to provide a universal, step-by-step field monitoring procedure for all possible locations. The following steps may need to be modified depending on the exact nature of the building. Factors that may influence the method of monitoring, and which may be useful to record, include:

Landfill gas fugitive emissions monitoring guideline

- dimensions of the building/structure
 - construction of the building/structure
 - use of the building/structure
 - proximity of the building/structure to the landfilled waste (note there is likely to be a difference between the extent of the waste and the extent of the site)
 - any known landfill gas dissipation or management measures (for example, gas membranes or voids beneath the building/structure)
 - sealing of the building/structure
 - locations of penetrations or entry paths for any landfill gas to enter the building/structure (e.g. around service ingress points such as pipework, cracks in floor, around the skirting board etc.)
 - location of likely accumulation points for any landfill gas that may enter the building/structure (for example, attics or cupboards)
 - accessibility of the various areas within the building/structure, including underfloor voids, wall cavities, roof cavities and so on.
5. Start monitoring with the instrument turned on. Inspect the building and monitor each identified location with the instrument running continuously.
 6. Record the type and location of each area monitored (for example, bathroom cabinet or roof void). Inspect the area and record observations (such as holes in floor for services pipes that may act as pathways for migration of landfill gas).
 7. Starting in the middle of each room, with the instrument probe at head height, monitor the ambient concentration of methane present. Next, monitor any locations/features as described in section 8.3 'Monitoring locations' above.
 8. Record the highest concentration of methane found at any location in each room. If methane is found to be entering the building/structure, pay particular attention to roof spaces, upper floors or enclosed spaces positioned in elevated positions, methane is lighter than air and could accumulate here.
 9. Once monitoring of the inside of the building/structure has been completed, monitor the outside of the building around airbricks, vents, services entries, manhole covers, drain covers, shallow excavations and cracks or gaps in any hardstanding/concrete etc.
 10. When monitoring has been completed, monitoring personnel should note the finish time and any issues that may have prevented representative data being obtained.

Landfill gas fugitive emissions monitoring guideline

Glossary

asphyxiant	A vapour or gas that causes unconsciousness or death by displacing oxygen.
cover	Material used to cover wastes deposited in landfills.
intermediate cover	Material used to cover waste for an extended period of time, and to assist the operation of a gas extraction system and reduce stormwater infiltration into the waste (typically, 500 mm of compacted clay/clay soil).
final cap	The final waste cover. An engineered structure, built under construction quality assurance to an EPA-approved design, which significantly reduces stormwater infiltration into the waste and allows a gas extraction system to be operated to a high collection efficiency.
FID	Flame ionisation detector.
flux	Movement of gas, generally measured as mass per unit of area, per unit of time e.g. mg/m ² /second.
GPS	Global positioning system.
landfill gas	Gas generated from the decomposition of waste in a landfill.
leachate	Liquid that has entered the landfill which has been contaminated by substances in the deposited waste.
peak concentration	The maximum concentration detected.
ppm	Parts per million, 1 ppm is volumetrically equivalent to 1 mg in a litre.
stabilised concentration	Stable gas concentration ($\pm 0.3\%$ v/v) after monitoring for a short period (three minutes).
QC	Quality control.
VOC	Volatile organic compound.
% v/v	Percentage expressed as unit volume per unit volume.

Landfill gas fugitive emissions monitoring guideline

References

- AS/NZS 4323.3:2009 Australian/New Zealand Standard. Stationary source emissions. Method 4: Area source sampling — Flux chamber technique
- BS 8485: 2007, Code of Practice for the characterisation and remediation from ground gas in affected developments, ISBN: 978-0-580-56934-0, BSI 2007
- BS 8485: 2015, Code of Practice for the design of protective measures for methane and carbon dioxide ground gases for new buildings, ISBN 978 0 580 83071 6, BSI 2015
- Barry DL, Watts M, Smith R (2004) Proc. *Waste 2004 Conf. Integrated Waste Management and Pollution Control: Policy and Practice, Research and Solutions*. Stratford-upon-Avon, UK, 28-30 September 2004, 315-324
- Card G et al CIRIA Report 665 (2007), Assessing risks posed by hazardous ground gases to buildings, ISBN: 978-0-86017-665-7
- EPA Victoria (2015), *Best Practice Environmental Management – Siting, design, operation and rehabilitation of landfills* (EPA publication 788.3)
- Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Environment Agency (2002), R&D Technical Report P1 – 471 - Techniques for the Interpretation of Landfill Monitoring Data
- Environment Agency (2004), Guidance on the management of landfill gas, LFTGN03, 2004
- Environment Agency (2010), Guidance on monitoring landfill gas surface emissions, TGN07 v2, 2010
- US EPA 1986, Measurement of gaseous emission rated from land surfaces using an emission isolation flux chamber. User's guide, EPA 600/8-86-008 (NTIS PB-223161), Washington, DC.

Landfill gas fugitive emissions monitoring guideline

Appendix A: General quality control considerations

It is important all landfill gas monitoring data collected is representative, and of a suitable quality, to ensure the overarching objectives outlined in section 2 can be achieved.

All landfill gas monitoring should be completed in accordance with an adequate quality control (QC) program. QC information allows third parties to confirm the landfill gas monitoring data is representative of conditions at the site.

An adequate QC system for landfill gas monitoring data will address and confirm the following items during an individual monitoring task:

- personal competence of monitoring personnel
- selection of appropriate instrumentation
- monitoring personnel are suitably trained in use of the instruments
- operation manuals for the selected instruments have been read
- this landfill gas monitoring guideline has been read
- the landfill gas section (6.7) of the BPEM has been read
- confirmation instruments have been calibrated over a suitable range in accordance with the manufacturers' recommendations
- appropriate use and maintenance of selected instrumentation in accordance with the manufacturers' recommendations
- completing the monitoring task in accordance with the appropriate method
- completing the monitoring task under appropriate meteorological/environmental conditions
- only adequately designed, installed and maintained monitoring locations are used (sub-surface geology)
- ongoing assessment of the data obtained during the monitoring task.

Sometimes it may not be possible to achieve the full chain of QC outlined above, but all efforts should be made to do so.

Any issues likely to reduce the representativeness of the landfill gas monitoring data should be noted and considered when interpreting the data.

Assessment of data during monitoring

It is good practice for the monitoring personnel to continually assess the data obtained during the monitoring task. This serves several purposes:

- it allows emissions to be identified and communicated as soon as possible to site personnel for further investigation or remedial action
- it allows monitoring personnel to confirm data collected is representative of expected site conditions.
- if monitoring personnel suspect a problem with operation of the instrument being used, the response of the instrument should be tested with calibration gas.

Meteorological and environmental conditions

Meteorological and environmental conditions have significant potential to impact the collection of representative monitoring data. Recent and prevailing meteorological and environmental conditions must be carefully considered when completing landfill gas fugitive emissions monitoring. Table A1 summarises the primary meteorological and environmental factors that should be considered for each type of landfill gas monitoring. Please note: this table is a guide only; in some cases, other meteorological and environmental conditions may need to be considered.

Factors that can affect landfill gas monitoring results include:

- Atmospheric pressure – rapid alterations in atmospheric pressure (increasing or decreasing) over short time periods immediately before or during monitoring can decrease or increase landfill gas emissions from a landfill site. Any consistent increases or decreases in atmospheric pressure over a longer time period can also influence landfill gas emissions and should be noted if occurring around the dates of monitoring. With these slower changes in atmospheric pressure, there is a delay in the landfill gas response, should pressure continue to rise or fall after 12 hours a change in landfill gas emissions may be evident.
- Rainfall – rain prior to monitoring may saturate the landfill cap on final or intermediate cover areas. This may temporarily reduce the gas permeability of the cap, resulting in temporarily lower surface emissions of landfill gas

Landfill gas fugitive emissions monitoring guideline

than would normally be observed. However, the temporary reduction of gas permeability of the landfill surface, and the ground between the landfill and the monitoring bores, may temporarily increase emissions of landfill gas in the sub-surface geology. The potential for these effects on surface emissions and sub-surface emissions should be noted, and considered in landfill gas risk assessments, when considering worst case scenarios.

- Wind (measured at approx. 50 mm above the ground) – wind speeds greater than 10 km/hr (approx. 0.3 m/s) can cause landfill gas emissions above final or intermediate cover areas to be diluted, making landfill gas emissions appear falsely low. Some FID / Laser spectrometer extendable probes feature a cone-shaped end which eliminates wind effects around the probe intake, alternatively a funnel can be fitted to the end of a standard probe to achieve the same result. Note that despite the design or alterations to probes high wind speeds will affect methane surface emissions via the Venturi effect.
- Frost and/or snow — low air temperatures causing frost and snow will cause expansion of the water held in the matrix of the capping / intermediate cover material. This can cause temporary surface sealing of final or intermediate cover areas, making landfill gas emission data appear falsely low.
- Excessive vegetation – excessively long vegetation will prevent placement of the extendable probe to within 50 mm of the landfill surface and can conceal features of interest in the walkover survey. Excessive vegetation must be removed prior to methane surface emissions monitoring, except where the vegetation forms part of an EPA approved phytocap.
- Temperature variance – an increase or decrease in temperatures of around 8°C can require a re-calibration of certain instrument sensors. Check the manufacturer’s information on temperature effects, particularly if calibration was performed at a temperature +/- 8°C of the expected temperatures during monitoring.

Weather data for the site on the day of monitoring should be downloaded from the closest Bureau of Meteorology weather station and taken into consideration when assessing the results. Weather data from an onsite weather station may also be used when assessing monitoring results, and is likely to be more representative of actual conditions at the site compared to the nearest Bureau of Meteorology weather station, which may be located several kilometres away.

Table A1: Primary meteorological and environmental factors

	Rainfall	Frost	Wind	Atmospheric pressure	Excessive vegetation
Final cap	✓	✓	✓	✓	✓
Intermediate cover	✓	✓	✓	✓	✓
Subsurface geology	✓	✓		✓	
Subsurface services				✓	
Buildings and structures	✓	✓		✓	

Meteorological conditions for surface emissions monitoring

Methane surface emissions monitoring should *not* be conducted under any of the following conditions:

- if atmospheric pressure at the landfill site is rising sharply or is very much higher than the average for the geographical area of the landfill
- during frost conditions
- in areas where water is standing/ponding
- if wind speed is in excess of 10 km/hr (at 50 mm above the ground)
- within two days of heavy rainfall
- during any other meteorological or environmental conditions that may significantly affect the representativeness of the data obtained.

At times, it may not be possible to avoid all the conditions listed above. If monitoring must be completed during some of these conditions, it should be noted these issues may have affected how representative the data obtained is and should be taken into consideration during subsequent assessment of the data.

A portable anemometer should be used when conducting surface emissions to measure the wind speed at 50 mm above the ground during the walkover survey.

Landfill gas fugitive emissions monitoring guideline

Appendix C: Guidance for determining background ground gas concentrations

In certain circumstances background concentrations of ground gas may be significant, and will therefore need to be determined in order to assess compliance against the action levels presented in the BPEM.

In particular:

- concentrations of carbon dioxide from aerobic microbial respiration in soil are sometimes greater than 1.5% v/v, and
- certain geological strata can yield carbon dioxide, for example from reactions between aquifer waters and the calcareous contents of the strata.

A robust conceptual site model is essential when determining any background (existing) ground gases. Ideally, background ground gas concentrations (in particular carbon dioxide) around a landfill site should be determined before any cell excavation works commence.

This is so data on the undisturbed ground gas regime can be gathered. Review of this monitoring data allows background concentrations of carbon dioxide (and other gases) to be established. Furthermore, it allows other sources of gases detected to be identified.

The frequency of such monitoring should be sufficient to enable the characterisation of seasonal and other meteorological and environmental influences. EPA should be consulted during the development of any new landfill to agree on an acceptable monitoring program to determine background gas concentrations.

It is often not possible to collect the above data, for example: when a landfill is located within a former quarry or where background ground gas was not considered during the landfill site development. In these circumstances, EPA advises that background ground gas data is collected before any waste disposal operations commence.

If data can only be collected after waste disposal has commenced, it should be as soon as possible before the onset of methanogenic conditions. Methanogenic processes commence approximately two months after waste placement and are well established at six months after waste placement (Barry et al, 2004).

It is difficult to establish representative background ground gas concentrations once a site has been developed and active waste disposal has occurred. It is particularly problematic when attempts are made to determine background gas concentrations from landfill gas perimeter monitoring bores as these are positioned purposefully to collect landfill gas should it migrate from the landfill. Possible approaches once a landfill has been established include:

- installation of background gas monitoring bores
- quantitative identification of non-landfill sources of carbon dioxide and methane.

Background gas monitoring bores

Several gas monitoring bores (a single bore will not provide sufficiently representative data) will need to be installed to determine background ground gas concentrations. Bores should be installed a sufficient distance from the landfill to not be impacted by landfill gas, but in geology considered to be representative of that found at the landfill site. The distance of bores from the landfill will vary depending on the local geology and topography.

Considerations for the identification of background gas monitoring bores locations include:

- geology
- topography
- ground moisture conditions
- distance from the landfill
- distance from other possible gas sources
- depth of bore
- screening of bore
- depth to groundwater and groundwater level variability
- maximum depth of landfilled waste.

Consult EPA when designing a background gas monitoring program.

Landfill gas fugitive emissions monitoring guideline

Identification of alternative gas sources

Other sources may be contributing to elevated background concentrations of gases. This may include geological sources, other landfills, legacy waste disposal sites, other biological sources and reticulated gas pipeline leaks. There are several methods that may need to be considered to differentiate between gas sources. These include:

- Radioisotope analysis – enables identification of ancient gas vs modern gas and is useful for distinguishing a thermogenic gas from a biogenic gas.
- Isotopic fractionation – enables identification of different sources of the same type of biogenic gas and can also identify thermogenic gas and oxidation signatures, for example where a thermogenically derived gas has subsequently been oxidised by microbes.
- VOC analysis for chlorinated hydrocarbons co-present with the suspected landfill gas. Caution is needed as, due to the volatile nature of these gases, their absence may be due to volatilisation and subsequent migration or oxidation rather than indicating the gas isn't from the landfill.
- ethane and/or butane content provides additional information to help identify biogenic vs thermogenic gas
- The methane to carbon dioxide and oxygen to balance ratios can provide important information about the source of the gas.
- Gas flow rate is important as it gives information on the magnitude of the gas source, assisting in its identification.
- Consider analysis of total organic carbon in soil at background bore locations if background CO₂ is considered to be from aerobic respiration utilising organic material in soil.

It is critical that more than one method is applied to determine the source of the gas. Two methods reporting a similar source or range is compelling evidence for successful identification. It is very important to understand the conceptual site model when undertaking background ground gas assessments, particularly as mixed sources often make up the gas which is analysed or sampled. Where a mixed source of landfill gas and background gases are present, the monitoring results will indicate this and thus be inconclusive for a single source.

The specifics of these methods, their selection for use and interpretation of the results are beyond the scope of this guideline — seek specialist advice from experienced consultants as well as EPA prior to undertaking any such testing.

Datasets used for determining background ground gases

When considering data to be used in determining background ground gas concentrations, care should be taken to use stable datasets with an approximately normal (Gaussian) distribution. The purpose of using stable data is to allow for natural variability in the ground gas to be accounted for so that unnecessary investigation is not undertaken. It is important the spatial and temporal variability of the data used in the stable dataset is considered, given that the purpose is to represent natural ground gas conditions.

For example, obtaining ground gas monitoring data during summer only would likely produce a stable dataset but would not be representative of seasonal variations. Subsequent statistical analysis on this dataset would produce a 'background' ground gas concentration that was either too high and would hide gas migration, or too low and would trigger unnecessary regulatory remedies or sanctions from EPA.

Outliers

After a stable dataset has been obtained, the standard deviation should be calculated and results outside of two standard deviations (2 sigma/95 per cent confidence level) should be treated as outliers and not considered as representative of background ground gas. As noted above, it is particularly problematic obtaining stable data from perimeter monitoring bores once waste has been placed in the landfill. Such data is likely to be much more variable and contain more outliers than data obtained from true background bores or pre-cell excavation/pre-waste disposal data. Analysis of outliers therefore becomes even more important (and difficult) on data obtained from perimeter monitoring bores after waste deposition has occurred.

Further statistical analysis of outliers can be undertaken by obtaining tMax values from the standardised dataset. The method is available in the Environment Agency R&D Technical Report 'Techniques for the Interpretation of Landfill Monitoring Data', P1 – 471 (2002). This report can be found here: <http://www.candpenvironmental.co.uk/docs/TRP1-471FINAL.pdf>

Landfill gas fugitive emissions monitoring guideline

Appendix D: Method for methane surface emissions quantification using a flux box (not for compliance purposes)

(ADAPTED FROM LTGN07 V.2 GUIDANCE ON MONITORING LANDFILL GAS SURFACE EMISSIONS, MARCH 2010, ENVIRONMENT AGENCY, UK.)

Use of flux boxes/chambers

Flux boxes or chambers should not be used for assessing compliance with the BPEM gas action levels for surface emissions of methane.

A walkover survey provides sufficient accuracy for monitoring surface emissions of methane for assessing compliance and is significantly quicker and cheaper than a flux box survey.

Flux box measurements of the mass of methane flux can be used in calculating the collection efficiency of a landfill gas collection system. In addition to measuring the flux of methane from the landfill surface, the other required measurements/information are:

- the mass of methane predicted to be generated by the landfill gas generation model
- the mass of methane collected for utilisation and/or flaring
- the mass of methane lost by lateral migration through the liner. The losses via the liner can be approximated using the flux results for the cap and relative gas permeability between the cap and the liner based on their construction.

When calculating landfill gas collection efficiency, EPA recommends the method in the UK Environment Agency guidance document LFTGN03 (2004) is followed. Once collection efficiency has been calculated, it allows validation of the landfill gas generation model values through comparison of the measurements of gas collected minus the measured emissions of gas through the cap and liner.

When undertaking the flux box/chamber survey, EPA recommends the AS:4323.3 (2009) flux chamber method is followed for obtaining flux readings at each box/chamber. Note the number and location of the boxes/chambers and the methane flux mass emission rate is determined in accordance with the UK Environment Agency guidance document LFTGN07 v2 (2010). The relevant sections of LFTGN07 v2 are reproduced and adapted for Australia in Appendix D of this guideline. EPA's reasons for these recommendations are that AS:4323.3 represents a standard method for obtaining methane flux at a single location, and LFTGN07 v2 describes the landfill specific considerations in positioning each flux box/chamber as well as how to extrapolate the individual box/chamber results into a site wide mass emission rate.

Design of flux box surveys — spatial distribution

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 require 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 'Number of monitoring locations' below), meteorological context (more detail in the meteorological considerations section later in this appendix) and temporal frequency of the monitoring (see temporal frequency below). 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 (US EPA 1986).

Selection of survey zones and features

- Before beginning a flux box survey, 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. Categories of typical zones and features that can contribute differentially to the overall emissions are in Table D1.
- Although most features will lie in 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 to improving the overall surface emission rate.

Landfill gas fugitive emissions monitoring guideline

Table D1: Categories of emission zones and features

Designation	Examples
Zones	Permanently capped (final cap) areas Temporarily capped (intermediate cover) 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 effects of gas, such as stressed vegetation

Typical zones and features zones

A zone is an extensive area of the landfill surface over which the average emission can be calculated from several representative monitoring points. It will generally be covered uniformly with a single capping system that is intact and has a consistent slope. A zone does not need to 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. Temporary capping may have been installed where placement of 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. On more mature sites, agricultural activity may affect measurements of methane at the surface. It is therefore important to record the land use at each of the zones.

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), whereas others may only be revealed through detecting a high flux at several adjacent sampling locations.

Although a feature may be as small as the surface area of a flux box, it must be emitting amounts of gas to warrant attention and remediation. This means a single, elevated flux measurement in an apparently homogeneous zone would not itself warrant designating it as a feature. It may be physically impossible to use a flux box to contain small features that stand proud of the surface. In these circumstances, check the gas concentration alone.

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

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, indicating gas emissions.

By identifying features, you ensure they can be readily defined and remediated if they do not comply with emission standards.

Potential features may have been apparent from the walkover survey. Although the most significant faults in the gas collection 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.

Landfill gas fugitive emissions monitoring guideline

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 fissure. There may be features where the surface has 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 m².

Side slopes, joins, edges and buried pipework

Sloping areas can be affected by differential settlement so it is 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 extraction system is likely to be lower near the landfill edges, with a consequent increase in emission potential. 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 m². For large areas of greater than 3500 m², 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.

These are unlikely to be emission sources during active gas extraction as 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 pipelines 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.

Junctions in liners or capping material

Where a synthetic membrane has been used as a lining or capping material, unwelded junctions may provide a higher-permeability pathway for gas. Although any cover material over the junction (i.e. 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 flux survey to check whether there is evidence of high flux of gas.

Annotation of site plan to indicate zones and features

Illustrate a site plan with the different zones and features that have been designated. The naming convention you use should aid later interpretation and grouping of similar features and zones.

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: less than 5000 m² and more than 5000 m². The classification is based on practical rather than scientific considerations to provide a pragmatic spatial distribution of the monitoring.

In both classes, the minimum number of monitoring locations in a zone is six (US EPA 1986). To make the survey representative, 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. 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.

Number of flux box locations required

Zones of area greater than 5000 m²

The number of required flux measurements (n) depends on the size of the zone (Z m²) and, based on US EPA (1986), is calculated as follows:

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

Landfill gas fugitive emissions monitoring guideline

Using this equation, Table D2 shows the number and average spacing of monitoring locations for zones of particular sizes. These recommended spacings on extensive areas of a cap are consistent with geostatistical analysis of research data.

Table D2: Recommended numbers of flux box locations and average spacing in large zones

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

- Example calculation:

$$\begin{aligned}
 \text{Zone area (Z)} &= 205 \text{ m} \times 135 \text{ m} &= 27,675 \text{ m}^2 \\
 \text{Number of measurements (n)} &= 6 + 0.15 \sqrt{27,675} &= 31 \\
 \text{Average monitoring spacing} &= \sqrt{(27,675 \text{ m}^2/31)} &= \sqrt{892.7 \text{ m}^2} = 29.9 \text{ m}
 \end{aligned}$$

Zones or features of area less than 5,000 m²

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 D3: 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

Meteorological considerations

Data quality can be directly influenced by weather conditions before and during the monitoring period. In particular, surface emission rates can be affected by factors such as rain and changes in atmospheric pressure. If surface soils and clay capping are saturated with water, they will be less permeable to gas which greatly reduces 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 small changes in the weather can alter the observed emissions from the surface.

Atmospheric pressure

When the atmospheric pressure is very low, methane fluxes can be higher than normal, and vice versa. Ideally, surveys should be conducted when atmospheric pressure is at neither extreme but preferably when atmospheric pressure is falling, to represent the worst-case scenario. Meteorological effects can be self-cancelling because low atmospheric pressure is usually accompanied by rainfall, which reduces the permeability of the soil and can reduce surface emissions.

Landfill gas fugitive emissions monitoring guideline

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, less than 3 m/s). If the site is normally windy, you may need to carry out 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 data interpretation.

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.

Temporal frequency

Because emissions monitoring is periodic, select sampling periods that are representative of normal operation of the gas collection 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.

Calculation of mass emission rates

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/m²/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 unnecessary for routine monitoring and lie outside the scope of this guidance.

Calculation of emissions from overall site

Table D4 gives an example of how a series of emissions from different zones and features are calculated and compared. This hypothetical data shows the wide variation in the flux and the mass flow from different site elements.

Landfill gas fugitive emissions monitoring guideline

Table D4: 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	33	400	30,000
Fissures 2 (F2)	23	33	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 An example site with these zones/features

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 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.

To compare the magnitude of surface emissions with other emission sources, it is convenient to convert the flux measurements to m³/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/m²/hour. Table D5 shows the relationship between data expressed in four sets of units.

Table D5: 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 at 50% v/v

Landfill gas fugitive emissions monitoring guideline

Potential sources of error and 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.

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.

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.

Homogeneous 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 that your reporting of the overall emission rate takes account of the variability in the individual measurements and the number of different zones or features 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, by refining the extent of the features and zones and/or by increasing the number of sampling locations in the variable region.