LFTGN 03

Lfd **Landfill** directive

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Guidance on the management of landfill gas

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Statement of Use

This guidance is one **of** a series **of** documents relating to the management of landfill gas. It is issued by the Environment Agency and the Scottish Environment Protection Agency (SEPA) as best practice guidance and will be used in the regulation of landfills. It is primarily targeted at regulatory officers and the waste industry. It will also be of interest to contractors, consultants and local authorities concerned with landfill gas emissions. The document provides an update to Waste Management Paper 27.

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Overview of the guidance

The EU Landfill Directive 1999/31/EC, which came into force on 16 July 1999, aims to improve standards of landfilling across Europe by setting specific requirements for the design and operation of landfills, and for the types of waste that can be accepted in landfills. All landfills are required to comply with the Directive's requirements, although a transitional period is allowed for landfills existing at 16 July 2001. In England and Wales, the Directive is implemented through the Landfill Regulations (England and Wales) 2002, made under the Pollution Prevention Control Act 1999. In Scotland, the Directive is implemented through the Landfill (Scotland) Regulations 2003, as amended.

The role of the regulator is to condition the operation of an installation under the Pollution Prevention Control (PPC) Regulations 2000 by issuing a PPC permit. Once a PPC permit is issued, the regulator ensures that its conditions are met until such times as the regulator accepts its surrender. The regulator fulfils a similar role for landfill sites operating under waste management licensing.

This document, which updates Waste Management Paper 27 *Landfill gas* (DoE, 1991a), has been prepared to provide clear and concise guidance on the management of gas from landfill sites. The document sets out the legislative requirements of the Landfill Regulations, the PPC Regulations, the Waste Framework Directive and current good practice. This guidance will form the basis for setting conditions in PPC permits (including landfill permits) that provide for all appropriate measures to be taken against pollution, to limit emissions and impact on the environment, and when setting appropriate conditions in waste management licences. Future revisions of this guidance will further develop Best Available Techniques for landfill gas utilisation.

Readers of this guidance are expected to be familiar with the Landfill Directive requirements and the national regulatory frameworks. This includes the Defra guidance, *IPPC: a practical guide* (Defra, 2002a), which sets out how Government expects the PPC regime to operate in England and Wales. In Scotland the relevant PPC guidance is, *The Pollution Prevention and Control (Scotland) Regulations 2000: a practical guide* that is issued by the Scottish Executive Environment and Rural Affairs Department and SEPA.

This overarching guidance on the management of landfill gas is supported by a number of specific guidance documents. The series comprises:

- Guidance on landfill gas flaring
- Guidance for monitoring enclosed landfill gas flares
- Guidance for monitoring landfill gas engine emissions
- Guidance for monitoring trace components in landfill gas
- Guidance for monitoring landfill gas surface emissions (in England and Wales);
- Guidance on gas treatment technologies for landfill gas engines.

Scope

This guidance sets out a structured approach to the management of all gases generated from landfilled waste. It covers the assessment of landfill gas impacts, the implementation of control methods and the monitoring required to demonstrate proper performance of the control measures.

The document consists of three parts:

- Part A sets out the regulatory framework under which landfill gas is to be managed.
- Part B sets out the legislative requirements for landfill gas management and the role of risk assessment.
- Part C provides technical information and details of current best practice on landfill gas management.

Where technical standards explicitly required by the Landfill Regulations (England and Wales) for landfill gas management and control are referred to in this document, they are highlighted in a box for clarity.

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Guidance on the management of landfill gas

Part A: Regulatory framework

Regulatory framework

1.1 Introduction

The management of landfill gas at permitted landfills is covered by three pieces of European legislation:

- Waste Framework Directive (75/442/EEC as amended)
- Landfill Directive (1999/31/EC)
- Integrated Pollution Prevention and Control (IPPC) Directive (96/61/EC).

For permitted landfills in England and Wales, these Directives are implemented by the Landfill (England and Wales) Regulations 2002 and the Pollution Prevention and Control (England and Wales) Regulations 2000, both of which were made under the Pollution Prevention and Control (PPC) Act 1999.

In Scotland, these Directives are implemented by the Landfill (Scotland) Regulations 2003 (as amended) and the Pollution Prevention and Control (Scotland) Regulations 2000 (as amended), which were both made under the PPC Act.

The Waste Management Licensing Regulations 1994 (as amended) still apply to landfills, which are closed, have ceased accepting waste and are unable to enter into the PPC regime, but remain licensed.

1.2 The Landfill Directive

The overall aim of the Landfill Directive as expressed in Article 1 is:

> *by way of stringent operational and technical requirements on the waste and landfills, to provide for measures, procedures and guidance to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment, including the greenhouse effect, as well as any resulting risk to human health, from landfilling of waste, during the whole life-cycle of the landfill.*

Item 16 of the recital to the Landfill Directive intimates that measures should be taken to reduce the production of methane gas from landfills (amongst other things to reduce global warming) through a reduction in the landfilling of biodegradable waste and requirements to introduce landfill gas control.

This will, in part, be achieved by:

- reducing the amount of biodegradable municipal waste (BMW) disposed of to landfill;
- banning the deposit of certain wastes in landfills;
- pretreating most wastes prior to disposal in landfill.

Implementation of the Landfill Directive will result in a reduction of the volume of gas generated from waste. Changes in the waste composition may also result in significant changes both in the generation and constituent components of landfill gas.

The Landfill Directive sets out three classes of landfill:

- landfill for inert waste
- landfill for non-hazardous waste
- landfill for hazardous waste.

The Landfill Directive provides minimum requirements for the design and operation of all classes of landfill, including landfill gas control. It defines landfill gas as

> *'all the gases generated from landfilled waste'.*

Based on this definition, landfill gas includes gases generated by the biodegradation of waste and those arising from chemical reactions and the volatilisation of chemicals from the waste.

1.3 The Landfill (England and Wales) Regulations 2002

The technical requirements of the Landfill Directive have been implemented in England and Wales via the Landfill (England and Wales) Regulations 2002. The general requirements for all classes of landfills are set out in Schedule 2 of the 2002 Regulations. Schedule 2 paragraph (4) of the Regulations requires the following gas control measures.

(1) appropriate measures must be taken in order to control the accumulation and migration of landfill gas;

(2) landfill gas must be collected from all landfills receiving biodegradable waste and the landfill gas must be treated and, to the extent possible, used;

(3) the collection, treatment and use of landfill gas under sub-paragraph (2) must be carried on in a manner, which minimises damage to or deterioration of the environment and risk to human health; and

(4) landfill gas which cannot be used to produce energy must be flared.

The requirements for landfill gas control set out in the Landfill Regulations are, with the exception of minor text changes, the same as the requirements in Annex 1 (4) of the Landfill Directive. Chapter 7 provides guidance on how the requirements for landfill gas control are to be met.

1.4 The Landfill (Scotland) Regulations 2003

The technical requirements of the Landfill Directive are implemented in Scotland via the Landfill (Scotland) Regulations 2003. The general requirements for all classes of landfills set out in the Regulations re-iterate the requirements of the Landfill Directive.

1.5 Waste management licensed landfill sites

Landfill sites that hold waste management licences will continue to be regulated under the Waste Management Licensing Regulations 1994 (as amended) until such time as the regulator accepts surrender of the licence **if** the landfill:

- is deemed closed before implementation date of the Landfill Directive at 16 July 2001; or
- has not been granted a PPC permit after the submission and consideration of a site conditioning plan and where application for a PPC permit has been made or an appropriate closure notice has been served.

Sites that closed after 16 July 2001 will have to comply with the Landfill Directive and subsequent regulations in relation to site closure and aftercare. Much of the guidance presented in this document will therefore also apply to sites regulated under a waste management licence.

1.6 Unlicensed (closed) landfill sites

Closed landfills that do not have a waste management licence issued under Part II of the Environmental Protection Act 1990 may fall within the definition of contaminated land contained in Part IIA Section 57 of the Environment Act 1995. Section 78A(2) of the 1995 Act defines contaminated land for the purposes of Part IIA as:

> *Any land which appears to the local authority in whose area it is situated to be in such a condition, by reason of substances in, on or under the land, that:*
>
> *(i) significant harm is being caused or there is the significant possibility of such harm being caused; or*
>
> *(ii) pollution of controlled waters is being or likely to be caused.*

The statutory guidance uses the concept of a 'pollutant linkage', i.e. a linkage or pathway between a contaminant and a receptor. Landfill gas from old, unlicensed sites may form part of a significant pollutant linkage.

The Environment Agency is not responsible for the regulation of closed unlicensed landfill sites and, as such, this guidance document represents good practice for landfills permitted under the PPC or the waste management licensing regime. However, local authorities that are responsible for unlicensed landfill sites under Section 57 of the Environment Act 1995 may find this guidance a useful source of best practice.

1.7 Pollution Prevention and Control Regulations 2000

The Integrated Pollution Prevention and Control (IPPC) Directive has been implemented in England and Wales through the Pollution Prevention and Control (England and Wales) Regulations 2000 (made under the PPC Act 1999). In Scotland, it has been implemented through the Pollution Prevention and Control (Scotland) Regulations 2000.

The IPPC regime employs a permitting system to achieve an integrated approach to controlling the environmental impacts of certain industrial activities. An important feature of the IPPC Directive is the requirement on the regulator to ensure, through appropriate permit conditions, that installations are operated in such a way that all the appropriate preventive measures are taken against pollution, in particular through application of the Best Available Techniques (BAT). BAT is defined in Regulation 3 of the PPC Regulations and matters that must be considered when determining BAT are set out in Schedule 2 of the Regulations.

However, the condition making powers of the PPC Regulations are largely dis-applied by the Landfill (England and Wales) Regulations 2002 (Landfill Regulations) in respect of landfilling activities. Instead, the relevant technical requirements of the Landfill Regulations, together with its condition making powers, will cover the aspects of the construction, operation, monitoring, closure and surrender of landfills.

Notwithstanding the situation with regard to the landfill, landfill gas utilisation plant may be regulated individually by the Agency in England and Wales under the PPC Regulations as a combustion activity burning fuel manufactured from or comprising a waste other than waste oil or recovered oil. The threshold for such control is plant with a thermal input of greater than 3 MW. Landfill gas utilisation plant may also be regulated by the Agency through a landfill permit, where it forms part of the installation. Although BAT cannot be applied to the activity of landfilling, the principles of BAT should be applied in the landfill permit to directly associated activities and other listed non-landfill activities.

In England and Wales, there will also be circumstances where the landfill and the gas management system require separate permits while still being part of the same installation. A separate PPC permit may be required if the gas management system is operated by another party (albeit under contract to the operator of the landfill). This is because PPC permits can only be issued to ‘operators’ of installations or mobile plant and the operator is defined as ‘someone who has control’ of its operation (or who will have control in the case of proposed plant) (Environment Agency, 2001a). This is interpreted to mean someone who has direct day-to-day control over the activities (i.e. landfill gas management).

This guidance forms the basis for setting conditions in PPC permits (including landfill permits) which provide all appropriate measures to be taken against pollution, to limit emissions and the impact on the environment and when setting appropriate conditions in waste management licences. This guidance is best practice; it does not cover all aspects of BAT as set out in Schedule 2 of the PPC Regulations. The Agency intends to review the guidance and to further develop best available techniques for landfill gas utilisation.

1.8 Environment Agency’s strategy for regulating landfill gas

The Environment Agency’s strategy for the future regulation of landfill gas is focused on environmental outcomes and is based upon the concept of emission-based regulation. This strategy will improve the performance and regulation of landfill gas management systems in three ways.

- Operators will be required to detail their proposed landfill gas control methods, monitoring, procedures and actions through the development of a site-specific Gas Management Plan. This will be reviewed annually and revised in the light of updates of the risk assessment and recent monitoring data.
- Operators will be required to measure the emissions from landfill gas flares, engines and landfill surfaces. These emissions will be assessed against emission standards.
- Landfill sites, including the gas management system, will be inspected regularly. This will be underpinned by the use of detailed site audits, including the use of Agency check monitoring.

These procedures will be introduced as landfill sites are permitted or re-permitted in accordance with the PPC regulatory regime (or sooner if site-specific risk determines that improvements should be completed earlier).

For closed sites where a waste management licence remains in force, the Agency will require the licence holder to produce a landfill gas Emissions Review, which will be based on the development of a risk screening/conceptual model of gas management for the site. Where this review identifies unacceptable site-specific risks from landfill gas, the licence holder will be required to prepare an emissions improvement programme that incorporates appropriate best practice from this guidance. This replacement programme will be undertaken on a risk basis, for completion as soon as reasonably practicable, and as identified by the site-specific Emissions Review. The improvements identified in an Emissions Review must be completed at all Agency-regulated landfills by 16 July 2009.

In the future, type approval for landfill gas engines and flares may form an important part of this landfill gas strategy. UK waste management companies are keen to see the development of a type approval system, as they consider it would provide a safer and more efficient method of achieving the appropriate standards. Under this system, specific landfill gas flare and engine models could be shown to be capable of meeting the emission standards set by the Agency and could be demonstrated to do so reliably in the field environment. The Agency supports a move towards this approach as it may lead to more cost-effective monitoring of landfill gas combustion equipment, in the knowledge that the Agency's emissions standards were being met.

1.9 Planning and development

1.9.1 Development of new or current operational landfill sites

Land-use issues at new or current operational landfill sites are controlled by the local planning authority (LPA) in England and Wales and the planning authority in Scotland. They are responsible for establishing a planning policy framework which meets the objectives of sustainable development under the Town and Country Planning Act (1990) England and Wales, and the Town and Country Planning Act (Scotland) 1997.

Planning consent is required for landfill developments before the regulator grants a PPC permit following a new application for operation of the site. Guidance on planning and waste management licensing for England is given in Planning Policy Guidance 10 (PPG10) *Planning and waste management* (ODPM, 1999) and in Planning Policy Guidance 23 (PPG 23) *Planning and pollution control* (ODPM, 2002).

In Scotland, advice is provided within National Planning Policy Guideline 10 (NPPG 10) *Planning and waste management* (Scottish Office, 1997). Advice is also provided through Planning Advice Note 51 (PAN 51) *Planning and environmental protection* (Scottish Office, 1997) and Planning Advice Note 63 (PAN 63) *Waste management planning* (Scottish Executive, 2002a).

As a result, landfill gas and its management has to be taken into consideration during the planning process. Most landfill developments, and in particular those involving inputs greater than 50,000 tonnes per year and/or occupying an area of 10 hectares or greater, are likely to require an environmental impact assessment (EIA) in support of a planning application under Schedule 2 of the Town and Country Environmental Impact Assessment Regulations (England and Wales) 1999. In Scotland, these requirements are contained in the Environmental Impact Assessment (Scotland) Regulations 1999.

The EIA must include the potential impact of landfill gas on the surrounding environment, including the air quality and the visual impact of gas flares and utilisation plants. Sites smaller than the criteria identified above may require an EIA, and advice from the relevant planning authority should be sought. Under the General Development Procedure Order 1995 as amended (GDPO), the regulator is a statutory consultee to the planning process on landfill sites, including planning issues associated with landfill gas.

Where it is appropriate and legitimate, the regulator encourages co-ordinated applications for planning permission and PPC permits. This facilitates the continual development of the conceptual model and technical details of the proposal through the planning and permitting process within a consistent framework (see Chapter 2 on risk assessment).

The regulator envisages that an Environmental Statement prepared to the standards required for the EIA Regulations will, for most non hazardous and hazardous landfills, constitute a Tier 2 risk assessment that will also form part of the PPC permit application. However, it is likely that the risk assessment prepared for the planning application will need to be extended and revised to reflect the detailed engineering design and operation of the site, and to accommodate any changes brought about by conditions within the planning consent.

Planning authorities are responsible for deciding an application for planning permission. This decision may be to approve, to approve with conditions, or to refuse.

1.9.2 Development on or adjacent to landfill sites in England and Wales

The Town and Country Planning (General Development Procedure) Order 1995 (GDPO) (as amended) requires the planning authority to consult with the Agency before granting planning permission for development within 250 metres of land which is being used for the deposit of waste (or has been at any time in the previous 30 years) or has been notified to the planning authority for the purposes of that provision.

The Agency has developed 'standing advice' to enable LPAs to make decisions on planning applications for hard development within 250 metres of a 'licensed' or 'permitted' landfill without consulting the Agency. The standing advice should be a material consideration in determining the planning application, as would advice received from the Agency under Article 10(5) of the GDPO (Environment Agency, 2003a).

For landfill sites that are no longer licensed or permitted, the Agency holds information that it can provide to local authorities to aid decision-making on relevant planning applications. Local authority records for landfill sites that closed prior to the requirements of waste management licensing regime are likely to be more complete than those held by the Agency.

1.10 Other regulations and guidance

This guidance has been compiled primarily to address the requirements of the Landfill Regulations 2002 and the PPC Regulations 2000. A list of other legislation, which may have an impact on the control or management of landfill gas, is given in Table 1.1.

Table 1.1 Current legislation relevant to the control and management of landfill gas

	Title
EU Directives	75/442/EEC Waste Framework Directive and amendments
	96/61/EC Integrated Pollution Prevention and Control
	97/11/EC Environmental Impact Assessment
	91/689/EEC Hazardous Wastes
	99/31/EC Landfilling of Waste
	96/62/EC on air quality assessment and management
	1999/30/EC relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead
	2000/69/EC relating to limit values for benzene and carbon monoxide in ambient air
Acts	Environmental Protection Act 1990
	Town and Country Planning (England and Wales) Act 1990
	Town and Country Planning (Scotland) Act, 1997
	Clean Air Act 1993
	Environment Act 1995
	Pollution Prevention and Control Act 1999
Statutory Instruments	Landfill (England and Wales) Regulations 2002, SI 2002 No. 1559
	Landfill (Scotland) Regulations 2003 SI 2003 No. 235
	Pollution Prevention and Control (England and Wales) Regulations 2000, SI 2000 No. 1973
	Pollution Prevention and Control (Scotland) Regulations 2000, SI 2000 No. 323
	Air Quality (England) Regulations 2000, SI 2000, No. 928
	Air Quality (Wales) Regulations 2000, WSI 2000, No. 1940
	Air Quality (Scotland) Regulations 2000, SSI 2000, No. 97
	Air Quality (Scotland) Amendment Regulations 2002, SSI 2002, No. 297
	Air Quality Limit Values Regulations 2001, SI 2001 No. 2315
	Air Quality Limit Values (Wales) Regulations 2002, WSI 2002 No. 3183
	Air Quality Limit Values (Scotland) Regulations 2001, SSI 2001, No. 224
	Waste Management Licensing Regulations 1994, SI 1056 as amended
	Control of Substances Hazardous to Health Regulations 2002, SI 2002, No. 2677
	Contaminated Land (England) Regulations 2000, SI 2000, No. 227s
	Contaminated Land (Wales) Regulations 2001, WSI 2001, No. 2197
	Town and Country Planning General Development Order 1988, SI 1998, No. 1813
	Town and Country Planning (General Permitted Development) Order 1995, SI 1995, No. 418
	Town and Country Planning (General Development Procedure) Order 1995, SI 1995, No. 419
	Town and Country Planning (General Development Procedure (Scotland) Order 1992 (as amended)
	Town and Country (Environmental Impact Assessment) (England and Wales) Regulations 1999, SI 1999, No. 293
	Environmental Impact Assessment (Scotland) Regulations 1999, SSI 1999, No. 1
	Planning (Control of Major-Accident Hazards) (Scotland) Regulations 2000, SSI 2000, No. 179

Table 1.1 Current legislation relevant to the control and management of landfill gas *(continued)*

	Title
Guidance	Planning Policy Guidance Note 10 Planning and waste management, 1999 Planning Policy Guidance Note 22 Renewable energy, 1993 Planning Policy Guidance Note 23 Planning and pollution control Planning Guidance (Wales) Planning policy, 1999 (under review) Technical Advice Note (Wales) 8 Renewable energy, 1996 Technical Advice Note (Wales) 21 Waste, 2001 National Planning Policy Guideline 6 Renewable energy, 2000 (applies in Scotland) National Planning Policy Guideline 10 Planning and waste management, 1996 (applies in Scotland) Planning Advice Note 51 Planning and environmental protection, 1997 (applies in Scotland) Planning Advice Note 58 Environmental impact assessment, 1999 (applies in Scotland) Planning Advice Note 63 Waste management planning, 2002 (applies in Scotland) Planning Advice Note 45 Renewable energy technologies (revised 2002) (applies in Scotland)

1.10.1 Air quality and odour control

Air quality

Occupational air quality limits that apply to the workplace are established for a range of compounds that are present in landfill gas. These are listed in the Health and Safety Executive (HSE) *Guidance Note EH40* (HSE, 2002), which is reviewed annually.

Local authorities are responsible under the Air Quality Strategy for England, Scotland, Wales and Northern Ireland to ensure that the public is not exposed to an air quality that poses a significant risk to human health or quality of life. The strategy addresses the following air pollutants.

- benzene
- 1,3-butadiene
- carbon monoxide
- lead
- oxides of nitrogen
- ozone
- particulates (PM_{10})
- sulphur dioxide.

The Strategy lays down objectives to be met by 2005 for each pollutant. Several of the listed pollutants may be associated with landfill gas and emissions from the gas management system. Local authorities have a critical role in delivering these objectives through action plans as part of the Local Air Quality Management regime. This involves the review and assessment of air quality in their area against the objectives. Where the objectives are unlikely to be met, local authorities must develop action plans that set out how they can be obtained.

The regulator takes into account the Air Quality Strategy and its objectives when setting licence or permit conditions. In addition, Council Directive 1999/30/EC set limit values for the concentration of for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air and dates for their attainment. Where the impact of an installation is likely to lead to a breach of these limit values, the operator may be required to go beyond BAT to comply with the limit values.

Odour

The Waste Framework Directive requires that waste is recovered or disposed of without causing nuisance through noise or odour. In addition, the Landfill Regulations require the following.

> Measures shall be taken to minimise nuisances arising from the landfill in relation to:
>
> - emissions of dust and odours;
> - wind-blown material;
> - noise and traffic;
> - birds, vermin and insects;
> - the formation of aerosols;
> - fires.

Odour can present potential health issues (even if only in perception) and it is important to remember that the regulator has powers and duties to address human health issues in addition to pollution and amenity issues.

Guidance has been produced on odour control for landfills in England and Wales (Environment Agency, 2002a). Odour is discussed in more detail in Chapter 6.

Odour and its impacts, if deemed a statutory nuisance, can be regulated by the environmental health departments of local authorities under Sections 79–80 of the Environmental Protection Act 1990. This allows local authorities to serve abatement notices on 'premises' where a statutory nuisance exists or is likely to occur or recur. Abatement notices can require abatement of the nuisance or the prohibition of its occurrence and actions to remedy the situation.

COSHH

The Agency is not responsible for the regulation of health and safety at landfills. The Control of Substances Hazardous to Health Regulations (COSHH) 1988, 1994, 1999 and 2002 place a legal obligation on landfill operators to demonstrate that the workforce engaged in landfill operations is not exposed to a significant health risk. This includes those directly employed by the landfill operator and those employed as contractors to undertake secondary tasks such as engineering or monitoring. The Regulations require employers to comply with the occupational exposure limits established by the HSE and to undertake studies to assess the risk posed to workers where the level of exposure is unknown.

1.10.2 Clean Air Act 1993

Local authorities may require that a planning application is submitted for the installation of landfill gas flares or gas utilisation plant. They may also wish for an application for chimney height approval to be made under the Clean Air Act 1993. This would require landfill gas flare/combustion operators to submit evidence that the height of the flare or exhaust stack is sufficient to prevent emissions being prejudicial to human health or likely to cause a nuisance.

Guidance on the management of landfill gas

Part B: Legislative requirements and risk assessment

Risk assessment

2.1 A risk-based strategy

The Agency's strategy for the future regulation of landfill gas is based on environmental outcomes. This places great emphasis on emissions monitoring and compliance assessment. The strategy augments, but does not replace, the existing philosophy of best practice regulation of landfill gas infrastructure, which retains a key role.

At a fundamental level, this strategy requires an understanding and quantification of landfill gas through risk assessment and the development of a conceptual model of the site. The conceptual model and proposed level of risk assessment should be the subject of early pre-application discussions with the regulator.

The risk assessment approach involves:

- the assessment of potential impacts on local environment, health and amenity;
- the development of a Gas Management Plan.

The Gas Management Plan includes:

- management options, procedures and collection efficiency determination;
- emissions monitoring and assessment from various parts of the landfill gas infrastructure.

The feedback of monitoring and assessment information enables the validation/improvement of both the conceptual model and the Gas Management Plan. This provides opportunities for improvements based on environmental outcomes.

2.2 Risk assessment framework

The regulator requires the use of a structured approach to the assessment of the risks posed by a landfill to human health, the environment and local amenity. This is a pre-requisite for the permitting of all landfills under PPC and a fundamental part of preparing a Gas Management Plan. The ongoing assessment of risk for operational sites will be a requirement for the maintenance of a PPC permit.

Risk assessment should be a transparent and practical process that aids decision-making. The recommended framework for environmental risk assessment and management is described in DETR *et al*. (2000). This consists of a tiered approach where the level of effort put into assessing each risk is proportionate to its magnitude and its complexity. A conceptual approach to the tiered risk assessment is shown in Figure 2.1.

This process emphasises the:

- importance of developing a robust conceptual site model at the risk screening stage, based on a source–pathway–receptor approach that is continually reviewed and updated as new information is collected;
- need to screen and prioritise all actual and potential risks before quantification;
- need to match effort and resources in evaluating potential risks to the magnitude of environmental damage that could result from each hazard;
- need for an appropriate level of measures to manage the risks;
- iterative nature of the process, with annual reviews being an integral part.

Operators of existing landfill sites transferring to the PPC regulatory regime as part of transitional arrangements will be required to undertake a risk assessment to support their PPC application. Operators should apply an appropriate tier of risk assessment in accordance with the guidance given below. For non-hazardous and hazardous waste landfill sites, this is likely to require the application of Tier 2 or Tier 3 risk assessments.

The risk assessment must address the key issues raised by the Landfill Regulations (see Box 2.1). For a new site, these issues are dealt with by the planning authority at the planning application stage. They are likely to be the subject of the EIA submitted with the application. The regulator is a statutory consultee at the planning stage and is likely to have a view on all of these issues.

For an existing site, the pathways and receptors identified in the box should be on the list of those considered in the risk assessment. This should demonstrate that there will be no unacceptable emissions from the site in both the short and the long term.

Box 2.1 Risk assessment issues identified by the Landfill Regulations

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

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

The Landfill Regulations also require that:

- landfill gas must be collected from all landfills receiving biodegradable waste and the landfill gas must be treated and, to the extent possible, used.
- the collection, treatment and use of landfill gas is required and must be achieved in a manner, which minimises damage to or deterioration of the environment and risk to human health.

The assessment of risk from landfill gas and gaseous emissions must be developed in conjunction with the risk assessment for aqueous emissions. The guidance below focuses on the assessment of gaseous risks.

The risk assessment is likely to develop in four stages:

Stage 1: Hazard identification and risk screening – the initial development of the conceptual model and provides the basis for pre-application discussions for planning applications or for existing sites seeking a PPC permit.

Stage 2: Simple quantitative risk assessment – submitted in support of the planning application and forming part of the EIA for the site or in support of a PPC permit application.

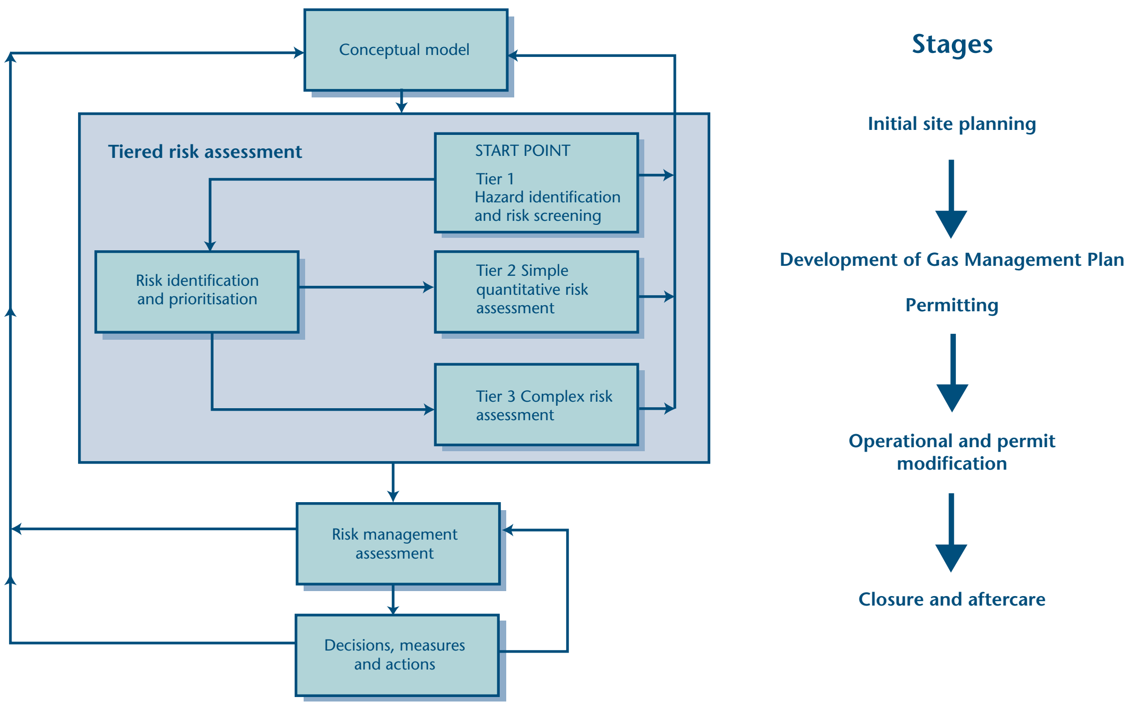
Stage 3: Complex quantitative risk assessment – submitted in support of a PPC permit application for sites where a Stage 2 approach is not sufficient due to either the significance of risks posed by landfill gas at the site or the complexity of the issues associated with landfill gas. The Gas Management Plan should be developed from the risk assessment. Continuous review of site investigations and monitoring data produced as part of the Gas Management Plan will indicate whether:

- the data validate the conceptual model;
- there is a need to modify/update both the conceptual model and the Gas Management Plan.

Stage 4: Completion – a thorough review of the conceptual model and monitoring data will be undertaken to determine whether the site meets the surrender test and to confirm that it no longer poses any pollution risk.

The risk assessment should follow a tiered approach as shown in Figure 2.1 and outlined in the following sections, which provide guidance on the level of risk assessment necessary to provide sufficient confidence to allow decision-making.

Figure 2.1 Conceptual approach to risk assessment for landfill gas (adapted from DETR *et al.*, 2000)



2.3 The conceptual model, hazard identification and risk screening

Conceptual model

This is the initial development of the conceptual site model and involves the development of an understanding of the landfill site in its surroundings.

The conceptual site model should identify the nature of the site and its planned development. With respect to landfill gas, it should include the following information:

- the nature of the waste and the source term including:
  - an initial indication of the likelihood of gas production;
  - whether gas extraction is required;
  - an estimation of the likely volumes of gas generated;
  - whether utilisation is proposed.
- the environmental setting in which the site is located including identification of all receptors (including the atmosphere);
- an initial selection of appropriate environmental benchmarks, e.g. Environmental Assessment Levels (EALs) and odour thresholds;
- a design of the containment, collection and treatments systems;
- the operational management and gas control practices to be employed;
- an identification of the pathways to receptors including release (emission) points/areas for landfill gas and combustion products.

The conceptual model developed for the purposes of the landfill gas risk assessment must not be produced in isolation from that required for the hydrogeological risk assessment. There should be one conceptual model for the landfill, which covers all environmental media. The development of a conceptual site model is an iterative process; the model must be reviewed and updated as new information becomes available or as the understanding of the system is improved. This process will form part of the required periodic review.

The conceptual model should consist of site plans, outline designs and sketches; these may be underpinned by spreadsheets and standard templates listing locations and similar details. The initial conceptual model will provide a useful platform for discussions between the site operator and the regulator as part of the pre-application process. By the time an application for a permit is submitted, the conceptual model should be based on detailed site plans and designs contained in the permit application and the Gas Management Plan.

Hazard identification and risk screening

The hazard identification and risk screening stage should have the following overall objectives:

- development of an understanding of the proposed or existing landfill in its environmental setting (the conceptual model described above), including identification of all possible sources of risk, the pathways and the potential receptors;
- consideration of the sensitivity of receptors and initial selection of the appropriate environmental benchmark, e.g. EALs for each receptor or groups of receptors;
- consideration of the potential impacts on each receptor. This may be achieved by using a simple quantitative or qualitative process that systematically examines each source–pathway–receptor linkage and determines the potential impact. For each receptor, this analysis should prioritise the risks and the requirements to be evaluated for further risk assessment.

The following sections deal with each of these outputs.

2.3.1 The source of risk

The source term for all landfills needs to be considered and assessed during risk screening and hazard identification. This applies whether or not the landfill site accepts inert, non-hazardous or hazardous wastes, and whether the waste is biodegradable or inorganic. However, the approach for assessing the source term may be different depending on the type of landfill (see below).

If landfill gas generation cannot be shown to be negligible, then this will trigger the best practice requirements for active extraction, utilisation, flaring and the provision of barriers to minimise gas movement (see Chapter 4). These measures must be set out in the conceptual model and the Gas Management Plan, and their impact assessed.

A number of factors influence gas generation and a variety of models can be employed for predicting rates of gas production (see Section 2.4). For the purposes of risk screening, an approach is outlined below that will give a first estimate of the likely requirements for different types of landfills and for existing waste deposits. One necessary output from this initial screening is to determine whether landfill gas is a significant concern.

Inert waste landfills

For inert landfills, the landfill gas risk assessment will not normally have to progress beyond the risk screening stage. New inert landfills ought not to pose a landfill gas hazard. The emphasis in the risk assessment should, therefore, be placed on the Waste Acceptance Procedures and particularly the waste characterisation and compliance monitoring measures introduced to ensure that only inert waste is deposited at the site. If these measures can be shown to be robust, then the landfill gas source should be demonstrably negligible. Provisions for the monitoring of gas within the waste body will normally be required at inert waste landfills (see Chapters 5 and 8).

For existing sites, previous deposits of non-inert waste introduce a greater level of complexity and may require a more detailed level of assessment as outlined below.

Biodegradable waste landfills

An initial approximation of the landfill gas generation for sites that have taken biodegradable waste can be produced by simply assuming that each tonne of biodegradable waste will produce 10 m^3 of methane per year. The equation shown in Box 2.2 can then be used to calculate the approximate gas flow that would be generated. This equation produces an overestimate of gas flow at peak production and gas flow from historic waste deposits. More sophisticated models of gas generation (including GasSim; see Environment Agency, 2002b) can also be used at this stage.

Box 2.2 Calculating the approximate gas flow

$$Q = M \times 10 \times T / 8760$$

Where:

Q = methane flow in m^3/hour
M = annual quantity of biodegradable waste in tonnes
T = time in years

A predicted methane flow (Q) that exceeds a simplistic benchmark value of 50–100 m^3/hour provides an initial indication that flaring or utilisation will be required. These measures will then need to be built into both the conceptual model and the Gas Management Plan. As the technology for flaring and utilising landfill gas develops, the regulator will revise this simple benchmark.

If the proposed mix of wastes or depth of waste is predicted to generate landfill gas but only at levels that make collection inefficient, this may be an unacceptable landfill proposal. The proposed mix of wastes must have a viable landfill gas risk management scheme, i.e. a low level of biodegradable waste input would not be permitted without a coherent gas management strategy.

Where it is clear from the risk screening process that landfill gas will be generated in more than negligible quantities, this will trigger the introduction of measures that implement best practice requirements for the management of landfill gas. These requirements are discussed in more detail in Chapter 4. These measures must be included in both the developing conceptual model and the Gas Management Plan, and their impact evaluated.

Best practice requirements for landfill gas are:

- **Containment** – barriers to prevent sub-surface migration and minimise surface emissions of landfill gas.
- **Collection** – an active gas extraction system to achieve the maximum practicable collection efficiency. The annual collection efficiency for methane should be compared against a value of 85 per cent. The operator or regulator may use this simple assessment to trigger further investigation. This collection efficiency should be achieved in that part of the landfill where gas collection must be taking place (i.e. the capped areas of the site). Box 2.3 shows how to estimate collection efficiency.
- **Utilisation, flaring and treatment** – a system of combustion processes (or other treatment processes) meeting the emission limits for that process. Treatment of the gas stream pre- or post-combustion will be a site-specific issue based on the precise composition of the gas stream.

The measures to be applied to meet these requirements will be determined by site operators in consultation with the regulator. However, their application must be fully evaluated and supported by further risk assessment work. For example, the specification of the side wall lining needed to control sub-surface migration will depend on the specific pathways identified. These will also govern the migration monitoring requirements in terms of location and frequency.

The timing for beginning active gas extraction is a key risk management provision at all landfill sites/cells where this is required. Where the risk assessment demonstrates that flaring is necessary, the first flare (or utilisation plant if appropriate) should, as an indicative standard, be operational within six months of waste being accepted into the site or cell. This period may be extended if the waste input rate is low or specific site conditions make it likely that there will be insufficient gas to sustain flaring. However, it is best practice to design cells in such a manner that waste emplacement and final capping can be achieved quickly, thus facilitating early gas collection.

The following indicative benchmarks (Environment Agency, 2000a) can be applied during the risk screening process to indicate when landfill gas utilisation is likely to be required. The presumption is that landfill gas must be utilised and, if any one of the indicative benchmarks listed in Table 2.1 is met, then landfill gas utilisation should be considered. These criteria are considered in more detail in Chapter 4. Where comparison against these benchmarks indicates that utilisation is required, then measures will be required in order to demonstrate best practice requirements (see above).

Box 2.3 Estimating collection efficiency

Collection efficiency (**E**) = Mass of gas collected/Mass of gas produced

$$E = A / (A + B + C)$$

Where:

A = mass of methane sent to utilisation and treatment
B = mass of methane emitted through cap
C = mass of methane lost by lateral migration through liner

C is related to **B** by the relative permeability of the cap and the liner; this can be estimated from first principles and knowledge of design of engineered containment or, alternatively, through GasSim using information on the construction of the cap and liner.

If **K** is the relative amount of gas emitted through the cap compared with that through the liner, **K** =

(Permeability of cap) x (Surface area of cap)/(Permeability of liner) x (Surface area of liner above saturated zone).

Substitution in the equation above gives:

$$E = A / (A + B(1+K))$$

Parameters **A** and **B** are reported by the site operator. Parameter **K** can be calculated from information provided within the risk assessment.

Table 2.1 Indicative benchmarks for landfill gas utilisation

Parameter	Value
Total quantity of emplaced waste	≥ 200,000 tonnes
Gas flow rate	≥ 600 m^3/hour
Depth of waste	≥ 4 metres
Waste composition	≥ 25% weight/weight (w/w) organic wastes

Inorganic waste landfills

Inorganic landfills that have not accepted biodegradable waste will produce a landfill gas of different composition to that produced from biodegradable landfills. This gas may not contain methane and carbon dioxide in the bulk proportions normally associated with gas from biodegradable landfills. It is, however, possible that gaseous emissions (landfill gas) (e.g. hydrogen) will still be produced from the inorganic wastes deposited. This will also apply to the separate cells used for the disposal of hazardous wastes.

Rigorous waste acceptance procedures including waste characterisation and compliance monitoring will be necessary at such sites to ensure that biodegradable waste is not accepted.

The method of determining this source term will be site-specific and dependent upon the waste types accepted by the site/cell. Unless it can be demonstrated that the source and risks associated with the landfill gas are negligible, then extraction and utilisation/flaring of the landfill gas will be required. For certain landfills (e.g. in-house landfills that are well characterised and monitored), there may be sufficient confidence at the risk screening stage that the risk is negligible, but a more detailed risk assessment is likely to be required.

Where gas collection and combustion are required, the risk management measures introduced must be capable of dealing with the uncertainty associated with the source term. Monitoring of gas generation and composition will form a vital part of the iterative risk assessment process in order to characterise this uncertainty.

Existing waste deposits

Where PPC applications cover previously landfilled areas, the historic waste inputs are unlikely to conform to the strict requirements for inert, non-hazardous or hazardous landfills. Assessment of the source term should be based on records of the wastes accepted and the results of landfill gas monitoring.

During the risk screening process, the following outputs will be required for waste already deposited within the installation:

- dates of landfill commencement and any cessation of deposits (both temporary and final);
- a summary of waste types and quantities in broad categories, e.g. inert (based on the Landfill Directive definition), construction and demolition, household, industrial, commercial and special;
- an estimate of the biodegradable fraction of the waste deposited;
- a summary of landfill gas monitoring records within and external to the waste body;
- all trace gas analyses and a summary of the analytical results;
- gas control measures currently applied and gas generation rates (including pumping trials);
- odour complaints or recorded instances of odour episodes.

This information will allow an initial assessment of the existing waste deposits and their contribution to gas generation.

2.3.2 Receptors

A number of potential receptors need to be considered with respect to landfill gas and the conceptual model should identify site-specific examples of the generic categories. These are:

- domestic dwellings (human occupation in bands: closer than 50 metres, between 50 and 250 metres and 250 to 500 metres);
- hospitals;
- schools and colleges;
- offices, industrial units and commercial premises;
- sensitive habitats and environmental areas e.g. sites of special scientific interest (SSSIs);
- public footpaths or bridleways;
- major highways and minor roads;
- open spaces;
- parks;
- allotments;
- farmland (e.g. crop damage);
- air quality management zones.

Where the risks are likely to be the same (e.g. a particular street or small group of houses), it may be useful to group receptors together.

Each receptor or group of receptors should be identified on the site plan. The information should be set out on a standard template such as contained in Horizontal Guidance Note H1 (Environment Agency, 2002c), where additional information on this subject is provided. This will create a transparent record for each of the site-specific receptors that can then be linked to the predicted impact, the risk management measures and the monitoring requirements.

2.3.3 *The initial selection of environmental benchmarks*

In order to determine the sensitivity of the environment within the vicinity of a landfill, risk screening should identify the most appropriate environmental benchmarks to be applied. These may include air quality standards, EALs and odour thresholds.

These benchmarks should be used in the risk screening of each hazard (e.g. air quality, odour) associated with the specific emissions. A comparison of the concentrations in the environment resulting from the emissions against these environmental benchmarks will allow their significance to be assessed and a decision to be made on whether the landfill's impact is acceptable or whether further risk assessment work is required.

EALs for both the short-term (1-hour reference period) and long-term are given in Horizontal Guidance Note H1 (Environment Agency, 2002c). Releases (emissions) should be expressed according to any relevant standard conditions and the statistical basis from which they are derived should be indicated. The same measurement period should be used for comparison against environmental benchmarks.

Table 2.2 Example environmental benchmarks for air quality*

Emission	EAL (μg/m^3)	
	Long-term	Short-term
Combustion gases NO_2		
Nitrogen dioxide (NO_2)	40[#]	200[#]
Sulphur dioxide (SO_2)	50	267
Carbon monoxide	350	10,000[#]
Hydrogen chloride	20	800
Raw landfill gas		
Hydrogen Sulphide	140	150
Benzene	16.25	208
Chloroethane	27,000	338,000
2-butoxyl ethanol	1,230	–
Chloroethene (vinyl chloride)	159	1851
1,1-dichlorethane	8,230	165,000

* Adapted from Environment Agency, 2002c.

[#] See Table D1 (Environment Agency, 2002c).

Table 2.2 presents a selection of EALs that can be used at the risk screening stage for biodegradable non-hazardous landfills. The Agency has also identified a number of priority compounds that should be considered with specific reference to landfill gas. Estimated emissions at the site of receptors identified in the conceptual model should be compared with the EALs.

At hazardous and inorganic landfills, a wider range of substances need to be considered depending upon the proposed waste types. When selecting appropriate EALs for use as assessment levels at existing sites, the trace gas composition and flare/engine emission data/limits should be considered. Horizontal Guidance Note H1 (Environment Agency, 2002c) provides useful information in formulating these benchmarks.

Most of the environmental benchmarks available for use in the risk assessment for releases to air are currently based on occupational exposure data or odour threshold data for human receptors. There are a number of short-term and long-term benchmarks available that are taken from EU air quality limit values and national objectives (e.g. for benzene, carbon monoxide, nitrogen dioxide, particulates (PM_{10}) and sulphur dioxide. The most appropriate benchmark, e.g. for nitrogen oxides (NO_x) and sulphur oxides (SO_x), should be selected on the basis of the appropriate averaging period for the identified receptors.

For the sub-surface migration of landfill gas, an appropriate environmental benchmark for methane and carbon dioxide is 1 per cent and 1.5 per cent volume/volume (v/v) above background, respectively. The consideration of site-specific background levels is essential in the determination of absolute risk and should not be ignored.

Section 2.3.6 explains how these benchmarks should be used in the receptor assessment process.

2.3.4 *Pathway*

Receptors may be exposed to landfill gas emissions through:

- direct release to atmosphere;
- sub-surface migration through the ground or along service ducts and/or pipelines, etc;
- indirect release to atmosphere, e.g. from sub-surface landfill gas migration, or dissolution from leachate and condensate;
- direct release of combustion products to atmosphere, e.g. enclosed flares and engines.

Any landfill is likely to have a variety of potential release points and fugitive emissions related to landfill gas. The conceptual model must be based on the reality of the situation for each landfill and the assessment of pathways must start from the assumption that the appropriate best practice requirements are in place. Release points/areas will include:

- freshly deposited wastes;
- the surface (cap) of the landfill (including areas of permanent and temporary capping, the intermediate batters to the landfill and the working area);
- the interface of the landfill with the surrounding geology and engineering features;
- leaks from the gas and leachate collection systems (pipework, valves, wells);
- gas and leachate treatment plant;
- degassing of leachate and condensate during collection and/or treatment;
- flare stacks;
- exhaust emissions from utilisation plant;
- intermittent emissions during excavations, well drilling, leachate pumping or other engineering works.

The relative importance of each of these will vary on a site-specific basis. All the potential site-specific release points/areas should be identified and listed in a standard format. A site plan should identify the potential release points/areas.

The releases identified through the risk assessment process will require management and monitoring, and the standard template provides this link. For instance, a potential leak from a well head will require routine management inspection and monitoring. Where the well head is close to a receptor (e.g. a footpath), the frequency of monitoring may be greater than where the well head is more remote. An odour complaint from the receptor should feedback into further monitoring and a re-evaluation of risk management measures.

2.3.5 Receptor prioritisation and impact assessment

The prioritisation process will be a qualitative assessment based on consideration of the estimated impact (roughly quantified as described below), the sensitivity of the receptor (qualitative) and the likelihood of exposure (qualitative).

The potential hazards that exist from landfill gas are:

- toxicity (acute and chronic)
- ecotoxicity
- fire and explosion
- asphyxiation
- odour.

For the purposes of risk screening, potential emissions and simple air dispersion (including a general allowance for wind directions and topography) should be considered and compared with suitable environmental benchmarks. This will indicate whether landfill gas poses a risk.

The trace components of landfill gas pose an odour and toxicity risk, while the bulk gases pose a risk due to explosion and asphyxiation (although carbon dioxide is also toxic and should be considered in the assessment of toxicity). Explosion and asphyxiation risk is generally related to sub-surface migration and accumulations in enclosed spaces. This is more difficult to quantify and, for the risk screening stage, the impact assessment should be based on:

- the presence of potential pathways and site-specific receptors;
- a qualitative assessment of the severity of the consequences.

Risk screening using simple air dispersion modelling may employ the methodology reflected in Horizontal Guidance Note H1 (Environment Agency, 2002c) to estimate the potential impact of the emissions. The following outlines the requirements at the risk screening stage.

2.3.6 Dispersion of emitted gas

Emission rate

To quantify the effect of emissions, it is necessary to know the emission rate, e.g. grams per second (g/s). The landfill gas emission rate should be based on the estimated generation rate from future deposits, i.e. it should reflect the period of maximum gas generation at the site.

For existing sites, determination of emission rates should also consider monitoring data. The gas flow estimates should be used, together with an assumption of gas stream composition, to produce an emission rate in grams per second. Where uncertainties exist in estimated values, it is usual to assume the ‘worst case’ and to state any assumptions made.

For the purposes of risk screening, emissions should be quantified for flares and engines. For existing sites, one option is to use monitoring data for the existing combustion plant. An alternative is to extrapolate data from a similar site and plant to the maximum predicted gas flow. To ensure a conservative assessment, emissions from flares and engines for new sites should be based on typical emission levels obtained from literature – although these should be rationalised by reference to the manufacturer’s published performance data. Unless there is auditable evidence available of compliance, emission levels based simply on assumed compliance with Agency best practice emission limits should not be used for the risk assessment. Models such as GasSim (Environment Agency, 2002b) can be used to derive a release rate for risk screening. For GasSim, the value used for the release rate should be the predicted maximum 95th percentile emission rate over the life of landfill site.

In the absence of site-specific design data, the default assessment of fugitive emissions should consider a flux of 85 per cent of the theoretical generation for comparison with short-term environmental benchmarks (e.g. short-term EALs) and 30 per cent for comparison with long-term environmental benchmarks (e.g. long-term EALs; see Table 2.2). Both short-term and long-term effects should be considered in the risk screening process. The predicted impact should be calculated, as far as possible, on the same basis as the corresponding environmental benchmark, e.g. over the same averaging period or percentile exceedence.

All assumptions made and data sources used during the risk screening process should be recorded.

The simple calculation method shown in Box 2.4 can be used for screening purposes, but it does not take into account all the parameters that may influence dispersion of substances to air. This equation will generally provide a more conservative estimate of ground level concentration (GLC) than more complex models. Fit-for-purpose models (including GasSim for long-term impacts) may be used instead of the equation to provide estimates of the predicted concentration for risk screening.

The appropriate value for GLC can be obtained from Horizontal Guidance Note H1 (Environment Agency, 2002c) and from tables such as Tables 2.3 and 2.4, which are specific for landfill gas engines/enclosed flares. The calculations in these tables assume typical exit velocities and emission temperatures for a range of stack heights, with off-site maxima dependent upon the distance from the stack to the landfill boundary. These are derived from mathematical dispersion models and presented as maximum average GLC for unit mass emission rates for different stack heights. The predicted concentrations of short-term and long-term releases are based on the use of dispersion factors assuming 'worst case' situations, i.e. highest concentration and impact. For long-term releases, the GLCs are presented as maximum annual averages and, for short-term releases, as maximum hourly averages.

Box 2.4 Estimating predicted concentrations in air

$$PC_{air} = GLC \times RR$$

Where:

PC_{air} = predicted concentration (µg/m^3)

RR = release rate of substance in g/s

GLC = maximum average ground level concentration for unit mass release rate (µg/m^3/g/s), based on annual average for long-term releases and hourly average for short-term releases.

Table 2.3 Estimation of maximum off-site hourly GLCs for a unit mass emission rate (µg/m^3 per g/s emitted)

Distance to site boundary (m)	Gas engine height (m)				Flare stack height (m)		
	5	6	7	8	6	8	10
<50	255	185	135	100	285	140	75
50	240	185	135	100	215	140	75
100	140	125	115	100	110	90	75
150	95	85	80	75	70	60	55
200	70	65	60	55	50	45	40
250	55	50	50	45	40	35	35
300	45	40	40	40	30	30	25
350	35	35	35	35	25	25	25
400	30	30	30	30	20	20	20
450	30	25	25	25	20	20	15
500	25	25	25	25	15	15	15

Table 2.4 Estimation of maximum off-site annual mean GLCs for a unit mass emission rate (µg/m^3 per g/s emitted)

Distance to site boundary (m)	Gas engine height (m)				Flare stack height (m)		
	5	6	7	8	6	8	10
<50	13	11	9.5	8	7	5.5	4
50	13	11	9.5	8	7	5.5	4
100	13	11	9.5	8	7	5.5	4
150	9.5	9	8	7.5	5.5	5	4
200	7	6.5	6.5	6	4.5	4	3.5
250	5.5	5	5	5	3.5	3	3
300	4	4	4	4	3	2.5	2.5
350	3.5	3.5	3.5	3	2.5	2	2
400	3	3	3	2.5	2	2	2
450	2.5	2.5	2.5	2.5	1.5	1.5	1.5
500	2	2	2	2	1.5	1.5	1.5

Those substances that are emitted in such small quantities that they will have an insignificant impact on the receiving environment should be screened out at this stage (see Box 2.5). A summary table of their predicted concentration (PC) should be produced and their significance assessed. This should be carried out using the method described below.

The short-term and long-term PC of substances emitted should be compared with the relevant short-term and long-term environmental benchmarks for emissions to air. The same statistical basis for mass concentration as the environmental benchmarks must be used to ensure a meaningful comparison.

Box 2.5 Is an emission insignificant

An emission is insignificant where the PC is less than 1 per cent of the environmental benchmark (long-term).

An emission is insignificant where the PC is less than 10 per cent of the environmental benchmark (short-term).

Where the predicted concentration is judged insignificant by these criteria, then the risk can be regarded as negligible and need not be considered further. Where the predicted concentration is judged as potentially significant, it will be necessary to use the following guidelines to decide whether detailed modelling is required.

Information should be collected on the ambient concentrations for the appropriate substance. When assessing short-term effects, the short-term background should be taken to be equal to twice the long-term background. The total predicted environmental concentration (PEC) of that substance is calculated by adding together the background concentration and the contribution from the engine/flare as identified in the equation in Box 2.6.

Box 2.6 Calculating the total PEC

$$\mathrm{PEC_{air}} = \mathrm{PC_{air}} + \text{Background concentration}_{\mathrm{air}}$$

- **Long-term benchmarks** – Modelling of long-term effects may be appropriate if the long-term PEC is above 70 per cent of the relevant environmental benchmark or, in locations where there is an Air Quality Management Plan, for the identified substance.
- **Short-term benchmarks** – Modelling of short-term effects may be appropriate if the short-term PC is more than 20 per cent of the difference between the short-term background concentration and the relevant short-term environmental benchmark.

In addition, nitrogen oxide and nitrogen dioxide are commonly measured as NO_x but the benchmarks are expressed as the individual constituents. In time, emissions of NO oxidise to form NO_2 and the following guidelines should be followed when assessing emissions from landfill gas engines and flares.

- For short-term impacts, convert all measured or estimated nitrogen oxide emissions to NO_2 and assume 50 per cent of this value when making comparisons with the short-term NO_2 environmental benchmark.
- For long-term impacts, convert all measured or estimated nitrogen oxide emissions to NO_2 and use this value when making comparisons with the long-term environmental benchmark.

Gas migration

For those risks that cannot be quantified through air dispersion (i.e. sub-surface migration), a qualitative assessment is required. Standard templates should be completed for the comparison of predicted impact against the environmental benchmark.

The template should list the possible risks to each receptor and one of three possibilities should be recorded:

- that the risk is negligible;
- that the risk will be further quantified in a more detailed assessment;
- that a reference made to the risk management measures that will be included in the application.

The template should list the risks in a prioritised order, with the most significant risk for that receptor listed first. The information can be presented according to the example of the standard template shown in the Horizontal Guidance Note H1 (Environment Agency, 2002c) and should include, for each substance, information on:

- its properties;
- release point;
- PC for long-term and short-term emissions;
- short-term and long-term environmental benchmarks;
- PC as a percentage of the relevant benchmark;
- identification of significant emissions.

For sub-surface migration, a qualitative or semi-quantitative assessment should be carried out of the risk of exceeding 1 per cent of the environmental benchmarks for specific pathways.

For existing sites, the performance of the risk management measures should form part of the consideration of whether a risk needs further quantification. Any monitoring (e.g. external boreholes) and incidents (e.g. odour complaints) should be used when assessing the potential impact and the effectiveness of the current and proposed corrective (risk management) measures.

2.3.7 Recommendation for further risk assessment

Two further tiers of risk assessment can be conducted, i.e. simple and complex. These correspond to Tiers 2 and 3 (see Figure 2.1) and are described in more detail in Section 2.4. The appropriate level of assessment will always be site-specific, but the decision will be based on the confidence in the ability of the risk assessment to address the risks and uncertainties. This must be sufficient to allow the regulator to make a decision on the issue of the permit.

Risk screening (Tier 1) should be sufficient to deal with most of the risks from inert sites. For non-hazardous and hazardous sites, a more detailed quantification of the impact of some emissions will normally be required. Not all risks will, however, require the same level of consideration and the prioritisation exercise during the risk screening should make this clear.

The conceptual model should be discussed with the regulator at the pre-application stage and the appropriate level of risk assessment agreed. However, risk assessment is an iterative process. Although a simple assessment may be agreed, it will be necessary for the operator to apply a more complex risk assessment if there is a lack of confidence that the risks have been addressed appropriately.

More detailed modelling can be required to address the following factors:

- the presence of sensitive receptors;
- the magnitude of error in initial estimates of predicted concentration in relation to the potential;
- the predicted concentration compared to the environmental benchmarks;
- background air quality.

Where receptors have been identified in the conceptual model (e.g. footpaths, domestic dwellings, schools and hospitals, etc.), then further assessment of the risks (including modelling work) will normally be required at the permit application stage for all the non-negligible emissions identified through the risk screening process.

Where the uncertainties are large (e.g. emissions from a new hazardous landfill), there will be a greater need for a complex risk assessment. The higher the predicted concentration in relation to the environmental benchmark, the more likely it is that a detailed consideration of risk will be required.

2.4 Tier 2 and Tier 3: simple and complex quantitative risk assessments

Simple risk assessments

Simple risk assessments should be carried out for landfills when the previous risk screening is insufficient to make an informed decision on the risks posed by the site. They should consist of quantitative calculations, typically solved deterministically using conservative input parameters, assumptions and methods.

Simple risk assessments can be used when the potential source, pathway and receptor terms can be defined with sufficient certainty such that they can be confidently represented by conservative inputs, models and assumptions. Simple risk assessments will generally be applicable in less sensitive locations where risk screening and prioritisation have not identified any receptors that would be particularly susceptible to the consequences of landfill gas. A complex risk assessment should be carried out when there is uncertainty about the source, pathway and receptor terms, and a robust decision cannot be made using conservative inputs, methods and assumptions.

A Tier 2 risk assessment is a simple quantitative process that examines the source–pathway–receptor links using a mixture of site-specific data and projections of site performance based on either:

- generic sources of information (e.g. the rate of gas generation and the expected composition of the landfill gas); or
- the range of values over which the parameters may vary are specified based on probabilistic models, generic experience or generic field data.

Complex risk assessments

Complex risk assessments should be carried out when the site setting is sufficiently sensitive to warrant detailed assessment and a high level of confidence is necessary to ensure compliance with legislation. They should be carried out in a quantitative manner using stochastic (i.e. probabilistic) techniques leading to analytical or mathematical solutions.

A complex risk assessment is effectively tailored to the characteristics of the specific site. The use of generic input data is therefore replaced, where appropriate, by specific information derived from site monitoring, site investigations and operational experience at the site. The types of risk assessment tools likely to be applied in complex risk assessment include fault and event tree analysis, and detailed dispersion models will be used to estimate the behaviour of released components in the environment. Sophisticated models can encompass specific characteristics of the landfill site and surrounding environment, e.g. air dispersion models that can account for particular types of terrain. Specialist and expert assistance is likely to be required for complex risk assessment.

There are many uncertainties associated with the risk assessment of landfill gas and the emphasis must be on the use of best practice standards to minimise the uncertainty risk. The objectives of Tier 2 and 3 risk assessments are:

- further quantification of the hazard, where the source of emissions, the properties and concentrations of the parameters of concern are defined (e.g. hydrogen sulphide emitted from the site surface, odour threshold and EAL);
- consideration of the timescales of the landfill gas generation and completion criteria with respect to landfill gas;
- re-evaluation of the appropriate environmental benchmark;
- exposure assessment to:
  - refine the understanding of receptors and the characteristics of the exposed populations
  - model emissions and pathways to the population
  - estimate the concentration or dose to which the population may be exposed (e.g. consideration of local topography and built environment);
- risk evaluation – an assessment of the significance of the risk and its acceptability. This should provide a robust platform for decisions in the management of risk.

2.4.1 Gas generation and composition

A Tier 2 or 3 quantitative risk assessment should rigorously examine the likely composition and volumes of the landfill gas produced.

For existing sites, monitoring data should be used to consider the bulk and trace composition of the gas. Further sampling should be undertaken where such information does not exist or is limited. The extent of this additional sampling and analysis will be site-specific, but a complex assessment generally requires more extensive work.

Parameters that should be considered under gas production include:

- waste types
- waste quantities
- rate of infill
- leachate and water management
- site geometry
- the rate of gas production
- period of gas production.

A number of models can be used to predict gas generation (see Section 2.4.4), but their limitations should always be recognised when using their results. Prediction of trace gas composition is particularly difficult and, here, the use of probabilistic models can be useful.

Monitoring must be designed to test the assumptions regarding gas generation. Validation of models via site investigation and monitoring results should form part of the annual review process.

2.4.2 Completion

Agency guidance on landfill completion (Environment Agency, 2004a) considers residual gas generation and criteria for PPC permit surrender. Completion will be achieved when passive fluxes no longer pose a risk to human health, the local environment or amenity in the short or long-term.

With respect to emissions that may lead to global warming, the overall principle is to maximise methane oxidation to carbon dioxide over the entire life of the landfill. This will require long-term collection and treatment. Assumptions should be made about the efficiency of existing technologies such as low calorific burners and methane oxidation. These assumptions should be updated as part of the annual review; as technology advances, the ability to collect and treat at lower levels will improve and assumptions can be revised.

An estimate of the period of time predicted for active gas extraction and treatment is required as completion cannot be achieved until after such activities are no longer necessary.

2.4.3 Revision of environmental benchmarks selection

The risk screening stage is intended to give a first indication of the level of risk posed by the site. Where it is clear that the risks are low, sufficient confidence may have been provided to enable decisions to be made at this stage. Where more complex assessments are required, a review of the source term and receptors may indicate that more and/or different environmental benchmarks need to be considered.

The World Health Organization (WHO) has issued air quality guidelines for several compounds that are found in landfill gas. These guidelines have no statutory status and have been developed by the WHO to provide a basis for protecting human health from the adverse effects of air pollution. The guidelines provide background information designed to assist governments in making risk management decisions, particularly when setting standards.

Toxicological assessments

The receptors can be subdivided into those that are at risk through acute (short-term, event or fault-driven) exposure and those that are at risk through chronic (long-term) exposure.

Alternative methods of hazard assessment should be used:

- where no appropriate air quality or environmental assessment thresholds are available for use as environmental benchmarks;
- pathways other than direct inhalation are being considered;
- multiple pathways are being examined.

These methods generally provide a more complex means of risk assessment than direct comparison with threshold and guideline data. They can make use of human and animal toxicity data to produce a 'tolerable daily intake' for the purpose of assessment and hazard indices for assessing exposure by multiple pathways. Expert advice should be sought on the use and application of appropriate toxicity data and models for this purpose.

Ecotoxicity

Root zone displacement of oxygen by landfill gas during lateral migration is the most likely cause of local ecotoxicity (Parry and Bell, 1983). Vegetation stress is likely if the concentrations of methane and carbon dioxide in the soil exceed approximately 25.5 per cent and/or the oxygen concentration falls below 10 per cent.

Risk assessment can facilitate the prediction of likely impacts of landfill gas releases upon local flora and fauna. This may be particularly important where:

- agricultural land is adjacent to landfill sites
- residences with gardens lie alongside landfills
- landfills are near areas of special scientific or ecological interest, e.g. for protected habitats and species.

2.4.4 Models

Simple and complex quantitative risk assessments make considerable use of computer models to predict gas generation and the dispersion of emissions. All models are simplified representations of reality and their output must always be considered in the light of the assumptions, uncertainties and limitations of the process.

All input data should be referenced and their use justified. For example, gas generation rates derived from a kinetic model will contain assumptions based on the type and mixture of waste to be accepted at the site. These assumptions should be recorded on a standard template and form an important part of the annual review process. Where the assumptions prove to be inappropriate, this should trigger a re-evaluation of the risk management measures.

Risk screening should deal with issues such as prevailing wind direction, while quantitative assessments should look in much more detail at dispersion issues. In particular, the risk assessment must consider the meteorological conditions that usually result in low levels of dispersion and relate this to the topography of the site (e.g. gas rolling down into valleys).

For environmental emissions, the analysis is undertaken with the support of computer-based models. These are designed to estimate the size and nature of the source (e.g. gas production models) and to simulate the distribution and transport of pollutants from the source to receptors (e.g. air dispersion models). The Agency's GasSim model (Environment Agency, 2002b) can be used for this purpose. Other models can be used to examine particular pathways, e.g. ADMS 3 (Cambridge Environmental Research Consultants, 2002) and AERMOD are sophisticated air dispersion models.

There are circumstances where the use of dedicated and sophisticated models is necessary in order to provide a reliable analysis of risk (see Section 2.4.5). These are likely to be situations where there are sensitive receptors (e.g. domestic dwellings) in close proximity to the landfill or point source emissions (e.g. less than 500 metres).

It may be necessary to evaluate more than one operating scenario and a variety of operational conditions in order to ensure that the impacts resulting from the worst case situation are assessed.

GasSim

GasSim (Environment Agency, 2002b) was developed to assist risk management decisions about landfill gas as part of the planning, regulation and operational aspects of a landfill site. GasSim can be used to help:

- assess the risks from current or planned landfill gas emissions;
- provide a framework that will contribute to the assessment and valuation of the inventory of burdens associated with the landfilling of wastes;
- the regulator and other relevant organisations compare the relative risks associated with different landfill gas management options.

The user can define the mix, composition, biodegradability, moisture content of the waste and other parameters, thus allowing the model to be tailored to an individual landfill site. This information is used by the model to estimate the generation of landfill gas at that site for any period up to 150 years in the future. The model also makes allowances for the diverse rates of degradation of differing waste components. Landfill gas flux to the environment (for bulk and trace components) is then calculated, taking into account gas collection, flaring, energy recovery and biological methane oxidation. Finally, the model also includes an assessment of the health and environmental risks from a number of other bulk and trace landfill gas components, including a range of volatile organic compounds (VOCs). Using this model in a simple risk assessment and/or as part of complex risk assessment facilitates the quantitative evaluation required in the risk assessment process.

The use of quantitative risk assessment is an important aid to judgement and decision-making, but is not a mechanism in itself for making decisions. The models employed will only be as reliable as the quality of input data and will always contain an inherent level of uncertainty. The outputs, assumptions and input parameters should be critically re-examined if experience suggests that the results of the risk assessment differ from what is expected. The re-evaluation of assumptions will play an important part in the annual review process.

2.4.5 Impact assessment

The emissions of substances from the proposed landfill development should be evaluated against the existing quality of the ambient air to assess potential harm. This should be done by comparison of the long-term and short-term PEC of each substance released to air with its corresponding long-term and short-term environmental benchmark. The information should be presented according to the example format given in Horizontal Guidance H1 (Environment Agency, 2002c) and recorded on a standard template. Such information includes:

- PC;
- background concentration (with location and measurement basis);
- corresponding short-term and long-term environmental benchmarks, e.g. EAL or environmental quality standard (EQS);
- PEC;
- comparison of PEC to the environmental benchmarks (EAL or EQS).

Sub-surface migration should be quantified on the basis of predicted leakage through the proposed barriers in a scenario where active extraction is not occurring and a cap is in place. Predicted levels should be compared to the environmental benchmarks derived at the risk screening stage.

Any releases where the environmental benchmark (e.g. EAL or EQS) is already being breached, or where the contribution from the installation will result in the environmental benchmark being breached, should be identified.

In addition, a number of relevant air quality standards that form part of the Government's Air Quality Strategy must be considered against the outputs of the risk assessment. Many of these standards are updated regularly and may vary in the different parts of the UK. Regulations currently contain air quality objectives for nine pollutant species (nitrogen dioxide, PM_{10} particulate matter, sulphur dioxide, ozone, lead, carbon monoxide, benzene, 1,3 butadiene and polyaromatic hydrocarbons (PAHs)). These statutory objectives are based on standards in the EU Air Quality Daughter Directives and on the recommendations of the Expert Panel on Air Quality Standards (EPAQS) and the WHO.

Some of the pollutants have several objectives with lower ambient concentrations to be achieved in different parts of the country over time; the dates for the objectives range from 2003 to 2010. The Government is required to achieve the objectives for ozone and PAHs, but the remaining objectives are for local authorities 'to work towards achieving' using a mechanism called Local Air Quality Management. In this process, ambient levels of pollutants are assessed against the objectives; if compliance is unlikely, an Air Quality Management Area is declared and an Air Quality Action Plan is constructed to achieve the objectives. This process is repeated in cycles over time. The Agency takes account of the Air Quality Strategy to ensure that the sites and installations it regulates do not contribute significantly to any exceedence of an air quality objective.

In the subsequent determination of appropriate emission standards for landfill gas engines and flares, it is important to take into account the relative contribution of their combustion products to ambient local air quality (Environment Agency, 2000b). The EU Air Quality Framework and Daughter Directives place a legal obligation on the UK to achieve the specified air quality limit values for individual pollutants by the required dates. In addition, the PPC Regulations require that, where an environmental quality standard as set out in EU legislation (such as those in the air quality directives) requires a stricter emission standard than would be achieved by applying BAT, the Agency should incorporate those stricter limits. When setting permit conditions, however, the Agency will take into consideration the extent to which controls upon other sources should reduce pollution levels to below the limit value. Therefore, in areas exceeding a limit value, there is a link between the process of setting permit conditions under PPC and Local Air Quality Action Plans.

In addition, where a landfill is responsible for, or contributes significantly to, a breach of a national air quality objective, the subsequent emission standard may need to be more stringent than the Agency's generic emission standards. However, where the relative contribution to the national air quality objective (where these are more demanding than EU limit values) is relatively minor, the landfill would be required to meet the generic emission standards for landfill gas engines and flares, but not go beyond them.

Where the air quality strategy has adopted a European limit value as an objective but has set an earlier compliance date than given in the EU directive, the need for measures which go beyond the generic standards to meet the limit value would be assessed in relation to the compliance date given in the appropriate directive.

2.5 Accidents and their consequences

The risk assessment should examine a number of accident and failure scenarios in order to quantify the impact of given events. The scenarios to be considered should be agreed with the regulator. The more serious the impact, the greater the effort necessary to ensure – through risk management measures – that the event will not occur.

The reliability of landfill gas control systems and site engineering should be assessed in the risk assessment process. Where this is performed, the environmental analysis should be accompanied by fault tree and consequence analysis. This should cover the baseline system/plant performance and all potential causes of failure. The main hazards that could lead to accidental emissions should also be identified.

The final output from a consideration of accidents and their consequences should be one risk assessment report for the landfill.

The general categories of accident for a landfill that would affect landfill gas control are:

- loss of containment, e.g. leakage, liner failure, spillage;
- loss of collection and/or treatment capability, e.g. failure of pipework, well, equipment/control system, etc.;
- explosions and fires, e.g. deep-seated landfill fire.

Examples of accident and failures scenarios that should be considered include:

- deep-seated fire and its effect on landfill gas containment and emissions;
- failure of leachate extraction systems and the effect of this on landfill gas management;
- explosion of a flare;
- failure of gas treatment plant;
- extraction system failure.

For existing sites, the actual occurrence of incidents can be used to inform the consideration of probability. Other sites managed by the operator can also be considered in this assessment, as management practices are often standard across an operator's landfills.

The maximum concentration should be estimated for each emitted substance in the event of an accident. The resulting predicted concentration of the substance as dispersed into the ambient air should be calculated using the methods described in Section 2.3 and the information presented on a standard template. This information should include:

- description of potential accident risk;
- substances emitted as a consequence of the accident;
- maximum concentration of the accidental emission;
- medium to which emission is released;
- PC of the accidental emission.

For each release, a comparison of the PC of the accidental emission to the short-term environmental benchmark (e.g. EAL or EQS) should be made. Tables 2.5 to 2.8 can be used to assess the likelihood, severity and risk.

For each of the incidents identified, a likelihood category can be assigned as set out in Table 2.5.

Using Table 2.6, an estimate of the severity of the likely consequences can be made and the incident can be assigned an appropriate category.

For each release, the overall risk can be evaluated by multiplying the severity of consequence by its likelihood (see Table 2.7).

For each incident, identify which of the score categories shown in Table 2.8 it falls into.

Table 2.5 Likelihood categories

	Category	Range
1	Extremely unlikely	Incident occurs less than once in a million years
2	Very unlikely	Incident occurs between once per million and once every 10,000 years
3	Unlikely	Incident occurs between once per 10,000 years and once every 100 years
4	Somewhat unlikely	Incident occurs between once per hundred years and once every 10 years
5	Fairly probable	Incident occurs between once per 10 years and once per year
6	Probable	Incident occurs at least once per year

Source: Environment Agency, 2002c

Table 2.6 Severity categories

	Category	Definition
1	Minor	Nuisance on site only (no off-site effects) No outside complaint
2	Noticeable	Noticeable nuisance off-site e.g. discernible odours Minor breach of permitted emission limits, but no environmental harm One or two complaints from the public
3	Significant	Severe and sustained nuisance, e.g. strong offensive odours Major breach of permitted emissions limits with possibility of prosecution Numerous public complaints
4	Severe	Hospital treatment required Public warning and off-site emergency plan invoked
5	Major	Evacuation of local populace Temporary disabling and hospitalisation Serious toxic effect on beneficial or protected species Widespread but not persistent damage to land
6	Catastrophic	Major airborne release with serious off-site effects Site shutdown

Source: Environment Agency, 2002c

Table 2.7 Severity likelihood matrixs

Likelihood	Severity of consequence					
	Minor	Noticeable	Significant	Severe	Major	Catastrophic
Extremely unlikely	1	2	3	4	5	6
Very unlikely	2	4	6	8	10	12
Unlikely	3	6	9	12	15	18
Somewhat unlikely	4	8	12	16	20	24
Fairly probable	5	10	15	20	25	30
Probable	6	12	18	24	30	36

Table 2.8 Risk evaluation

Magnitude of risk	Score
Insignificant	6 or less
Acceptable	8 to 12
Unacceptable	15 or more

The scores for releases to air and water can be added. The cumulative risk score for the proposed landfill should be calculated and the results presented according to the template provided in Horizontal Guidance Note H1 (Environment Agency, 2002c).

Negligible risks will score ‘insignificant’ in risk evaluation. Any risks that score as ‘unacceptable’ should be eliminated or revised. Detailed modelling of the consequences of accidental releases should be undertaken.

The monitoring requirements of the Gas Management Plan should be developed by considering incidents as outlined above. Contingency planning should also be linked to this risk assessment stage.

2.6 Monitoring and reviews

The main objectives of environmental monitoring are to:

- define a baseline against which to compare actual or predicted impacts;
- allow compliance with permit conditions to be assessed;
- confirm that engineering measures are controlling landfill gas (as they are designed to);
- produce information on the processes occurring within the landfill;
- provide an early warning of any departures from design conditions;
- give an early warning of adverse environmental impacts;
- provide an early warning of any breach of emission standards;
- supply information to enable decisions on the management of the site to be taken;
- provide information to support an application for permit surrender.

Information from monitoring programmes should be integrated into the conceptual model to:

- test assumptions in the conceptual model;
- evaluate reductions in the performance of extraction systems and their effects on collection efficiencies;
- confirm that risk assessment and management options are meeting their desired aims.

The design of the monitoring plan for each landfill should be based on the conceptual model and specific regulatory requirements. Identified pathways and release points, both potential and actual, must be monitored. Monitoring is also required to evaluate any assumptions made in the risk assessment.

The review process will largely be based on the results of monitoring and should aim to ensure that the input parameters, emissions and assumptions in the conceptual model are all realistic. For example, it is not possible to predict the trace gas composition of the landfill gas accurately (particularly with changing waste types and landfill classifications). Monitoring data on gas generation rates and the trace composition of landfill gas are, therefore, an essential part of the continued development of the conceptual model, which is used in reviewing the risk assessment.

The risk assessment should direct the monitoring strategy for:

- validation of critical assumptions in the risk assessment, e.g. trace gas composition and gas generation rates;
- monitoring of identified release points, e.g. well heads, pipework, engines, flares and surface flux;
- external monitoring, e.g. migration control boreholes and ambient air monitoring at receptors.

Monitoring locations, frequencies and determinands should be justified in terms of the risk assessment and the identification of release points and pathways, receptors and critical assumptions. More information on monitoring is given in Chapters 5 and 8.

The PPC permit requires a periodic review of the performance of the landfill. Standard templates are important for the review process as they provide the link between the assumptions made and the real situation with the risk management provisions in place.

Each potential release point should have been identified through the risk assessment process and the periodic review must consider the implications of the real data for each release.

Consideration of odour complaints and/or incidents (such as fires or down times for flares and engines) is another vital part of the review. Odour problems indicate that landfill gas is not being collected and treated adequately. They should be recorded against the receptors at which the odour is detectable and must trigger an evaluation of the risk management measures.

2.7 Global warming potential

Landfill gas, which contains principally methane and carbon dioxide, is a greenhouse gas and therefore contributes to global warming. The UK has made specific obligations under the Kyoto Protocol to reduce its emissions of greenhouse gases: the landfill industry's contribution to these aims will be significant as landfills accounted for an estimated 27 per cent of the UK's methane emissions in 2000 (Defra, 2002b).

The global warming potential (GWP) of methane is approximately 21 times that of carbon dioxide. Therefore, efficient collection and combustion of landfill gas is required in order to protect the global atmosphere and environment. The potential contribution of individual chemicals to climate change can be quantified by reference to their relative GWP. This parameter is a function of the radiative properties of the gas and its atmospheric half-life, and may be defined as the time integrated change (usually 100 years) in the radiative properties of the atmosphere due to instantaneous release of 1 kg of gas relative to that from 1 kg of CO_2. The GWPs for a variety of compounds found in landfill gas are given in Table 2.9.

The contribution of landfill gas from the landfill to global warming should be estimated, as part of the risk assessment process, using GWPs together with quantitative concentration and flux data. The benchmark for global warming should be based on achieving an annual 85 per cent efficiency for the collection and treatment of methane emissions.

Table 2.9 Ozone depletion and global warming potentials

Chemical	CFC/HCFC no.	Ozone depleting potential	Global warming potential
Carbon dioxide			1
Methane			21
Chloroform			4
Nitrous oxide			310
Dichloromethane (methylene chloride)			9
1-Chloro-1,1-difluoroethane	HCFC-142b	0.065	2300
Chlorodifluoromethane	HCFC-22	0.055	1900
Chlorofluoromethane	HCFC-31	0.020	
2-Chloro-1,1,1-trifluoroethane	HCFC-133a	0.060	
Chlorotrifluoromethane	CFC-13	1.0	14000
Dichlorodifluoromethane	CFC-12	1.0	10600
Dichlorofluoromethane	HCFC-21	0.040	
1,1,1,2-Tetrafluorochloroethane	HCFC-124	0.02–0.04	620
Trichlorofluoroethane (Freon 113)	HCFC-131	0.007–0.050	
Trichlorofluoromethane	CFC-11	1.0	4600
Trichlorotrifluoroethane	CFC-113	0.8	6000
1,1,1-Trichlorotrifluoroethane	CFC-113	0.80	6000

CFC = chlorofluorocarbon; HCFC = hydrochlorofluorocarbon

Adapted from DETR *Climate change: draft UK programme* (2000)

Gas Management Plan

3.1 Definition

The Gas Management Plan provides a framework for the management of landfill gas based on the site characteristics and the nature and extent of the gas control system. The Plan should provide a clear and auditable route-map setting out the methods, procedures and actions to be implemented at the site for the duration of the PPC permit, up to the point of surrender.

The Gas Management Plan should be prepared either as a stand-alone document or as part of the documented site operational details and procedures, e.g. as part of the PPC application. Applications for permits must include 'the proposed operation, monitoring and control plan' and the Gas Management Plan will be an integral part of any submission.

The risk assessment should be used by the operator when developing the Gas Management Plan for a particular landfill. The Plan should set out the risk factors and illustrate how these risks are to be minimised and monitored. It should be used as a tool to demonstrate that the gas control system is appropriate for the landfill conditions during site development, operation, closure and post-closure stages.

The Gas Management Plan is a live document and should be reviewed and updated regularly to ensure that adequate controls are in place to meet identified standards and objectives.

3.2 Objectives

The objectives of the Gas Management Plan are to:

- bring together all aspects of gas management considered during the risk assessment and proposed operational controls;
- provide an estimate of gas production;
- set out performance criteria for the gas control measures;
- set out the design objectives and principles for the gas control measures;
- set out the methods of implementing site-specific gas management systems to:

    - prevent the migration of and control any release of landfill gas
    - minimise the impact on local air quality
    - minimise the contribution to climate change
    - control the release of odorants
    - minimise the risk of accidents
    - prevent harm to human health

- set out the installation criteria and construction quality assurance procedures for the gas control measures;
- set out the procedures and responsibilities for installation, operation, maintenance and monitoring of the gas control measures;
- demonstrate that performance of the control measures meets the requirements and objectives for gas management;
- set out the procedures for managing changes and reviewing the performance of the gas control system.

3.3 Framework for the Gas Management Plan

The following sections set out the framework for the Gas Management Plan. The key elements of the Gas Management Plan are:

- risk assessment (see Chapter 2)
- control measures (see Chapters 4 and 7)
- operational procedures (see Chapter 7)
- monitoring plan (see Section 3.3.3)
- action plan (see Section 3.3.4)
- aftercare and completion plan (see Section 3.3.5).

3.3.1 Waste inputs

The type of waste deposited at the site will form the basis for the estimation of gas production, while the estimation of the source term will determine the type and extent of gas management at the site. Although the principles and many of the techniques to manage and control landfill gas are generic across the range of site categories, individual Gas Management Plans must be based on the site-specific conditions and circumstances.

The following should be identified:

- waste types – the quantities and types of waste to be disposed of, and the rates and methods of filling;
- landfill gas source – the estimated nature and the anticipated quantity of gas that could be generated during each phase of development (i.e. operational, closure and post-closure);
- landfill gas risk assessment – this forms the basis of the Gas Management Plan as it evaluates the risks to receptors. It should be prepared using the approach set out in Chapter 2.

3.3.2 Control measures

The elements of gas control are:

- containment
- collection
- treatment.

These are considered as part of the risk assessment (Chapter 2) and are discussed in more detail in Chapter 7. The method of controlling landfill gas will depend on a number of factors, which should be detailed in the Gas Management Plan. In particular, it should consider:

- landfill development – details for containment (lining and capping) and the phasing of landfill development and operation (Chapters 4 and 7);
- emission standards – these should be clearly stated based on agreed emission limits and the outcome of the risk assessment (Chapter 2);
- collection system – the plan should describe the measures to collect landfill gas from the waste body, including the approach to be taken from initial development of the site through to the aftercare stage (Chapters 4 and 7), and should include details of the layout, etc;
- condensate management – the plan should describe the measures to manage condensate from the gas control system (Chapter 7);
- inspection, maintenance and servicing – details should be provided, for each element of the gas collection and control system, utilisation/flaring plant and supplementary processing/treatment equipment (Chapter 7);
- utilisation, flaring and treatment – the plan should set out in detail the measures to manage the collected landfill gas, including such methods as supplementary processing, utilisation, flaring, and methane oxidation (Chapter 7). If utilisation is not proposed, this must be justified. A detailed appraisal of the proposed measures should be included in all cases.

3.3.3 Monitoring and sampling plan

The monitoring and sampling plan is an integral part of the overall Gas Management Plan. It allows the performance of the gas management system to be established and assessed against the conceptual site model and provides for developments of the model. This offers increased confidence in environmental protection and the ability to demonstrate that the objectives of the Gas Management Plan are achieved. Further details on monitoring and sampling are given in Chapter 8.

The monitoring and sampling plan should include as a minimum:

- a schedule for specific data collection and frequency of monitoring at all stages of the site (i.e. prior to site development to obtain background data and beyond the closure of the site to demonstrate site completion);
- a layout showing the construction and location of monitoring points in relation to the site, surrounding area, geology, and phasing of operation;
- a description of the measurement techniques and sampling strategy;
- an analysis and testing schedule;
- a methodology for data storage, retrieval and presentation;
- the background and action/trigger values against which collected data will be evaluated;
- the methodology for data interpretation, review and reporting;
- the means of communicating the results of the monitoring and interpretation to the regulator.

Monitoring data will be used by the regulator to verify compliance with the Gas Management Plan and the permit conditions.

3.3.4 Action plan

The Gas Management Plan must set out the actions to be taken by the operator as a result of:

- any abnormal changes observed in collected monitoring data;
- all identified operational problems or failure of the gas control system established as part of the routine inspection or maintenance programme;
- a reported event, e.g. an odour complaint.

As outlined in Section 2.5, scenarios should be established during the risk assessment to determine the actions necessary to manage potential accidents and failure scenarios that might lead to occurrences such as:

- migration and release of landfill gas
- impact on local air quality

- release of odorants
- harm to human health.

Failure scenarios should be identified for each component of the gas management system and appropriate action values should be assigned to specific monitoring locations for elements of the gas control system.

The implementation of appropriate action should be considered in conjunction with an assessment of the severity of the event. This is particularly important in the case of emergencies and can be defined by setting one or more of the following:

- compliance criteria, i.e. specific compliance requirements such as emissions standards;
- assessment/action criteria – derived values based on compliance/trigger criteria which form an early warning and/or may instigate additional monitoring or emergency procedures. This will become a compliance requirement when it is specified in the permit, e.g. greater than 1 per cent methane, above background concentration, in a monitoring borehole;
- a systems failure criteria, e.g. accidental disconnection of gas collection wells;
- an event report criteria, e.g. reported odour beyond site boundary.

The plan should set out the procedures and protocols by which the operator will manage the effects of these events by identifying requirements for:

- emergency actions – immediate measures to counter extraordinary events, e.g. evacuation of buildings;
- changes to gas management techniques and other operational control measures required to control gas on-site, e.g. installation of additional gas collection wells;
- changes to the strategy for routine monitoring using identified monitoring guidance to provide improved data to evaluate the event, e.g. increased perimeter monitoring.

The action plan should be developed as part of the structured development and application of the appropriate Gas Management Plan to the satisfaction of the regulator. The PPC permit holder must undertake a periodic review of the action plan in consultation with the regulator.

Emergency procedures and protocols

Significant events identified at the risk assessment stage, which result in either an unacceptable level of risk or which are an extraordinary occurrence, should be identified as emergency scenarios. Specific procedures should be set out to manage these events, including the immediate actions required. In the case of an emergency, the regulator and other appropriate authorities should be notified immediately.

The risk assessment should identify the mechanisms by which such extraordinary events can occur. The emergency actions, procedures and protocols resulting from these should be submitted to the regulator as part of the preparation of the PPC application.

The emergency procedures for each identified event must be included in the action plan, which should clearly define:

- the name of the person/position responsible for managing the emergency actions;
- emergency notification and contact procedures (e.g. regulator and emergency services phone number and contact names);
- assessment parameters for each emergency scenario;
- description of actions for each emergency scenario (what actions are to be taken and who will undertake them);
- monitoring requirements (specific monitoring procedures for each emergency scenario);
- reporting parameters (what should be reported to the parties or persons involved);
- completion parameters (what criteria identify the completion of the emergency action);
- procedures for reviewing emergencies and the performance of the Gas Management Plan.

These should be reviewed regularly in conjunction with the regulator. Personnel operating the site should be trained on how to implement the response to individual emergency scenarios.

An example emergency plan is included in Appendix E, which sets out the hierarchy of actions in relation to emergency response and notification.

Remedial actions

Where a deficiency is identified, either via routine monitoring, inspection, maintenance or failure of elements of the gas management system, then appropriate measures need to be identified. An appropriate remediation time-scale should be prescribed in the Gas Management Plan. For example, it should be possible to commence enhanced monitoring protocols within 24 hours or incorporate additional collection wells within 7 days (in the case of sacrificial pin wells).

3.3.5 Aftercare and completion plan

Details for the aftercare, closure and completion of the site should be developed as part of the structured application; where appropriate, they will be replicated in permit conditions. Before waste disposal activities at the site cease, the Gas Management Plan should be reviewed in order to revise the requirements for landfill gas management during the closure phase.

The plan should be based on the same principles as those identified above and should:

- define the measures for continued management and monitoring of landfill gas at the site (including maintenance requirements) following closure;
- indicate how the operator will meet the criteria for surrender of the permit for the site. Guidance (applicable in England and Wales) on this subject is available (Environment Agency, 2004a).

4

Requirements for gas control

This chapter sets out regulatory requirements for the control of landfill gas. Details of the specific measures and techniques for the control of landfill gas are presented in Chapter 7.

4.1 Introduction

In order to minimise the potential impact of landfill gas on the environment (as required by the Landfill Regulations), it is necessary to actively control landfill gas throughout the whole period for which the site has a PPC permit. The same principles also apply to sites that are regulated and will close under the waste management licensing regime.

In the context of this document, the key gas control measures are:

- containment
- collection
- treatment (i.e. utilisation and flaring).

The general design and operational requirements for all classes of landfills are set out in Annex 1 of the Landfill Directive, Schedule 2 of the Landfill Regulations 2002 and Schedule 3 of the Landfill (Scotland) Regulations 2003. They require the following gas control measures:

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

Guidance is given in the following sections on each element of gas control. Issues such as design, construction quality assurance (CQA) and phasing are typically common to all elements and as such are addressed collectively in Part C. The measures for containment, collection and treatment should be set out in detail in the Gas Management Plan.

4.2 Gas containment

4.2.1 Principles of gas containment

Site containment is provided by engineered barriers, which in combination with active gas collection, control and minimise the migration and emission of landfill gas. Containment is provided by:

- engineered lining of the sides and the base of the site to prevent uncontrolled movement of landfill gas through the base and sides of the site;
- engineered capping of the site surface to reduce the rate of direct emission of landfill gas to the atmosphere and control the ingress of air (as well as controlling the ingress of rainwater);
- reduction of any in-situ gas pressure by gas extraction.

Further details on the requirements for gas containment are set out in Chapter 7. More information on containment systems, applicable in England and Wales, is given in *Guidance on the development and operation of landfill sites* (Environment Agency, 2002f). In Scotland, reference should be made to the *Framework for risk assessment for landfill sites: the geological barrier, mineral layer and the leachate sealing and drainage system* (SEPA, 2002).

4.2.2 Lining

A number of issues need to be considered when engineering a landfill liner, which as a minimum, must meet the requirements of the Landfill Directive and the Groundwater Directive. For England and Wales, the engineering requirements of both Directives are addressed in Landfill Regulatory Guidance Note 6 *Interpretation of the engineering* *requirements of Schedule 2 of the Landfill (England and Wales) Regulations 2002* (Environment Agency, 2003c). In Scotland, reference should be made to the *Framework for risk assessment for landfill sites: the geological barrier, mineral layer and the leachate sealing and drainage system* (SEPA, 2002).

Engineering requirements should be decided after considering gas and leachate issues, and developing the conceptual model in conjunction with site investigations and risk assessment to achieve no unacceptable emission/discharge. The lining must restrict the transmission of landfill gas. The minimum standards for lining as required by the Landfill Regulations are set out in Table 4.1.

The selection of the artificial sealing liner should be based on the risk assessment, and on the ability of the lining system to contain landfill gas as well as controlling leachate migration and preventing groundwater ingress (where applicable). In most circumstances, the selection of the artificial lining system is determined by the groundwater risk assessment – although the selection of the landfill lining system should consider landfill gas containment. However, it must be remembered that the permeability of the lining system to gas will be higher than that for leachate

Table 4.1 Lining requirements for landfills

Classi-fication	Primary (sealing) liner	Attenuation layer (geological barrier hydraulic permeability)
Inert	Not required	≥1 m thick (≤1x10^{-7}m/s)
Non-hazardous	Required	≥ 1 m thick (≤1x10^{-9}m/s)
Hazardous	Required	≥ 5 m thick (≤1x10^{-9}m/s)

Notes

Where the attenuation layer does not naturally meet the above conditions it may be completed artificially and reinforced by other means providing equivalent protection but, in any such case, a geological barrier established by artificial means must be at least 0.5 m thick.

The above requirements may be reduced to an appropriate extent if, on the basis of an assessment of environmental risks and having regard in particular to Directive 80/68/EEC:

(a) it has been decided that the collection and treatment of leachate is not necessary; or

(b) it is established that the landfill poses no potential hazard to soil, groundwater or surface water.

4.2.3 Capping

Capping has several benefits, including:

- providing encapsulation of the waste
- reducing leachate formation
- improving the efficiency of gas collection and control
- assisting odour control
- reducing the ingress of air
- reducing surface emissions.

> The Landfill Directive and Landfill Regulations state that:
>
> Where the potential hazards to the environment indicate that the prevention of leachate formation is necessary, surface sealing may be prescribed.

Table 4.2 sets out the guidelines from the Landfill Regulations for surface sealing for each landfill classifications.

Table 4.2 Capping recommendations for landfills

Classi-fication	Inert	Non-hazardous	Hazardous
Gas drainage layer	Not required	Required	Not required
Artificial sealing layer	Not required	Not required	Required
Impermeable mineral layer	Not required	Required	Required
Drainage layer >0.5 m	Not required	Required	Required
Soil cover >1.0 m	Not Required	Required	Required

In England and Wales, guidance on the engineering requirements of the Landfill Directive is given in Landfill Regulatory Guidance Note 6 (Environment Agency, 2003c), which states that the Landfill Directive recommendations for capping can be changed on the basis of a risk assessment. As a result, the gas drainage layer may not be required for non-hazardous landfills.

The engineered cap forms an integral part of the gas management system and is thus expected to be required at all sites that produce landfill gas. The capping system allows for efficient gas capture in conjunction with an active gas collection system. It should be designed to provide maximum gas control compatible with the control of rain and surface water ingress.

4.3 Gas collection

The collection of landfill gas is a requirement of the Landfill Directive and Landfill Regulations for all sites accepting biodegradable waste. However, gas collection will be required in all landfills where gas production takes place. The type and nature of the gas collection systems for such sites will depend on the types of wastes and their gas generating potential.

To control the potential risk associated with gas migration and emissions, landfill gas must be removed from the waste, treated and, if possible, utilised. The gas collection system thus forms a key element of the control and minimisation of the risks from landfill gas, which would otherwise result in unacceptable impacts.

The collection system should be designed to:

- prevent migration
- minimise emissions
- optimise utilisation (where possible).

The elements of the gas collection system, which covered in more detail in Part C, include:

- collection wells
- collection layers
- collection pipework
- extraction plant
- condensate management system.

These elements should be incorporated at defined stages during the development of the site and set out in the Gas Management Plan. They may consist of a range of temporary measures to collect gas until the permanent systems can be installed.

Collection of gas is the primary means of controlling odour. If a landfill gas odour can be detected at the site boundary, then it is an indication that landfill gas is not being collected efficiently. Passive venting is an unacceptable control measure for landfill gas.

Further details on gas collection and monitoring are given in Chapters 7 and 8.

4.4 Utilisation, flaring and treatment

4.4.1 Indicative assessment criteria for utilisation

Before a landfill site can be considered for gas utilisation, the operator must provide either proof or demonstrate the amount of gas produced by the site and provide an estimate of the future rate of production over the lifetime of the site. This will determine if utilisation is feasible and will enable the sizing and costing of the required plant. Operators should note that the Landfill Regulations require that landfill gas must be collected from all landfills receiving biodegradable waste and that the landfill gas must be treated and, to the extent possible, used. Landfill operators will therefore be required to provide the regulator with a full justification if they do not propose to utilise landfill gas.

The following set out indicative criteria for establishing the viability for landfill gas utilisation (Environment Agency, 2000a). An assessment against each of the indicative criteria should be undertaken at the PPC permit application stage to confirm whether landfill gas utilisation is likely to be required. A similar consideration is appropriate for sites regulated under waste management licensing.

- **Size of site** – sites with less than 200,000 tonnes of waste are unlikely to produce sufficient landfill gas to generate more than 0.75 MW and are of limited commercial interest. However, the technology associated with the minimum capacity of utilisation systems is being continually improved and units with a capacity of around 0.3 MW are available.
- **Geometry of site** – recoveries of landfill gas are highest on large deep sites and it is often impractical to recover landfill gas from shallow sites or from peripheral areas of sites. It is generally accepted that the minimum depth of site from which landfill gas can be effectively and efficiently recovered is around 4 metres.
- **Gas flow rate** – a total landfill gas flow rate of between 600-750 m^3/hour (at 50 per cent methane) is required to generate 1 MW. The flow rate refers to what can actually be recovered from the site.
- **Waste composition** – if the waste within the site contains 75 per cent or more inorganic wastes, then landfill gas production from biodegradation will be minimal. Nevertheless, this may still be significant in terms of its potential environmental impact.
- **Site location** – if a direct use scheme is being considered, then the end user for the gas should be within 10 km of the landfill site; otherwise, the cost of transporting the gas can make the schemes uneconomic.

Where utilisation is not possible then landfill gas must be flared in accordance with relevant guidance (Environment Agency, 2002d).

4.4.2 Flaring

The final stage of processing in the absence of utilisation is thermal oxidation of the landfill gas in a flare. Where it has been demonstrated that utilisation is not viable or where the above criteria cannot be sustained, flaring of the gas must be provided.

There are a number of regulatory requirements.

- No ‘open’ flares are to be installed on Agency regulated landfill sites, except for emergency or test purposes.
- Operational ‘open’ flares at landfills subject to permitting or re-permitting under the Landfill Regulations shall be replaced with ‘enclosed’ flares or other techniques offering equivalent performance as they are re-permitted. Where appropriate, this requirement may be included in an Improvement Schedule, for completion within one year of date of issue of permit.
- Operational ‘open’ flares at landfill sites that remain subject to waste management licensing shall be replaced progressively with ‘enclosed’ flares or techniques offering equivalent performance. This replacement programme will be undertaken on a risk basis, for completion as soon as reasonably practicable, as identified by a site-specific Emissions Review. The improvements identified in the Emissions Review shall be completed at all Agency-regulated landfills by 16 July 2009.

In addition, enclosed flares that have a stand-by role for utilisation plant, do not need to be monitored as long as:

- the enclosed flare can be shown to be operating within the Agency’s operational standard;
- the enclosed flare is operational for less than 10 per cent of the time (on an annual basis);
- routine monitoring is not identified as necessary within the site-specific risk assessment.

Technical guidance on landfill gas flaring (Environment Agency, 2002d) and flare emissions monitoring (Environment Agency, 2004b), sets out the requirements for flare design, operating principles and monitoring.

4.4.3 Treatment

In some situations, treatment of landfill gas may be required to meet emission limits for landfill gas engines. Treatment of the gas stream pre- or post-combustion will be a site-specific issue incorporating cost-benefit analysis (Environment Agency, 2004c).

5

Requirements for monitoring

5.1 Introduction

This chapter deals with the regulatory requirements for monitoring. The technical aspects of monitoring are described in Chapter 8.

The objectives of environmental monitoring were set out in Section 2.6 and include:

- demonstrating that the performance of the control measures meet the requirements and objectives of the Gas Management Plan for the site, and establish a reliable data set;
- creating an information base so that the site can be adequately characterised and managed throughout its life;
- providing information from which to determine when completion criteria have been met.

The Landfill Directive and Regulations lay down minimum requirements for landfill gas monitoring (see Table 5.1).

The minimum explicit monitoring requirements for landfill gas from the Landfill Directive and Regulations relate to:

- the monitoring of gas within the waste (source);
- the efficiency of the gas extraction system;
- atmospheric pressure (during borehole/well monitoring at the site).

In addition to these minimum requirements, the depth to water/leachate and the pressure should be included in the monitoring of all wells.

The Landfill Directive and Regulations set the following monitoring requirements.

- The operator shall carry out, during the operational phase, the control and monitoring procedures set out in Annex III and Schedule 3 (respectively).
- Where the procedures reveal any significant environmental effects, the operator shall notify the regulator as soon as reasonably possible.
- When it receives a notification of significant adverse environmental effects the regulator shall determine the nature and timing of corrective measures that are necessary and shall require the operator to carry them out.
- The operator shall report at intervals specified by the regulator on the basis of aggregated data, the results of the monitoring and on such matters which the regulator requires to demonstrate compliance with conditions of the landfill permit or to increase its knowledge of the behaviour of the waste in landfill.
- The operator shall ensure that the quality of:

  (a) analytical operations of control and monitoring procedures;

  (b) analyses of representative samples taken are in accordance with regulatory requirements.
- Following definitive closure of a landfill, aftercare procedures shall ensure that:

  (a) The operator remains responsible for the maintenance, monitoring and control for such period as the regulator determines is reasonable, taking into account the time during which the landfill could present hazards.

  (b) The operator notifies the regulator of any significant adverse environmental effects revealed by the control procedures and takes remedial steps as required or approved by the regulator.

  (c) The operator is responsible for monitoring and analysing landfill gas and leachate from the landfill and groundwater regime in its vicinity in accordance with Annex III (Schedule 3 of the Landfill Regulations) as long as the regulator considers that the landfill is likely to cause a hazard to the environment.
- Measures shall be taken to minimise nuisances and hazards arising from the landfill through: emissions of odours and dust.
- Gas monitoring must be carried out for each section of the landfill.
- The efficiency of the gas extraction system must be checked regularly.

Table 5.1 Minimum monitoring requirements for monitoring wells and gas wells

	Frequency of monitoring in operating phase	Frequency of monitoring in aftercare phase
Potential gas emissions and atmospheric pressure[1] (CH_4, CO_2, O_2, H_2S, H_2, etc,)	Monthly[2,3]	Every six months[4]

[1] These measurements are related mainly to the content of organic material in the waste.

[2] Longer intervals may be allowed if the evaluation of data indicates that they would be equally effective.

[3] CH_4, CO_2 and O_2 regularly. Other gases as required, according to the composition of the waste deposited, with a view to reflecting its leaching properties.

[4] Efficiency of the gas extraction system must be checked regularly.

Table 5.2 Landfill gas component monitoring requirements

Component	Monitoring requirements
Source	Collection wells and monitoring wells
Emissions	Surface and lateral emissions
Combustion	Flares and engines
Air quality	Odour
Meteorological	Weather conditions

To provide for the requirements of the Landfill Directive, landfill gas monitoring should be undertaken for each component set out in Table 5.2. The specific requirements for monitoring of each component are given in Chapter 8. The regulator may require additional monitoring on a site-specific basis.

The monitoring of landfill gas is an essential factor in the management of any landfill site. A monitoring and sampling plan must be prepared and set out within the Gas Management Plan (see Chapter 3). The monitoring plan should provide objectives and describe a site-specific programme of monitoring to be undertaken at the landfill site. This will incorporate:

- the type of monitoring to be undertaken;
- the methods of monitoring (including detection limits, accuracy, etc.);
- monitoring locations;
- frequency of monitoring;
- appropriate action/trigger levels necessitating action;
- appropriate action plans to be implemented should any levels greater than the trigger levels be recorded.

To ensure the consistency and long-term reliability of monitoring records, gas monitoring programmes should be:

- targeted to answer specific questions required for permit compliance and to provide a robust assessment where specific risks are identified;
- designed to deliver minimum statutory and permit requirements;
- undertaken by competent personnel;
- robust and fit for the purpose for which they are designed, with proper regard to quality assurance and quality control;
- interpreted clearly and appropriately on a regular basis so that results can be reviewed and understood by non-technical personnel;
- reviewed against objectives and the conceptual model, and revised accordingly on a regular basis.

The development of a landfill gas monitoring programme needs to be based on a thorough understanding of the conceptual model of the site and therefore on its setting, its geology and the potential emission and migration pathways between the site and receptors. This information, along with leachate and groundwater monitoring records, will form an important part of the evidence required for determination of completion conditions for the surrender of a site permit. The key steps for landfill gas monitoring are shown in Figure 5.1.

The frequency of monitoring depends upon a number of factors. These include the following, which are all considerations for the conceptual model:

- age of the site
- type of waste accepted
- geology of the surrounding strata
- control measures installed
- potential hazard from migrating gas

- sensitivity and proximity of surrounding development and receptors
- results of previous monitoring.

The requirements for monitoring described in Section 5.2 are considered minimum standards. The frequency of monitoring and the parameters to be monitored must be based on an assessment of the risks posed by the site, incorporate the factors listed above, and be agreed with the regulator.

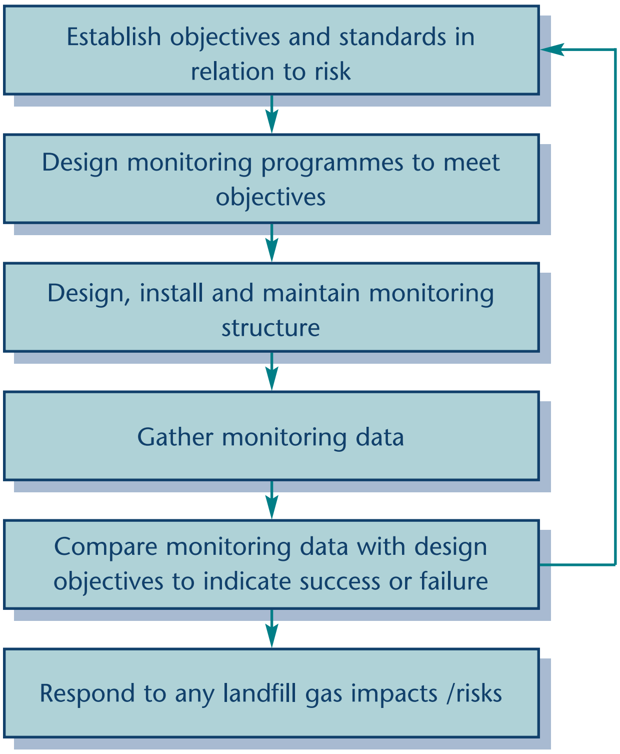


Figure 5.1 Process of landfill gas monitoring

Monitoring data must be reviewed on a regular basis against the objectives of the Gas Management Plan and any changes submitted and notified to the regulator. The monitoring frequency must not be regarded as fixed for any site and examples of where it should be varied include:

- where deviations in the concentrations expected from the risk assessment are detected during routine monitoring;
- the gas control system, or any element of it, has failed or been changed;
- the pumping of leachate has changed and leachate levels change within the wastes;
- capping of all or part of the site has taken place;
- new development takes place in the vicinity of the site;
- any emergency events that warrant further monitoring, e.g. landfill gas in buildings.

5.2 Monitoring at the site preparation phase

Gathering monitoring data before and during the site preparation phase is an important element of the development of the conceptual model, the site monitoring plan and the evidence that the site meets the completion criteria. It enables background concentrations to be established – an important parameter to consider when undertaking a risk assessment and setting trigger levels for a site. In addition, background monitoring allows other sources of methane and carbon dioxide to be identified if present. Such other sources of methane and carbon dioxide include marsh gas and mine gas (see Appendix B).

The frequency of monitoring should be sufficient to enable the characterisation of seasonal and other environmental influences. Table 5.3 gives details of the minimum monitoring frequencies required during the preparation of a site.

Table 5.3 Determinands and monitoring frequencies at the site preparation phase

	Frequency of monitoring during the site preparation phase	Parameters to monitored during the site preparation phase
Background gas levels in monitoring boreholes	12 data sets representative of a 12-month period	CH_4, CO_2, O_2 Atmospheric pressure Meteorological data

Note: Details of the meteorological parameters to monitor for are given in Chapter 8.

5.3 Monitoring during site operational and aftercare phases

The Landfill Directive and Regulations require the operator of a site to undertake site monitoring during the operational phase of a landfill site. They also require the operator to undertake monitoring during the closure and aftercare period of the site until the regulator deems the landfill no longer likely to cause a hazard to the environment. Table 5.4 summarises the typical/minimum frequencies considered necessary by the regulator for monitoring at the various types of gas sampling location associated with a landfill.

Table 5.4 Type of sampling location and typical monitoring frequencies for landfill gas

Monitoring points	Frequency of monitoring during operational phase	Frequency of monitoring during aftercare period	Parameters to be monitored
Surface emissions (i) Walk over survey (ii) Flux box monitoring	Annually Site-specific (1–5 yrs)	Annually Site-specific (1–5 yrs)	CH_4 concentration/flux Atmospheric pressure and temperature Meteorological data General surface type and condition
Monitoring boreholes (external to the landfill)	Monthly	Six-monthly	CH_4, CO_2, O_2 Atmospheric pressure Differential pressure Temperature Meteorological data
Monitoring wells (within the landfill)	Monthly	Six-monthly	CH_4, CO_2, O_2 Atmospheric pressure Differential pressure Temperature Meteorological data
Collection wells	Fortnightly	Six-monthly	CH_4, CO_2, O_2 Atmospheric pressure Differential pressure Gas flow rate or suction Temperature
Gas collection system (site-specific) e.g. manifolds	Annually	Annually	Composition of raw landfill gas (including trace components) from the extraction line and prior to the disposal system
Flares	Annually	Annually	NO_x, CO, VOCs, NMVOCs[1]
Utilisation plant	Annually	Annually	NO_x, CO, VOCs, NMVOCs

Note: Monitoring wells within the landfill are required to fulfil the requirement set out in the Landfill Regulations to provide representative gas monitoring for each section of the landfill. These wells should be sufficient to characterise the landfill gas source.

[1] Non-methane volatile organic compounds

5.4 Other guidance

A number of other documents related to the management, control and monitoring of landfill gas provide useful sources of information. These include:

- *Monitoring of landfill gas* (2nd edition). Institute of Wastes Management (1998);
- *Risk assessment for methane and other gases from the ground*. Report 152. CIRIA (1995);
- *Landfill gas development guidelines*. Prepared by ETSU for Dti (ETSU, 1996).

Guidance on the management of landfill gas

Part C: Technical considerations

6

Landfill gas production and emissions

This chapter reviews in detail the mechanisms by which landfill gas is generated, its composition, its chemical and physical characteristics, and its behaviour in landfills. The chapter also examines the behaviour of landfill gas within the wider environment and the effects of fugitive and controlled emissions to atmosphere. It is primarily concerned with the gases released by microbial action on organic materials in the waste, i.e. biodegradation.

The Landfill Directive defines landfill gas as '*all the gases generated from the landfilled waste*'. Landfill gas, therefore includes gaseous emissions arising from all physical, chemical and biological processes occurring within the waste, e.g. microbial production, chemical reactions and direct volatilisation.

The composition of emissions arising from predominantly inorganic landfill sites may be very different from biodegradable landfills. Such landfills need to be considered on a site-specific basis. They are not dealt with in detail in this document, but the main principles governing the production of gas from such waste are summarised below.

Gas can be generated from non-biodegradable wastes by the following chemical processes:

- corrosion of metals or reactions between metals, e.g. hydrogen is emitted;
- formation of free acidic gases by reaction of the waste with acidic material, e.g. hydrogen cyanide is emitted;
- release of free bases by reaction of the waste with alkali, e.g. amines are emitted;
- redox reactions within the waste, e.g. sulphur oxides are emitted.

Volatile substances may be released from the waste by the following physical processes:

- gas stripping with other released gas or water vapour
- heat generated in the waste
- aerosols carrying liquid droplets
- dust carrying sorbed materials
- reactions between organic compounds to form more volatile species, e.g. the formation of esters.

These processes will also occur in wastes containing biodegradable waste. However, the emitted gases will generally only be found as trace components mixed with the methane and carbon dioxide.

6.1 Composition of gas from biodegradable waste

Mature landfill gas is a mixture predominantly made up of methane and carbon dioxide, and small amounts of hydrogen. It may also contain varying amounts of nitrogen and oxygen derived from air that has been drawn into the landfill. These are typically referred to as bulk gases because they are often present at percentage concentrations (see Table 6.1).

Table 6.1 Typical range of bulk compounds in landfill gas

Bulk landfill gas	Typical value (%v/v)	Observed maximum (%v/v)
Methane	63.8	88.0
Carbon dioxide	33.6	89.3
Oxygen	0.16	20.9#
Nitrogen	2.4	87.0#
Hydrogen	0.05	21.1
Water vapour (typical % w/w, 25°C)	1.8	4.0

Derived entirely from the atmosphere.

Landfill gas will also contain a wide variety of trace components. Around 550 trace compounds belonging to a variety of chemical groups have been identified in landfill gas (see Environment Agency, 2002e); these groups are detailed in Appendix A. Together they may comprise approximately 1 per cent of the gas. Table 6.2 summarises both the variety and concentration of some trace components of landfill gas that have been reported in the UK.

Table 6.2 Average concentration of a variety of trace components of landfill gas

Name	Chemical group	Median concentration (µg/m^3)	Average concentration (µg/m^3)
1,1-Dichloroethane	Halogenated organics	13,260	476,223
Chlorobenzene	Halogenated organics	11,880	246,589
1,1,1-Trichloroethane	Halogenated organics	12,905	189,826
Chlorodifluoromethane	Halogenated organics	11,570	167,403
Hydrogen sulphide	Sulphured compounds	2,833	134,233
Tetrachloroethene	Halogenated organics	16,640	112,746
Toluene	Aromatic hydrocarbons	11,995	86,221
Chloroethane	Halogenated organics	5,190	77,867
n-butane	Alkane	13,623	67,412
Chloroethene	Halogenated organics	5,600	64,679
Carbon monoxide	Carbon Monoxide	5,822	62,952
Ethylbenzene	Aromatic hydrocarbons	6,480	37,792
1,2-Dichlorotetrafluoroethane	Halogenated organics	3,200	34,046
α-pinene	Cycloalkenes 2	9,300	33,248
cis-1,2-Dichloroethene	Halogenated organics	7,700	33,129
Xylene	Aromatic hydrocarbons	4,700	23,900
Dichlorofluoromethane	Halogenated organics	3,500	20,131
n-hexane	Alkanes	5,000	19,850
Dichloromethane	Halogenated organics	1,240	19,054
n-nonane	Alkanes	8,120	19,015
Butan-2-ol	Alcohols	5,400	18,704
1,2-Dichloroethane	Halogenated organics	1,575	16,495
3-Methyl-2-butanone	Ketones	1,984	13,614

Source: Environment Agency (2002e)

Three processes are responsible for the presence of these compounds:

- the volatilisation of chemicals disposed of as waste;
- biochemical interactions occurring within the waste;
- chemical reactions.

In addition to landfill gas, there are other sources of ground-based gas in the environment which are rich in methane. These gases may be of biogenic or thermogenic origin (see Appendix B) and include:

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

Other ground-based gases may also be rich in carbon dioxide (e.g. degassing limestone-rich sediments).

These categories of gas are not the central concern of this document, but knowledge of their occurrence and composition is important to distinguish methane in landfill gas from other, potentially interfering sources. A number of analytical techniques can be used to discriminate between landfill gas and methane-rich gas from other sources, including:

- hydrocarbon fingerprinting
- analysis of trace components
- radiocarbon dating
- isotopic ratio analysis.

In the event of potential landfill gas migration where the situation is complicated by the possible presence of other methane-rich gases, early analysis using the above techniques should be undertaken. Further information on other gas sources is given in Appendix B.

6.2 Landfill gas characteristics

6.2.1 Density

The density of landfill gas is variable and depends on its composition.

- A mixture of 10 per cent hydrogen (density 0.08 kg/m^3) and 90 per cent carbon dioxide (1.98 kg/m^3), as typically produced during the early stages of degradation, is denser than air (1.29 kg/m^3).
- A mixture of 60 per cent methane (0.72 kg/m^3) and 40 per cent carbon dioxide – typical of a mature anaerobic landfill gas – is slightly lighter than air.

Landfill gas is a mixture and, under most conditions, its components do not separate into layers. However, the potential for compositional stratification of different mixtures in monitoring boreholes must be considered in the design of any landfill gas monitoring plan (see Chapter 3).

6.2.2 Solubility

Landfill gas contains a range of components that can dissolve in aqueous media (including landfill leachate and condensate). These soluble, partially or sparingly soluble compounds include bulk and trace components of the gas.

Under equilibrium, the extent to which a compound enters into solution depends on factors such as:

- temperature
- the partial pressure of the gas/compound
- chemical interactions between the compound (the solute) and the aqueous media (the solvent).

Changes in these factors can also result in degassing of the aqueous medium and the evolution of a gas containing gases/compounds that were formerly in solution. Degassing can occur when the liquid containing the dissolved gases is exposed to changes in temperature and pressure and/or mechanical agitation in plant and pipework used to transport and treat leachate and condensate.

Methane is slightly soluble in water (35 ml methane/litre water at 17°C) (O'Neil *et al.*, 2001). Carbon dioxide is more soluble in water, ionising to form bicarbonate and carbonate ions. This disparity in solubility is partially responsible for observed variations in bulk gas composition.

Aqueous media such as landfill leachate and condensate can act as vectors for the migration of dissolved methane. The potential for leachate and condensate to act as a secondary source of methane emissions should be considered as part of the site-based risk assessment. It is particularly important to be aware of the potential for the accumulation in enclosed spaces of methane transported via this route.

6.2.3 Flammability and explosivity

Methane is a flammable gas, with a calorific value of 35.9 MJ/m^3, which forms explosive mixtures with air when present between the concentration limits of 4.4 per cent and 16.5 per cent v/v at 20°C and 1 atmosphere pressure. These limits are known as the lower explosive limit (LEL) and upper explosive limit (UEL) of methane, or the upper and lower flammable limits, respectively.

The migration and dilution of landfill gas with air can, therefore, result in the formation of highly explosive atmospheres. The minimum oxygen content that is required for methane ignition is approximately 14 per cent (by volume). The locations identified in the Section 6.2.4 on asphyxiation are also relevant for the formation of explosive mixtures of landfill gas and air.

Landfill gas can also contain variable concentrations of other flammable agents including hydrogen (flammable limits 4–75 per cent) and hydrogen sulphide (flammable limits 4–44 per cent). Other non-flammable components of landfill gas have an effect on the flammable limits indicated above. The effects of carbon dioxide on the flammable limits of methane are addressed more fully in Appendix C.

6.2.4 Asphyxiation

The accumulation of landfill gas in enclosed spaces can pose a direct risk to humans due to asphyxia. This may be caused when the oxygen content of the atmosphere in the breathing zone is reduced below 10 per cent by volume by admixture with migrating landfill gas.

There is evidence that, in extreme situations on landfills with significant depressions, gullies etc., concentrations of carbon dioxide greater than 5 per cent can accumulate when there is little wind.

Voids and enclosed spaces in or near to landfill sites can be locations that are particularly at risk from migrating landfill gas, which poses a potential explosive or asphyxiant hazard. Such locations include manholes, sewers, or tunnels and even poorly ventilated spaces below portable buildings.

In areas that are accessible to humans, action is needed to prevent the oxygen falling below 18 per cent by volume at atmospheric pressure (HSE, 2002). Where this is not practical, humans should be excluded unless they have appropriate personal protection (including breathing apparatus). Physiological effects arising from respiration in low oxygen environments are listed in Table 6.3.

Table 6.3 Physiological effects of asphyxiation

Oxygen concentration (%)	Physiological effects
18	Blood saturation adequate for resting, walking and heavy work
17	Faster, deeper breathing, slight impairment of judgement
16	First signs of anoxia. Dizziness, buzzing in ears
12–16	Increased breathing and pulse rate. Muscular co-ordination impaired
10–14	Emotional upset. Abnormal fatigue upon exertion
6–10	Nausea, vomiting unconsciousness. Collapse may reoccur with person unable to move or cry out
<6	Convulsions, gasping respiration, death

6.2.5 Toxicity

Some of the constituents of landfill gas, including carbon dioxide and a number of trace components, can have toxic effects if present in high enough concentrations. Table 6.4 contains information on the physiological effects of exposure to carbon dioxide. The trace components of landfill gas do not usually represent a health hazard following normal atmospheric dilution. However, this should be demonstrated on a site-specific basis through the application of a risk assessment.

Hydrogen sulphide, which may be present in landfill gas, is toxic at low concentrations and will dull the olfactory senses at higher concentrations such that its characteristic odour is no longer detectable. *Guidance Note EH40* (HSE, 2002) recommends occupational exposure standards of 10 ppm (8-hour time-weighted average (TWA) reference period) and short-term exposure standards of 15 ppm (10-minute reference period). Migration of trace gases through the ground to a receptor such as a dwelling without dilution by atmospheric air may cause toxicity thresholds to be exceeded.

Table 6.4 Physiological effects from respiration of carbon dioxide

Consentration of carbon dioxide (%)	Physiological effects
0.03	None, normal atmospheric concentration
0.5	Slightly deeper breathing
2.0	Lung ventilation increased by 50 per cent
3.0	Lung ventilation doubled
5–10	Three-fold increase in rate of respiration. Rapid exhaustion and headaches
10–15	Intolerable panting. Severe headaches, collapse
25	Death

6.2.6 Corrosion

Some components of landfill gas and its derivatives have a corrosive potential. This potential should be considered when designing appropriate gas collection and treatment systems. Corrosion accelerates wear on plant and equipment, and reduces their effectiveness as gas control measures. This issue must be addressed as part of a formal risk assessment and suitable site procedures for monitoring (e.g. oil analyses), maintenance and inspection, repair and life-cycle replacement must be developed. These procedures should be described in the Gas Management Plan.

Carbon dioxide is soluble in water and will form carbonic acid in aqueous solutions associated with the gas. Condensate will be acidic – typically with a pH in the range 3 to 6.5 – due to dissolved carbon dioxide and acidic trace compounds. Such aqueous media can corrode a range of metals.

The combustion of landfill gas in utilisation or control systems will generate substantial quantities of carbon dioxide. Combustion of certain trace components, such as halogenated or sulphuretted compounds, may give rise to highly acidic and aggressive products. Some of these may corrode equipment or dissolve in oils and lubricants causing corrosion of plant components. At elevated temperatures, carbon dioxide, hydrogen, hydrocarbons and water vapour can cause decarbonisation (removal of carbon from an alloy) and carbonisation (coking) reactions, with alloys strengthened by the addition of interstitial carbon.

Pretreatment of landfill gas prior to combustion can be used to reduce the corrosive potential of landfill gas. *Guidance on gas treatment technologies for landfill gas engines* (Environment Agency, 2004c) provides additional information.

6.2.7 Odour

Trace compounds present in landfill gas are responsible for many of the malodours associated with landfilling operations (see Appendix A). Odour may cause local annoyance and can be responsible for a considerable proportion of the complaints made to both landfill operators and regulators. The presence of odour is often linked to concerns about the impact of landfill gas emissions on human health.

Malodorous species can have very low odour thresholds (i.e. the concentration of a compound in air that is just detectable to the human nose). Important odorants (see Environment Agency, 2002e) sometimes reported in landfill gas include:

- hydrogen sulphide;
- organosulphur compounds, e.g. methanethiol and dimethyl sulphide;
- carboxylic acids, e.g. butanoic acid;
- aldehydes, e.g. ethanal
- carbon disulphide.

In complex mixtures such as landfill gas, the presence of several odorants may cause additive and hyper-additive effects (Warren Spring Laboratory, 1980).

Uncontrolled landfill gas emissions can, under certain meteorological conditions, give rise to odours extending over several kilometres from site boundaries. The emissions of landfill gas may need to be diluted several million times in order to render its odour undetectable.

The availability of such dilution will depend on the prevailing meteorological conditions and the physical characteristics of the site. Still, calm conditions during cold periods are more likely to give rise to poor dilution. Such conditions (Pasquill's atmospheric stability categories F and G) generally prevail for about 9.4 per cent of each year in the UK. Persistent odour can result in a number of impacts upon amenity and quality of life for neighbouring communities. The Agency has produced guidance on the regulation of odour at waste management facilities (Environment Agency, 2002a), which is applicable in England and Wales. Although this document is directed at facilities regulated under the waste management licensing regime, much of the guidance is relevant to landfills permitted under PPC.

6.2.8 Ecotoxicity

The lateral sub-surface migration of landfill gas can cause damage to vegetation on adjacent land and crop die-back (chlorosis). Although plant death in many situations has been attributed to root zone oxygen displacement by the bulk components of landfill gas, several trace components of the gas are known to exert phytotoxic effects when borne in sub-surface gas or ambient air. In addition, products of landfill gas combustion (e.g. acid gases such as hydrogen chloride, hydrogen fluoride and oxides of nitrogen and sulphur) will produce emissions that are potentially damaging to vegetation and ecosystems. Efficient gas collection and combustion systems should provide an effective control mechanism.

6.2.9 Global warming potential

Carbon dioxide, methane and a variety of halocarbons found in landfill gas are all greenhouse gases. This means that they can absorb infra-red radiation from the Earth's surface (in the 7–14 μm region of the spectrum), which is normally lost to space. This absorption produces thermal energy, a proportion of which is re-radiated back to earth as heat.

Methane is the second most important greenhouse gas after carbon dioxide. In 1998, the methane emissions inventory for the UK totalled some 2.6 million tonnes, of which approximately 29 per cent or 0.775 million tonnes were derived from landfills (Defra, 2002b). Landfill gas is therefore a major source of UK methane emissions.

Landfill gas may also contain CFCs and other halocarbons which are ozone-depleting substances and also contribute to global warming. Combustion of landfill gas can also lead to emissions of nitrous oxide, which has a global warming potential approximately 300 times greater than that of carbon dioxide. Further information on global warming potentials is given in Table 2.9.

6.2.10 Photochemical pollution

Hydrocarbons present in landfill gas that possess more than one carbon atom per molecule can yield highly reactive radicals when exposed to the ultra-violet radiation present in sunlight. Methane can also be 'activated' by reaction with hydroxyl radicals. Photo-activated hydrocarbons, such as the $CH_3O\bullet$ radical can react with atmospheric concentrations of nitrogen oxides to produce nitrous oxide (N_2O) and, after a sequence of reactions involving oxygen, tropospheric ozone, producing photochemical smog.

Photochemical smog is a mixture of chemicals, principally hydrogen peroxide and peroxyacyl-nitrate. Tropospheric ozone is potentially harmful to humans at a concentration of 200 µg/m^3 and gives rise to vegetation damage above 60 µg/m^3. The contribution to photochemical pollution is unlikely to be significant, but may be a localised air quality issue that requires consideration as part of the formal risk assessment for the landfill.

6.3 Gas production

Landfill gas is produced by complex biological and physiochemical processes within the landfill.

6.3.1 Methane production

Biodegradable organic material present in landfilled waste undergoes microbial degradation. This liberates the gaseous intermediates and end-products that make up landfill gas. The idealised evolution of these components from a single body of waste with time (from the moment of deposit) was described by Farquhar and Rovers (1973), and is shown in Figure 6.1.

In Stage 1 of Figure 6.1, oxygen contained within the waste upon deposit is consumed – primarily by aerobic microbial activity, which results in the evolution of mainly carbon dioxide, water and heat. Unless concentrations of oxygen and nitrogen within the fill are replenished by an influx of air, the concentrations of both of these gases will decay during the course of Stage 1 activity. This is due to consumption of oxygen and the purging of nitrogen from the fill due to the liberation of other gases. The presence of percentage concentrations of nitrogen and oxygen in landfill gas, which is collected from waste masses that are undergoing degradation in Stages 2–4 of Figure 6.1, is indicative of a failure in the gas management regime. This could reflect excessive suction on parts of the gas collection system, tears in the fabric of pipes and plant or other failures that allow air to enter the collection system.

Stage 2 of Figure 6.1 is associated with the onset of anaerobic conditions within the waste. This is characterised by hydrolysis and acetogenic processes mediated by hydrolytic and cellulolytic bacteria including species such as *Clostridium* and *Bacillus*. This activity breaks down large chain polymers present in waste (e.g. lipids, proteins and carbohydrates) to successively smaller molecules. Short chain organic compounds such as ethanoic acid (acetic acid), ethanoates (acetates) and ethanol are produced, together with ammonia, gaseous carbon dioxide, hydrogen, water and heat. The hydrogen and carbon dioxide produced during Stage 2 continue to purge the remaining nitrogen from the landfill atmosphere.

Stage 3 of Figure 6.1 is characterised by a period of transitional anaerobic activity during which

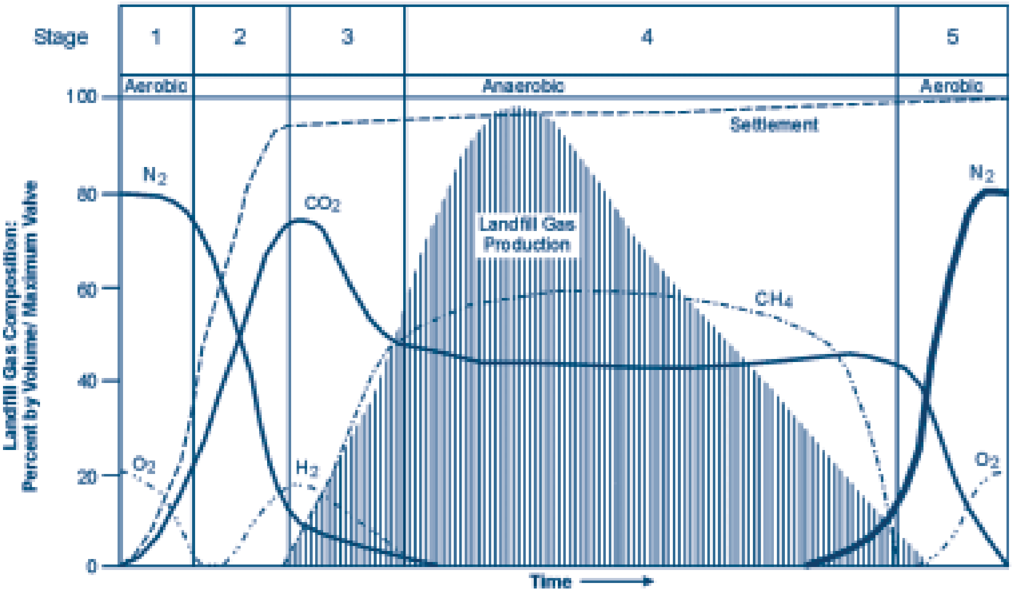


Figure 6.1 Idealised representation of landfill gas generation

Source: DoE, 1995

methanogenesis is initiated and gradually accelerates until a balance with the rates of hydrolysis and acetogenesis is achieved. Methanogenic bacteria are a distinct group of anaerobic micro-organisms, which occupy a crucial niche in anoxic ecosystems and play an important role in the anaerobic degradation sequence for landfilled wastes. They utilise substrates (ethanoate, hydrogen and carbon dioxide) produced by hydrolysis and acetogenic bacteria to produce gaseous carbon dioxide and methane. Importantly, this provides a route for terminal interspecies hydrogen transfer and electron removal, which allows the microbial and anaerobic degradation of organic material to proceed to completion.

Methanogenesis is achieved via two principal routes:

- the acetogenic mechanism, in which short chain organic compounds (principally ethanoates) are used as substrate;
- the lithotrophic mechanism, which utilises hydrogen and carbon dioxide.

In Stage 4 of Figure 6.1, the rates of hydrolysis/acetogenesis and methanogenesis are in relative equilibrium. This provides steady state conditions during which methane and carbon dioxide are evolved in the ratio of about 3:2. Figure 6.2 details the major steps in the decomposition of biodegradable waste to form landfill gas.

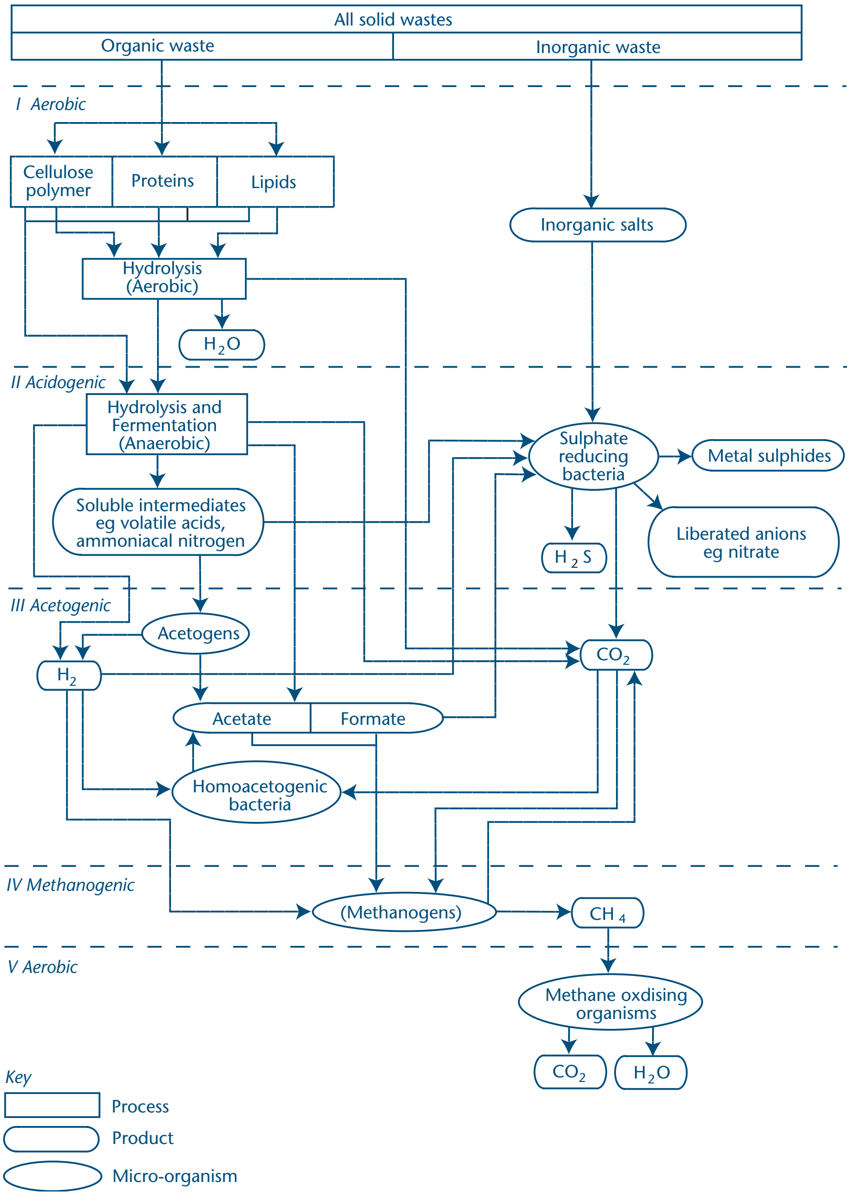


Figure 6.2 Major steps in the decomposition of biodegradable waste to form landfill gas (adapted from DoE, 1995)

Stage 5 of Figure 6.1 represents a period of endogenous respiration during which the organic substrate required for microbial activity becomes limited. At this time, the composition of the interstitial gases within the fill gradually assumes that of atmospheric air.

In practice, the idealised profiles described by the model (Figure 6.1) are rarely achieved. Varying degrees of phase overlap, phase omission and, even, temporary cessation have been reported from the field. In addition, the duration of particular phases and the overall length of time taken for a body of waste to pass through the full degradation sequence varies considerably from one site to another. This reflects the influence of a wide range of factors, which are discussed in more detail in the following sections.

6.3.2 The formation of hydrogen sulphide

Under the anaerobic conditions encountered in landfills, soluble sulphate salts can undergo microbially mediated reduction (see Figure 6.3) to produce hydrogen sulphide and other sulphur-containing odorous compounds. These reactions are mediated by a specific group of bacteria known as sulphate-reducing bacteria, which have been identified in the landfill environment. Hydrogen sulphide is an odorous, potentially toxic and flammable gas.

Sulphate may also be reduced chemically and microbially under anoxic conditions to produce insoluble metal sulphides. These reactions probably explain why, in many landfills accepting inputs of household and commercial wastes, hydrogen sulphide is not found in high concentrations in landfill gas.

However, hydrogen sulphide can be generated from landfills in which large amounts of sulphate-based wastes have been deposited. The ready availability of soluble sulphate results in the increased activity of sulphate-reducing bacteria and the liberation of hydrogen sulphide. The sulphate may originate from animal or vegetable materials (e.g. fermented grains and food processing waste) but, in most recorded circumstances, arise from industrial wastes containing large amounts of calcium sulphate (gypsum) such as plasterboard, gypsum quarry spoils and filter cakes rich in calcium sulphate (Young and Parker, 1984). Sulphate reduction is one of a suite of competing processes that occur within the landfill environment. Iron reduction – from Fe(III) to Fe(II) – is one of a number of such reactions that are energetically favourable to sulphate reduction. Consequently, the availability of ferric ions could potentially inhibit the onset of sulphate reduction.

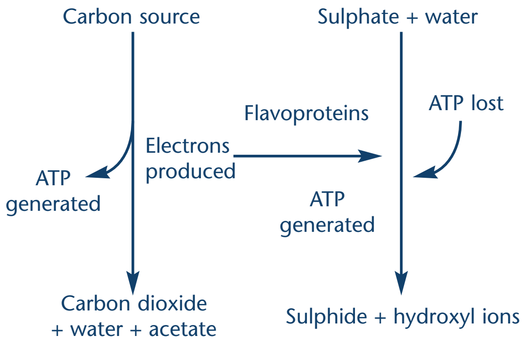


Figure 6.3 Dissimilatory sulphate reduction (adapted from Scott *et al.*, 1998)

Sulphate-bearing wastes should not be deposited in landfill cells that are also used for the deposit of biodegradable wastes. Leaching levels for sulphates are laid down by European Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC (Council of the European Union, 2003). The exclusion originates within Section 2.2.3 of this Decision concerning gypsum waste:

> *Non-hazardous gypsum-based materials should be disposed of only in landfills for non-hazardous waste in cells where no biodegradable waste is accepted. The limit values for TOC and DOC given in sections 2.3.2 and 2.3.1 shall apply to wastes landfilled together with gypsum-based materials.*

6.3.3 Compositional variations in landfill gas

The composition of landfill gas will vary from one site to another, from one cell of a landfill to another, and will change over time. Some of these changes can be attributed to:

- differences in waste composition, pretreatment and storage;
- changes in the rate and predominant form of microbial activity, e.g. aerobic/anaerobic;
- the age of the emplaced wastes;
- gas management regime;
- the hydraulic characteristics of the site;
- the physiochemical properties of waste components;
- the differing properties of the components of landfill gas, e.g. solubility;
- landfill temperature.

Temporal variations in landfill gas composition will reflect the long-term degradation of the waste, and short-term changes in site characteristics and environmental factors. Some of the most significant long-term trends include:

- initial increase in the total concentration of trace compounds released during early phases of landfill activity (including a high concentration of halogenated hydrocarbons);
- rapid depletion in the concentration of highly volatile CFCs and low molecular weight alkanes;
- pronounced reduction in the concentration of alcohols and esters as methanogenic activity is firmly established;
- accumulation of high molecular weight aliphatic and aromatic compounds over time under methanogenic conditions;
- overall decrease in the total concentration (but not necessarily mass flux) of trace components over time once methanogenic activity is established and progresses with time.

The composition of landfill gas can also vary within gas extraction and collection systems due to admixture with air and gas/condensate and other interactions.

The migration of landfill gas through sub-surface strata can also affect composition through physical (e.g. adsorption), chemical and biological (e.g. methane oxidation) interactions between the gas and the surrounding rocks and minerals (lithology). These processes can alter the relative concentration of methane and carbon dioxide, and the trace chemistry of the gas as it moves further from the landfill source. They can also promote changes in the ratio of stable isotopes present in the gas with migrated distance. Ward *et al*. (1992) reported such isotopic fractionation, where the methane associated with a sub-surface plume of landfill gas became isotopically heavier with migration distance while the carbon dioxide in the plume became isotopically lighter. These changes were associated with methane oxidation bacteria, which preferentially metabolised ^{12}C rather than heavier carbon isotopes (^{13}C and ^{14}C). These potential variations in landfill gas composition should be considered when assessing monitoring results from off-site boreholes and in investigations concerning migrating landfill gas.

6.3.4 Factors controlling gas production

Landfill gas production is typically affected by:

- waste composition
- density of waste
- moisture content and distribution
- pH and nutrient availability
- temperature
- presence of toxic agents and chemical inhibitors.

These are considered in the following sections. Further information can be found in the research report CWM 039/92 (DoE, 1992).

Waste composition

The composition of the waste deposited within a landfill will influence both the rate of production and the composition of the landfill gas generated. Inorganic waste landfills will yield landfill gas at a rate and with a composition that differs significantly from that generated by biodegradable waste landfills.

The biodegradable fraction of waste is the portion, which under landfill conditions can undergo microbial degradation to produce gas and liquids. Currently 60 per cent of the municipal waste produced in the UK is believed to be biodegradable waste.

Article 5.2 of the Landfill Directive sets three progressive targets to reduce the amount of biodegradable municipal waste sent to landfill. The magnitude of the reduction and required schedule for the UK is shown in Table 6.5.

Table 6.5 UK National target to fulfil Article 5.2 of the Landfill Directive

Objectives
By 2010, biodegradable municipal waste (BMW) to landfill must be reduced to 75 per cent of the total BMW (by weight) produced in 1995.
By 2013, BMW to landfill must be reduced to 50 per cent of the total BMW (by weight) produced in 1995.
By 2020, BMW to landfill must be reduced to 35 per cent of the total BMW (by weight) produced in 1995.

Source: DETR, 2001

The biodegradable fraction of the municipal waste, which can produce landfill gas, is primarily made up of cellulose and hemicellulose – although not all the cellulose in waste is available for biodegradation. Table 6.6 shows the principal landfill gas generating components of waste. Table 6.6 indicates that approximately 25–30 per cent by weight of municipal waste actually degrades to produce landfill gas. However, this fraction will be different for sites accepting a high proportion of industrial and other commercial wastes.

The overall biodegradable fraction of waste disposed at landfills will progressively reduce as the requirements of the Landfill Directive are met. This may result in changes to the composition and yield of landfill gas in the future. However, the proportion of biodegradable waste accepted by any one site and its consequent contribution to the source of landfill gas must be considered on an individual basis. This forms part of the source term definition required as part of the formal risk assessment for the landfill.

Table 6.6 Principal landfill gas generating components in waste

Waste Fraction	Domestic % w/w	Civic amenity % w/w	Com-mercial % w/w	Sewage sludge % w/w	Typical water content %	Cellulose (%)	Hemi-cellulose (%)	De-composition (%)	Percentage of biode-gradable material in waste fraction
PAPER/CARD									
Newspapers	11.4	10	10		30	18.5	9.0	35	20
Magazines	4.8	11			30	42.3	9.4	46	24
Other paper	10.1		50		30	87.4	8.4	98	94
Liquid cartons	0.5				30	57.3	9.9	64	43
Card packaging	3.8				30	57.3	9.9	64	43
Other card	2.8				30	57.3	9.9	64	43
TEXTILES									
Textiles	2.4	3			25	20	20	50	20
MISC. COMBUST.									
Disposible nappies	4.3				20	25	25	50	25
Other	3.6				20	25	25	50	25
PUTRESCIBLE									
Garden waste	2.4	22			65	25.7	13	62	24
Other	18.4		15		65	55.4	7.2	76	48
FINES									
10mm fines	7.1	15			40	25	25	50	25
SEWAGE SLUDGE									
Sewage sludge				100	70	14	14	75	21

Source: Environment Agency, 1999a

Density of waste

Waste density is a function of the waste deposited, its particle size and the degree of compaction. Theoretically, the landfill gas yield per unit volume increases with waste density. However, increased waste densities generally reduce waste permeability, thereby inhibiting the free movement of the soluble nutrients required by bacteria. Hence, highly compacted waste at the base of a deep landfill may have a relatively low rate of production. The mechanical characteristics of the waste deposit may also influence the efficiency with which landfill gas can be extracted from the landfill.

Moisture content and distribution

Moisture content is one of the most significant factors influencing landfill gas production rates. A high moisture content is normally associated with high rates of gas production, although rates do decline as saturation is approached. Moisture content can promote methanogenesis in a number of ways:

- water may prevent methanogenic inhibition by diluting the toxic products of acidogenesis;
- the dissolution and transport of soluble substrates and nutrients required for methanogenic activity may be promoted by increasing moisture content;
- water may facilitate bacterial transport within the waste;
- water will aid mixing and buffering within the landfill system.

Food and garden wastes within the municipal waste stream usually have a high moisture content, typically of the order of >25 per cent weight. Rainfall, surface water infiltration and the products of waste breakdown can provide additional moisture.

Moisture content can be distributed throughout the waste to a certain extent by recirculating leachate. Recirculation also serves to flush out the products of degradation. Figure 6.4 shows the gas production rates achieved in landfill test cells at the Brogborough landfill by liquid injection (recirculation) in comparison with other factors. The potential for process inhibition should be considered when designing a leachate recirculation system; unless leachate treatment is part of the recirculation system, the build-up of inhibitory concentrations of components in the leachate is a possibility. The use of leachate recirculation in relation to accelerated gas production is also discussed in Section 6.3.6.

Total gas quantity is mainly a function of the waste types and their degradable carbon content, although the rate of decomposition depends on site-specific factors. The time taken for waste to decompose will directly influence the period over which landfill gas will be generated at a particular site and thus the period over which control is required.

Excess moisture within the landfill mass and the subsequent dissolution of soluble materials results in the production of landfill leachate. Leachate quality is a function of the same decomposition processes that generates landfill gas. However, other waste components can also contribute to leachate composition and leachate quantity is influenced by other factors such as location, geology, hydrology and site engineering.

The hydraulic retention time (HRT) of leachate in a landfill is typically of the order of several decades (Knox, 1990). Gas retention times (GRTs) are usually orders of magnitude smaller – typically 2–4 weeks at gas generation rates of 5–10 m^3/tonne/year and a waste density close to 1 m^3/tonne. If gas generation rates are stimulated by recirculation or other methods, the GRT may fall to just a few days. Only in the very late stages of landfill stabilisation will gas emission rates fall to the point where the GRT is determined by external factors such as diffusion rates. Throughout most of the life of a landfill, gas quality therefore reflects more current processes. In contrast, leachate composition may reflect processes that occurred years or decades earlier.

Gas production within the saturated zone can be inhibited; thus, a high leachate head can result in poor gas production rates compared with similar wastes that are moist but unsaturated. A high head of leachate and/or perched leachate tables within landfill sites can also interfere with gas collection and make effective gas management difficult.

pH and nutrient availability

Waste degradation processes occur under a wider range of pH conditions than methanogenesis, which proceeds optimally between pH 6.5 and 8.5. Acidic conditions resulting from the rapid degradation of biodegradable wastes and an accumulation of breakdown products may inhibit or delay methane generation – unless this is buffered by other

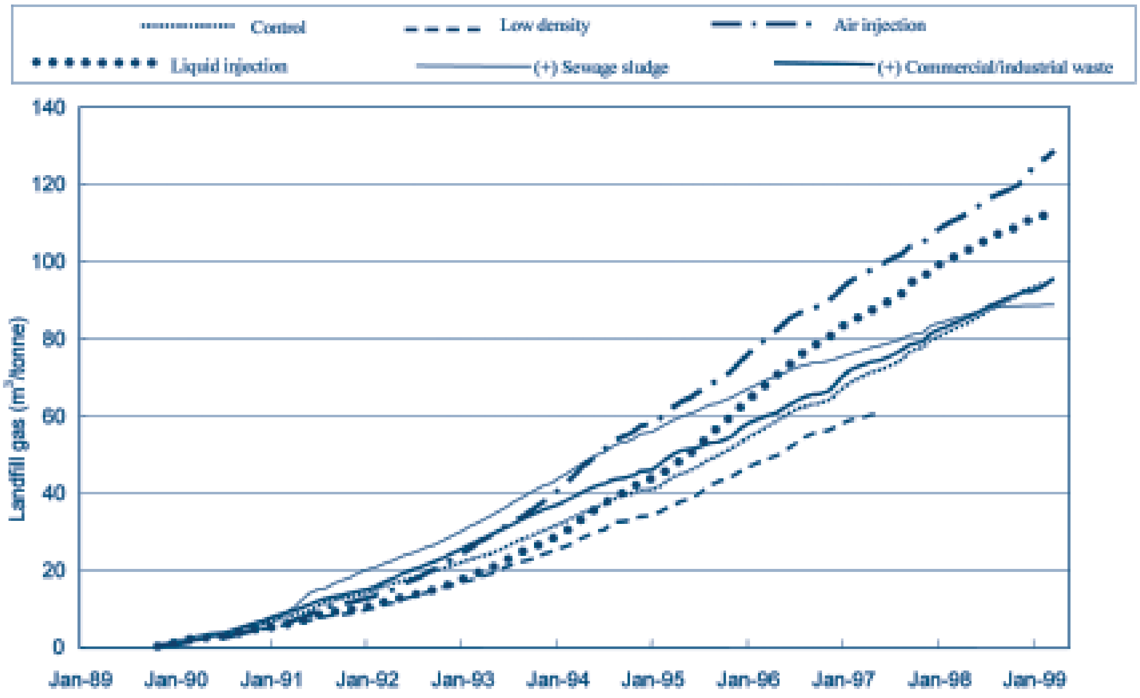


Figure 6.4 Brogborough: cumulative landfill gas production for all test cells

Source: Environment Agency. 1999b

components of the waste stream. This can ultimately result in the process of 'acid souring' where pHs fall below the optimum range in which methanogenesis occurs. In addition, a low pH may promote the dissolution of metal ions within the waste mass, which may inhibit methanogenic activity.

Low metal concentrations may produce a leachate that is poorly buffered against the carboxylic acids so that pH falls too quickly for methanogenic populations to reach a self-regulating size.

Under the equilibrium conditions associated with Stage 4 of the model shown in Figure 6.1 and where methanogenic bacteria are firmly established, an optimal pH of about 7.4 will generally be maintained.

Temperature

Temperature is an important factor influencing the rate of landfill gas production. During the initial aerobic phases of waste degradation (Stage 1 of the model shown in Figure 6.1), temperatures as high as 80–90°C can be encountered. In the majority of landfills, temperatures thereafter will subside, stabilising at an optimum of 35–45°C once methanogenesis is well established.

Shallow landfills may be more sensitive to climatic conditions than deeper ones and landfill gas production will tend to drop below 10–15°C. This may result in a seasonal pattern of waste decomposition and gas production. Deeper landfills can have temperatures over 60°C, with 40–45°C common in the first five years after landfilling.

Landfill gas fires may modify the composition of landfill gas due to the release of volatile compounds. The incomplete combustion of solid and gaseous components within the landfill will also release atypical compounds into the landfill gas.

Presence of toxic agents and chemical inhibitors

Methanogenesis can be inhibited completely or partially by chemical agents (Environment Agency, 2000c). Some of these chemicals may be present in household waste deposited at landfills such as commercial disinfectants and cleaning materials. Compounds shown to have an effect include chloroform, chloroacetate, formaldehyde, nitrate, ferric iron, sodium hypochlorite, hydrochloric acid, hydrogen peroxide, methanol and sulphate. The effects of these inhibitors on gas generation may be significant locally within a site.

6.3.5 Rates of production and emission

Gas production rates may vary substantially from one site to another and even between areas of a single landfill, reflecting differences in rate controlling factors including moisture content and the composition of the deposited wastes. In situ generation rates in UK landfills are typically in the order of 10 m^3 landfill gas per tonne of waste per year. These rates are equivalent to carbon turnover rates of approximately 7–14 g total organic carbon (TOC)/m^3/day.

Total methane emissions from UK landfills have been estimated to be approximately 775,000 tonnes/year (Netcen, 2000). This was equivalent to about 29 per cent of the total methane emissions in the UK in 1998. At a methane content of 60 per cent v/v, such emissions would be equivalent to 4.9 million m^3 methane per day or approximately 200,000 m^3 methane per hour.

Many models have been developed both for predicting gas production over the lifetime of individual landfills and for estimating national contributions to global emissions. Reviews of different approaches to modelling have been undertaken by Pacey and Augenstein (1990) in the USA, Sterritt (1995) in the UK and Gendebien *et al.*, 1992 in Europe. A commonly used approach in the UK for individual landfills is based on that described by Coops *et al.* (1995). Recent approaches to estimating the UK's national methane emissions from landfills are reported by DETR (1999) and Defra (2003).

The most common means of estimating rates of gas production used for individual landfills in the UK is a first-order kinetic model (i.e. exponential decline), with no lag or rise period, and with waste fractions categorised as being of rapid, medium or slow degradability (see Box 6.1). This equation (or similar first-order equations) is commonly used in combination with waste input predictions to produce a gas generation profile for the lifetime of the site. Such a multi-phase, first-order decay equation forms the core of the GasSim model (Environment Agency, 2002b), which is described in Section 2.4.4.

6.3.6 Accelerated gas production

The rate of landfill gas production at a site can be accelerated to some extent by the controlled modification of factors that influence waste degradation within the landfill environment. This may be carried out to enhance rates of site stabilisation or increase the commercial viability of gas utilisation. However, it must be carefully controlled so as not cause an adverse impact on other aspects of site emissions such as odour.

By optimising conditions for landfill gas production, laboratory studies have achieved very high rates of degradation and gas production (with short-term peaks of up to about 800 m^3 of landfill gas per tonne of waste per year). Test cell research undertaken in the UK and elsewhere using various techniques to enhance rates of landfill gas production has achieved rates equivalent to between 20 and 140 m^3 of landfill gas per tonne per year (see Figures 6.4 and 6.5).

As previously described, the most common method of accelerating gas production rates is to enhance the moisture content of the waste mass and flush out the degradation products. This can be achieved by recirculating leachate extracted from the waste.

Box 6.1 Estimating rates of gas production from UK landfills

$$\alpha_t = \sum_{i=1}^{n} 1.0846.A.C_i.k_i.e^{-k_i t}$$

Where:

α_t = gas formation rate at time t in m^3/year

A = mass of waste in place in tonnes

C_i = carbon content in fraction 'I' in kg/tonne

k_i = rate constant for fraction 'i' in $year^{-1}$

$k_1 = 0.185\ year^{-1}$ (fast)

$k_2 = 0.100\ year^{-1}$ (medium)

$k_3 = 0.030\ year^{-1}$ (slow)

t = time elapsed since deposit (years)

n = the number of iterations (from 1 until n = t)

Source: Coops *et al.* (1995)

A moisture content of 40–80 per cent is considered necessary for optimum levels of landfill gas production (Environment Agency, 1999b). Figure 6.5 shows the gas recovery profiles from two experimental test cells, one with the recirculation of leachate (Cell 1) and the other without recirculation (Cell 2). These test cells (Landfill 2000) demonstrated a doubling of gas production as a result of leachate recirculation.

Enhancement of landfill gas generation rates can also be accomplished by microbial seeding (e.g. by adding sewage sludge cake). However, some of the benefits of this treatment may be attributable to the increase in moisture content that this produces.

6.4 Landfill gas emissions

Landfill operations have the potential to release a range of pollutants to the atmosphere. It is essential that the emission of these pollutants to the environment is controlled and managed in a way that is consistent with the PPC permit or an existing licence. Gaseous emissions can arise from a wide range of sources including:

- freshly deposited wastes;
- uncapped wastes;
- caps or temporary cover materials;

Figure 6.5 Gas recovery profiles from the landfill 2000 test cells

Source: Environment Agency. 1999b

- intrusive engineering work and excavation;
- leachate and the infrastructure for leachate collection and treatment;
- cracks, gaps, fissures and along the edges of the site capping;
- lateral migration through surrounding geology;
- landfill gas flares and engines (utilisation plant);
- emissions through leakages in gas collection and distribution pipework, e.g. poorly sealed and balanced collection wells in which gas pressure exceeds the available suction.

Operators must be aware of the potential impacts associated with emissions to atmosphere. A number of the components present in landfill gas can give rise to air quality and/or odour impacts.

Three of the most significant emissions sources that may be associated with landfills are:

- landfill gas flares
- surface emissions from capped and temporary capped areas
- landfill gas engines.

The Agency has produced emissions guidance to cover these sources (Environment Agency 2004b; 2004d; 2004e) and, in conjunction with this guidance, has established emission limit values for them.

6.4.1 Surface emissions

Surface emission rates (fluxes) of landfill gas from landfill sites have been reported extensively (Environment Agency, 1999a; 2004d; Meadows and Parkin, 1999; Johnston *et al.*, 2000). Figure 6.6 shows methane flux rate data taken from the literature for a range of landfill sites with different capping and gas management controls.

Figure 6.7 summarises known emission rates through the landfill surface and associated capping and engineering infrastructure, and the likely dominant flow mechanism.

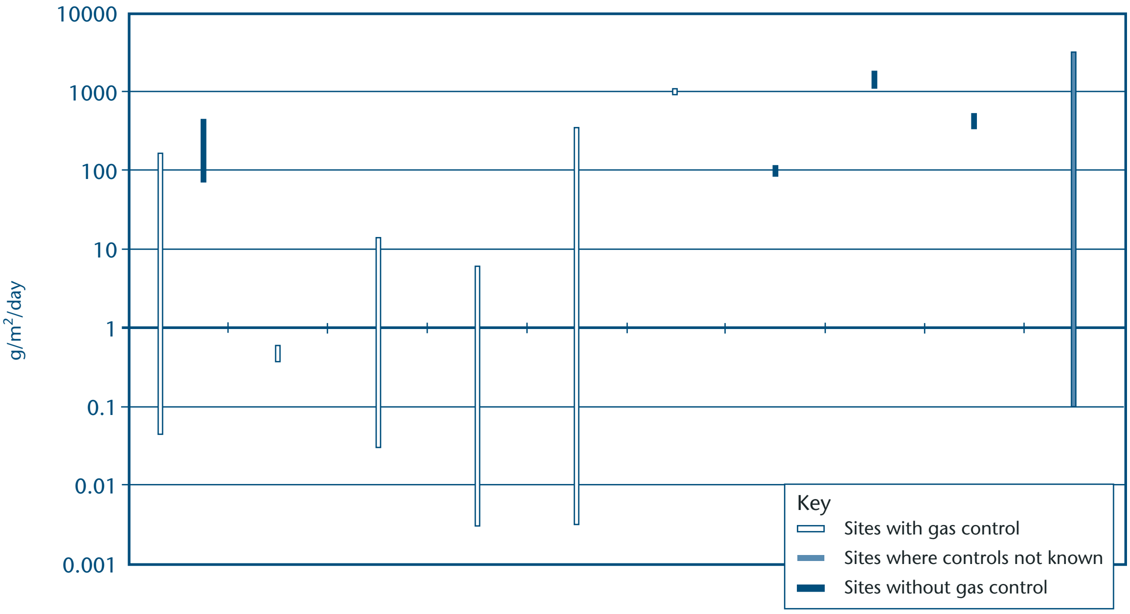


Figure 6.6 Methane flux rates reported from a range of landfills

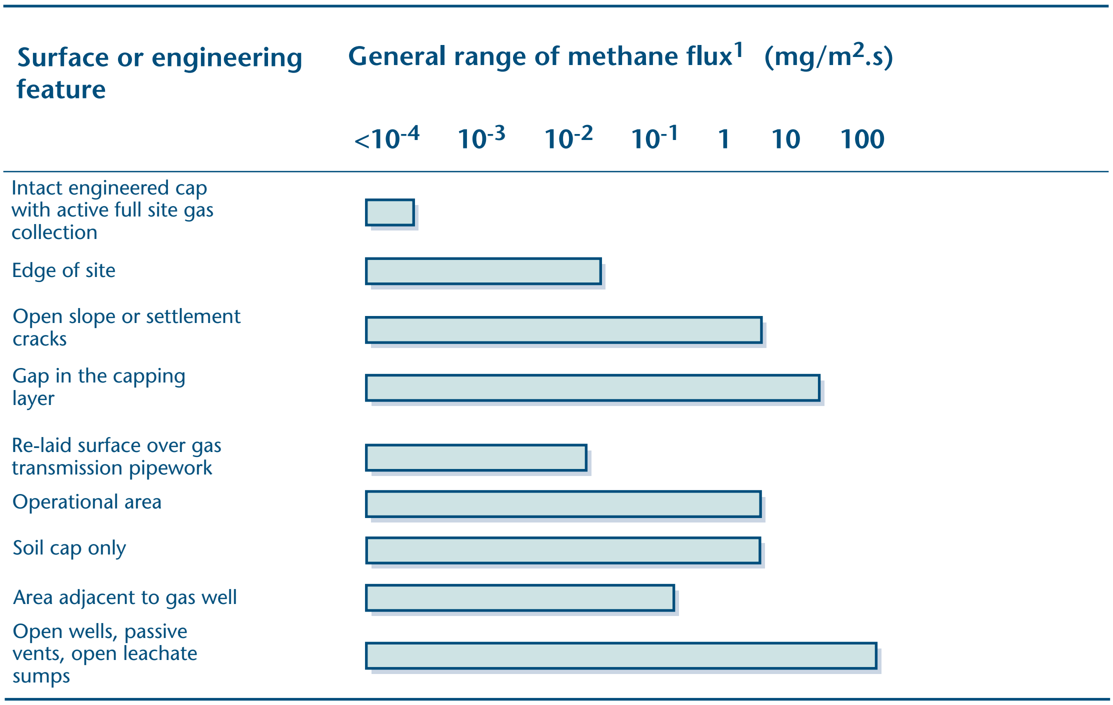


Figure 6.7 Surface emissions from areas with diffferent surface or engineering features

[1] 1 $mg/m^2.s$ is equivalent to approximately $50.4m^3/ha.h$ at standard temperature and pressure

Total yearly fluxes from individual landfills were estimated by Allen *et al.* (1997) on the basis of gas abstracted. If there is no gas collection, over 90 per cent of the methane generated by a landfill can be lost through surface emissions and the rate of emission on poorly capped sites can match that of generation. Under such circumstances, it can be estimated that non-methane volatile organic compound (NMVOC) emissions will be proportional to methane emissions. But, because of the higher molecular weights and other factors (e.g. higher boiling points), emissions of the heavier, semi-volatile NMVOCs will be subject to the additional effects of soil vapour pressure and Henry's Law partition coefficients (Eklund, 1992).

Modelling landfill gas emissions using HELGA (Environment Agency, 1999c) – the precursor model for GasSim – showed that the bulk of landfill gas produced within the waste will generally flow through the cap, even if this is well engineered. This is in preference to flow through a basal and lateral liner. Only when a cap is installed on an unlined landfill will lateral emissions dominate. This is due to the permeability differences between the waste and the liner, and the relative thickness of the liner.

6.4.2 Lateral emissions

Table 6.7 shows possible pathways for lateral migration of landfill gas. Rates for lateral emissions of landfill gas have seldom been measured, but diffusion-dominated flow is likely to occur over a similar range of values to surface emissions (Figures 6.6 and 6.7). Lateral emissions dominated by advective flow may occur at higher rates. These rates will generally reflect the pressure differential over the pathway and the co-efficient of permeability to gas of the migration pathway, which in turn may be influenced by the mechanical characteristics of the waste deposit, its degree of saturation and the surrounding geology.

Table 6.7 Emission pathways for lateral emissions

Lateral engineering feature or defect
Natural or engineered clay liner
Geomembrane or composite liner with CQA defects
No liner, clay geology
No liner, geology with matrix controlled permeability
No liner, geology with fracture controlled permeability
Landfill with lateral but no basal liner
Vent trench or cut off wall with welded polyethylene membrane
Vent trench or cut off wall with lapped polyethylene membrane
Vent trench or cut off wall with no polyethylene membrane

Emissions of landfill gas through the surface and boundaries of a landfill site are driven by concentration differentials (diffusive flow according to Fick's Law), or pressure differentials (advective flow), or both. Advective flows are promoted by pressure differentials between locations. Slower, diffusional flow will still exist in these situations, but flow will be predominantly advective. However, the impact of the slow diffusional flow of landfill gas into confined spaces should not be underestimated.

It may take many years for the gas diffusing into a confined space to achieve the same concentration as that achieved by an advective plume in a few days. However, both are equally significant, as the build-up of gases can lead to potentially harmful situations.

The probability of detecting a transitory advective plume is low and routine monitoring may only demonstrate transitory anomalies at monitoring points.

Advective gas migration can be caused by rapid differential pressure changes such as the passing of a low pressure weather system over the landfill site, coupled with a highly permeable migration pathway (e.g. a fracture or conduit). It can also be caused by changing liquid levels in the site or by the rapid relief of pressure, which has built up behind a gas barrier (e.g. a clay liner).

Slow advective flow can be represented by Darcy's Law, which gives an empirical relationship between the pressure gradient and the gas velocity for slow flow. Box 6.2 outlines this relationship.

It is evident from this relationship that a large and rapid drop in atmospheric pressure – say 3 kPa (30 mbar) – can provide a significant driving force if the slight positive pressure within a landfill (compared with atmosphere) is only a few kPa (millibars). This effect is much more dramatic if the rate of change of pressure is fast, i.e. it takes place over a few hours than if it takes place over a few days.

Box 6.2 Representation of slow advective flow

$$u = K.\,\Delta P$$

Where:

u = mass flux of gas (m^3 gas/m^2.s)

K = gas permeability of the medium (m^2/s.Pa)

ΔP = pressure gradient (Pa/m)

This was exactly the situation that occurred at Loscoe, Derbyshire, in March 1986, where the sub-surface migration and accumulation of landfill gas caused an explosion that destroyed a domestic property. Modelling Loscoe 'after the event' led Young (1990) and Young *et al.* (1993) to conclude the following qualitative guidelines.

- When the atmospheric pressure is steady, the rate of gas venting is constant and is independent of the atmospheric pressure.
- When the atmospheric pressure is rising, the rate of venting decreases by an amount proportional to the rate at which the pressure is rising.
- When the atmospheric pressure is falling, the rate of venting increases by an amount proportional to the rate at which the pressure is falling.
- The composition of vented gas can exhibit large fluctuations even though the internal gas generation rates and compositions are steady.
- Although the effects are complex, the size of the changes are likely to increase as the moisture content of the site and the migration pathway increases, and as the pH of the leachate and/or groundwater rises.
- The size of the short-term compositional fluctuations will increase as the gas generation rate decreases, i.e. older sites with a relatively small residual amount of biodegradable waste are especially vulnerable to this phenomenon.
- Trace gases show the same variability as bulk gases.
- Within a site, the compositional changes decrease with distance from the surface.
- It is impossible to gauge the state of degradation of the waste in a site from measurements of gas composition taken from shallow monitoring points at a single time or at infrequent intervals.

- Practical experience has shown that the critical rate of fall in pressure is approximately 0.5 kPa (5 mbar) per 3 hours for at least 3 hours. Statistics based on UK monitoring records over the ten years from 1982 to 1991 show that this type of pressure event occurs about six times per year over the UK.

Recent analysis of atmospheric pressure drops at the Building Research Establishment (Hartless, 2000) showed that nearly three-quarters of the top 10 per cent of falls (≥0.35 kPa (3.5 mbars) had a mid-point atmospheric pressure greater than or equal to 100 kPa (1,000 mbar). Landfill gas monitoring should not, therefore, be restricted to periods below 100 kPa (1,000 mbar). Analysis of a 35-year atmospheric pressure data set at Ringway Airport (Manchester) (Young *et al*., 1993) suggests the likely occurrence of an atmospheric pressure fall equal to or greater than that experienced at Loscoe is once every 28 years.

6.4.3 Point source emissions

Point sources of raw landfill gas emissions will include leaks from the gas collection system, monitoring wells, leachate wells and leachate holding/treatment facilities. The actual rate of emissions of landfill gas from these sources is difficult to quantify without measurement of specific cases. Minimisation of such point sources must be carefully managed through regular inspections and routine maintenance as set out in the Gas Management Plan.

6.4.4 Utilisation and flaring plant emissions

During combustion processes, fuel is admixed and reacted with oxidant to produce heat and visible radiation. In landfill gas utilisation and flaring systems, landfill gas is used as the fuel and air used as the oxidant (containing approximately 21 per cent oxygen). The stoichiometric ratio of air to methane for idealised combustion is 9.52:1 with the basic combustion reaction:

$$CH_4 + 2O_2 + 7.52N_2 \longrightarrow CO_2 + 2H_20 + 7.52N_2 + \text{Heat} + \text{Light}$$

If more oxygen is supplied in the fuel air mixture than is required for stoichiometric combustion, then the mixture is termed lean and oxidising. If less oxygen is supplied than is needed for stoichiometric combustion, then the mixture is rich and reducing. The latter condition will result in incomplete combustion and the formation of intermediate combustion products such as carbon monoxide and NMVOCs (Environment Agency, 2004e).

Incomplete combustion may arise from lean mixtures where insufficient turbulence is provided to fully mix the fuel and oxidant, and where the excessive addition of air cools parts of the combustion zone.

The emissions from combustion systems can contain compounds that are:

- derived from an unburnt fraction of the gas;
- products of complete combustion;
- products of incomplete combustion;
- contaminants from lubricants and materials used in the gas extraction and utilisation system and their combustion products;
- contaminants present in the air used in combustion;
- products of pyrosynthesis and pyrolysis during combustion.

The main groups/compounds of emissions associated with landfill gas combustion systems are discussed below.

Carbon dioxide (CO_2) is a component of raw (unburnt) landfill gas and is a product of its complete combustion. It will generally be measurable at percentage concentrations by volume in both the landfill gas and the emissions from combustion plant. The concentrations measured in the emissions from combustion plant will generally be lower than those measured in the raw landfill gas. This is due to its dilution with primary and secondary air introduced during the combustion process.

Carbon monoxide (CO) is a product of incomplete combustion and may be monitored as a measure of combustion efficiency in landfill gas utilisation and flaring systems. Carbon monoxide has been measured at relatively moderate concentrations in the emissions from some landfill gas utilisation plant (Environment Agency, 2004e).

Nitrogen oxides (NO_x) are combustion products derived from the oxidation of nitrogen and nitrogen-containing compounds during combustion. The principal oxide of nitrogen produced during combustion is nitric oxide (NO), but this may be further converted to nitrous oxide (N_2O), particularly during low temperature combustion; the mixture is known as NO_x. Due to oxidation by atmospheric oxygen, NO_x is converted to nitrogen dioxide (NO_2) over a period of time, once emitted into the air. When quoting concentration data for the oxides of nitrogen, the convention is to express them collectively as NO_x.

The three potential sources for the derivation of NO_x in landfill gas combustion systems are:

- oxidation of nitrogen present in the air drawn into the plant during the combustion process;
- oxidation of nitrogenous species (including nitrogen) present in the fuel;

- reactions between nitrogen and hydrocarbon radicals in hot exhaust gases.

Higher concentration of NO_x will tend to be found in the emissions from landfill gas combustion plant when temperatures are higher and the combustion is more efficient.

Oxides of sulphur are oxidation products from the combustion of fuels containing sulphur. Landfill gas can contain a variety of sulphur-bearing species including mercaptans, dialkylated sulphides and disulphides (e.g. dimethyl sulphide and hydrogen sulphide). These species oxidise during combustion to sulphur dioxide (SO_2) and, to a much lesser extent, sulphur trioxide (SO_3) – collectively known as oxides of sulphur (SO_x). These compounds, in turn, may react with water vapour at lower temperatures to yield sulphuric acid.

Hydrogen chloride (HCl) and hydrogen fluoride (HF). These acid gases are produced during the complete combustion of landfill gas from the wide range of chlorinated and fluorinated organic compounds that can be found in the gas. These highly reactive acid gases are associated with accelerated rates of corrosion of plant and equipment in landfill gas utilisation schemes.

Particulates. The majority of landfill gas utilisation systems have filters designed to remove particulate matter above 0.3 to 10 mm in size. This is done to protect the system from adverse rates of abrasion, although some US research suggests that even solids with a diameter of less than 1 mm can result in increased wear. Although a significant fraction of the particulate burden in the gas will be removed before combustion, additional particulate matter may be produced during the utilisation processes and from the plant post-filtration. This matter is likely to include metal salts derived from the corrosion of plant and equipment, and carbon produced by incomplete combustion.

Polychlorinated dibenzodioxins (PCDDs) and polychorinated dibenzofurans (PCDFs). These are thermal products arising from the combustion of materials/fuel containing both organic compounds and chlorinated compounds. Their formation is favoured where the emissions contain particulates (which provide a reaction surface for the formation reactions). PCDDs and PCDFs have typically been found at relatively low concentrations in the emissions from landfill gas combustion plant.

Non-methane volatile organic compounds (NMVOCs). A wide range of organic compounds have reportedly been detected in both landfill gas and the emissions from a variety of landfill gas combustion plant at trace concentrations. The compounds detected in exhaust emissions are believed to derive from a number of potential sources, including:

- residual unburnt fuel
- incomplete combustion
- synthesis reactions within the hot exhaust gases.

A number of the compounds detected in the emissions from utilisation plant have not been reported as components of raw landfill gas used as fuel, suggesting a thermal origin within the combustion system. These include compounds such as benzaldehyde and nitromethane observed in the exhaust emissions from landfill gas fired internal combustion engines and turbines, but not in the landfill gas fuelling such plant.

Typical emissions recorded from a range of landfill gas flares are given in Appendix D. Complete combustion of landfill gas will reduce the impact of emissions whether related to health, environment and amenity. The potential impacts of raw landfill gas and emissions from combustion systems are compared in Table 6.8.

Table 6.8 Comparison of potential impacts of raw landfill gas and emissions from combustion systems

Impact	Raw landfill gas	Incomplete combustion of landfill gas	Complete combustion of landfill gas
Explosion risk	✓✓✓	✓✓	0
Toxicity and asphyxia	✓✓	✓✓	✓
Odour	✓✓✓	✓✓	✓
Phytotoxicity	✓	✓	✓
Stratospheric ozone depletion	✓✓	✓	✓
Global warming	✓✓✓	✓✓	✓
Photochemical smog	✓	✓	✓ to ✓✓✓
Acid gas formation	0	✓✓	✓✓✓

0 = No impact
✓ = Comparatively low potential impact
✓✓ = Comparatively moderate potential impact
✓✓✓ = Comparatively high potential impact

Gas control measures

The following chapter sets out specific measures and techniques for controlling landfill gas, based on the regulatory requirements identified in Chapter 4.

7.1 Design and construction quality assurance

7.1.1 Design

The design of each element of the gas control system needs careful consideration in the context of its end use and site setting. All elements of the proposed control systems should be designed and assessed in accordance with recognised standards and methodologies. These processes should be documented to provide an adequate audit trail.

The approach to the design process should be discussed with the regulator. Designs should reflect the development of the conceptual model.

The design of gas control systems should consider the:

- performance required to achieve the standards derived from the risk assessment;
- context of the elements of the gas control system under consideration, e.g. whether a temporary or a permanent system;
- design life of the elements of the gas control system;
- purpose of the elements of the gas control system and the environment in which they are situated;
- selection of materials and products;
- compatibility of the installed elements of the control system in terms of the phased development of the site, e.g. the sizing of appropriate gas extraction plant for the gas production of the site and not just individual phases or power output;
- operational and maintenance requirements;
- health and safety issues.

Designs should be prepared to a sufficient level of detail to allow them to be easily interpreted and implemented. Where possible, construction should be carried out using commonly available techniques. Where this is not possible, sufficient details should be provided to allow alternatives approaches to be considered.

Designs should be set out using drawings and specifications supported by calculations and method statements.

7.1.2 Construction quality assurance

Construction quality assurance (CQA) refers to the means and actions employed to assure conformity of all the elements of the gas control measures, including installation in accordance with the drawings and specifications. It forms an essential part of site development. The CQA measures applied should be pragmatic and commensurate with the potential consequences of failure of the plant and equipment concerned.

The CQA plan should cover:

- responsibilities
- specification of products and materials
- handling and installation processes
- testing and inspection
- requirements for plant commissioning and trials
- requirements for validation process.

A CQA plan must be prepared for all elements of the control systems (containment, collection and treatment). Following completion of each phase of the installation works, a CQA validation report must be prepared. The report should provide details that the works have been carried out in accordance with the approved designs and CQA plan. It should include:

- details of the nature and extent of works undertaken
- CQA records
- conformance test results
- details of relevant commissioning and trials
- as constructed drawings of the works.

The CQA plan should encompass works set out in the site emergency plan and undertaken as emergency measures.

The installation of site containment (lining and capping) is likely to be undertaken separately from that for gas collection and treatment systems. However, this will not be the case with built-up collection wells installed during site lining and the interface between collection and monitoring wells with the site cap. Depending on the nature of the works, installation should be supervised either by in-house personnel or a third party.

The minimum requirements for the validation of collection and treatment systems in order to demonstrate the integrity of the installed measures at the time of installation (i.e. not to demonstrate on going performance) are as follows:

- visual inspection of pipework prior to covering;
- functional testing of the integrity of pipework (e.g. pressure testing) to an appropriate standard (and commensurate with the function of the pipework as required by the design) to verify competence of the pipework and joints;
- supervising and recording the installation of collection wells;
- surveying the location of pipework, collection wells and other installed control measures;
- establishing that collection pipework and wells have been constructed in accordance with the design, e.g. verifying the correct pipe diameters/well size, well depth, pipe gradients and locations;
- checking that all elements of the collection systems and treatment plant meet the design and the objectives set out in the CQA plan;
- details of plant commissioning and trials.

The preparation of the designs, CQA plan, supervision of installation works and the preparation of the CQA validation report should be undertaken by a competent person in consultation with the regulator.

7.1.3 Phasing

During the planning of site development, consideration should be given to the phasing of:

- landfill lining
- waste placement
- implementation of gas controls (collection and treatment systems)
- capping/restoration.

Site phasing should be part of the conceptual model. This will allow critical stages of site operation to be identified and appropriate control measures to be designed and set out in the Gas Management Plan. The Gas Management Plan must clearly define the sequence of development, operation and capping/restoration.

The emphasis for the control of landfill gas should be to optimise the use of engineered containment in association with gas collection/control. Following waste placement, particular attention should be given to the programming of site capping and the installation of the gas collection and control system.

The following elements should be evaluated as part of the planned development of the site:

- engineering of contained void space to meet the needs of waste placement at the site;
- ensuring measures for gas collection and treatment are implemented to meet the needs of the anticipated rate of development and gas production at the site;
- planning the capping of individual phases to provide the earliest practical gas containment to meet the needs for gas control.

Other constraints such as odour (e.g. collection of landfill gas from operational phases to deal with odour problems), noise and hours of operation also require consideration at all stages of site preparation, operation and development.

7.2 Containment

7.2.1 Lining

The basic requirements for landfill lining are set out in Section 4.2.2. For new sites, they arise from Annex I of the Landfill Directive and Schedule 2.3(2) of the Landfill Regulations as follows:

> Soil, groundwater and surface water is to be protected by the use of a geological barrier combined with:
>
> (a) a bottom liner during the operational phase/active phase of the landfill;
>
> (b) a top liner following closure and during the aftercare phase

All landfills (new and existing) must meet the following fundamental requirements:

- a low risk of trigger levels or emission standards being breached over the whole lifetime of the landfill;
- landfill engineering must have structural/physical stability in the short-, medium- and long-term.

A variety of natural and artificial lining materials are commonly available, although the use of natural materials normally depends upon their availability near the site. Lining materials include:

- engineered clay
- bentonite enhanced soils (BESs)
- geosynthetic clay liners (GCLs)
- geomembranes:
  - high density polyethylene membranes (HDPE) (typically used)
  - medium density polyethylene membranes (MDPE)

  - linear low density polyethylene membranes (LLDPE)
  - polypropylene (PP);
- dense asphaltic concrete (DAC).

The lining systems necessary to fulfil the requirements of the Landfill Directive can consist of a composite of different types of these materials. The use of these lining materials may involve the incorporation of an artificially enhanced attenuation layer such as clay or a BES layer with a geomembrane liner such as HDPE. The lining system should be designed to take account of the development of the conceptual model in relation to the gas permeabilities of the individual components.

The selection of lining types will be driven by the capacity of the lining system to provide groundwater protection as well the containment of landfill gas. Careful consideration should be given during the development of the conceptual model to the choice of the elements of the containment system.

Potential failures in landfill gas control due to seals between the side wall liners and capping being disrupted by settlement should be specifically considered in the design of appropriate monitoring of lining systems. Lining systems should be designed and installed in accordance with the criteria set out in Section 4.2.2.

7.2.2 Capping

Common types of capping materials used include:

- low permeability mineral layers:
  - engineered clay
  - bentonite enhanced sand;
- artificially sealing layer (geomembranes):
  - HDPE
  - LLDPE
  - GCL.

Emission standards (applicable in England and Wales) have been established for permanently and temporarily capped landfills (Environment Agency, 2004d). These should be considered during both the risk assessment and the preparation of the gas control measures including capping design (which will lead to the selection of the capping material). Particular attention should be given at the design stage to the mechanisms by which changes in the waste mass (e.g. settlement) may affect the cap's integrity.

Regardless of whether there is an active gas collection system, surface methane emissions can occur through imperfections in capping systems due to the constraints of construction and the limitations of the materials. The Landfill Directive provides recommendations for capping:

> *If the competent authority after a consideration of the potential hazards to the environment finds that the prevention of leachate formation is necessary, a surface sealing may be prescribed.*

Recommendations include a topsoil cover >1 metre at non-hazardous and hazardous sites. Provision is to be based on a site-specific assessment. A subsoil/top soil layer above the capping layer to provide protection will prevent desiccation cracking and can also be beneficial when the materials permit the oxidation of methane (see Section 7.4.5 for details of this process).

Geomembranes may also require additional protection to prevent puncture, particularly during the placement of the restoration soils. Such protection measures may involve the incorporation of geotextiles, geo-nets or sand layers, which can also function as a drainage layer above the cap.

Preventing point source emissions at the interfaces with the containment system around the perimeter of the site and at engineered features in the cap (e.g. for leachate and gas monitoring and collection wells) should be considered carefully at the design stage. Appropriate methods of monitoring and maintaining the performance of these features, following installation, should be incorporated (see Chapter 8).

Risk assessment and the development of the conceptual model should be used as a tool for the design of the gas containment and collection systems. The capping of unlined landfills may encourage gas migration laterally, and special care must be taken when designing the gas management system for such sites in order that gas can be successfully collected from the entire depth of the landfill. The type of the collection system and the rationale for operation, utilisation and flaring may be considerably different from that for a fully contained site, where the focus on gas migration may not be as significant.

Like lining systems, capping layers should be subject to the same process of design and CQA as described in Section 7.1.2.

7.3 Gas collection

The regulatory requirements for the control of landfill gas are set out in Chapter 4. Before the design and/or installation of permanent gas collection systems, an appropriate risk assessment is required to demonstrate the suitability of the proposed controls.

The following section provides details on the methods and techniques for gas control. The detailed design of pipe networks can be complex and expert assistance is likely to be required to complete the design of this part of the Gas Management Plan.

The layout of the gas collection system should be designed after careful consideration of:

- risk screening and the development of the conceptual model;
- positions of gas collection wells;
- preferred alignment of permanent connection pipework in relation to the pre- and post-settlement profiles, and temporary control pipework during operation of the site;
- the design and sealing of leachate collection systems (particularly how they may affect the efficiency of gas collection by providing routes for air ingress);
- consideration of the need to provide condensate drainage;
- the need to make provision for expansion and contraction of the collection pipework;
- proposed capping and restoration;
- phasing of site operations;
- facilities for routine maintenance and system disconnection.

Guidance on the design and installation of gas collection systems is given in Section 7.1.

Gas pumping trials are often undertaken to establish the performance of the gas collection system, and to assist decisions in the design process and the selection of extraction plant and other equipment.

7.3.1 Collection wells

Networks of landfill gas collection wells are normally installed to enable the removal of landfill gas from the waste in order to achieve the objectives of the Gas Management Plan. Gas wells can either be built up as landfilling proceeds or bored into the waste mass following filling.

A variety of designs is available depending upon site-specific issues such as the depth of waste or the rate of infill (see Figures 7.1 and 7.2). Some use has also been made of horizontal collection wells installed within the waste mass in trenches. The performance of both horizontal and vertical wells is known to deteriorate due to general damage, settlement, biofouling and leachate perching.

If it is not possible to install a permanent collection system, the use of temporary or sacrificial wells should be considered in order to control landfill gas during the operation of the site. Shallow gas probes or 'pin' wells (see Figure 7.2) can be used to give additional or temporary controls in such circumstances and are often used to provide protection against uncontrolled gas movement in areas such as sensitive boundaries prior to capping. However, the effectiveness of such shallow probes/wells should be reviewed regularly. Such collection measures are also not appropriate for the recovery of landfill gas at depth. The installation of shallow probes and pin wells should also be subject to appropriate CQA measures as set out in the CQA plan.

Collection wells are normally formed by the incorporation of perforated pipework, surrounded by a natural stone or crush aggregate with a low calcareous content. Specifications vary, but the materials and products should be suitable for the application in which they are to be used (Cooper *et al.*, 1993).

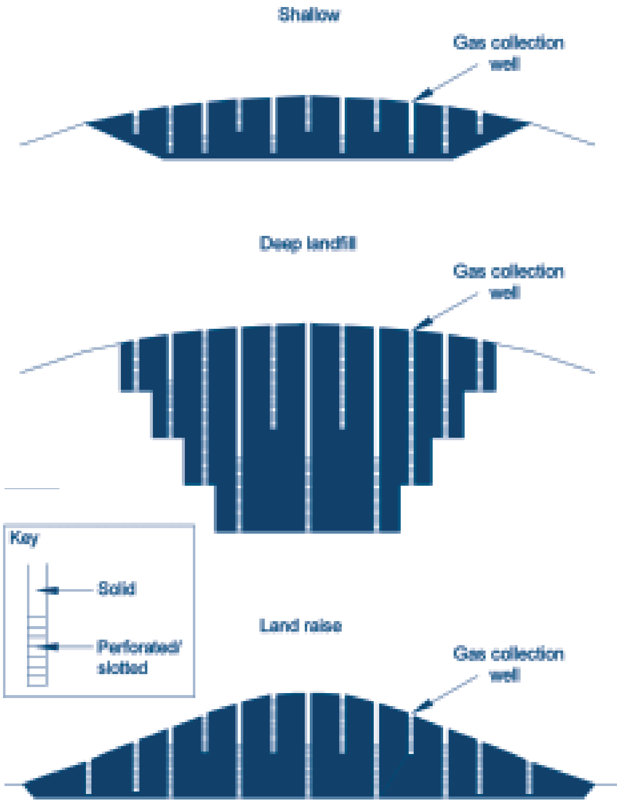


Figure 7.1 Well arrangements for a variety of different landfill site types

Layout

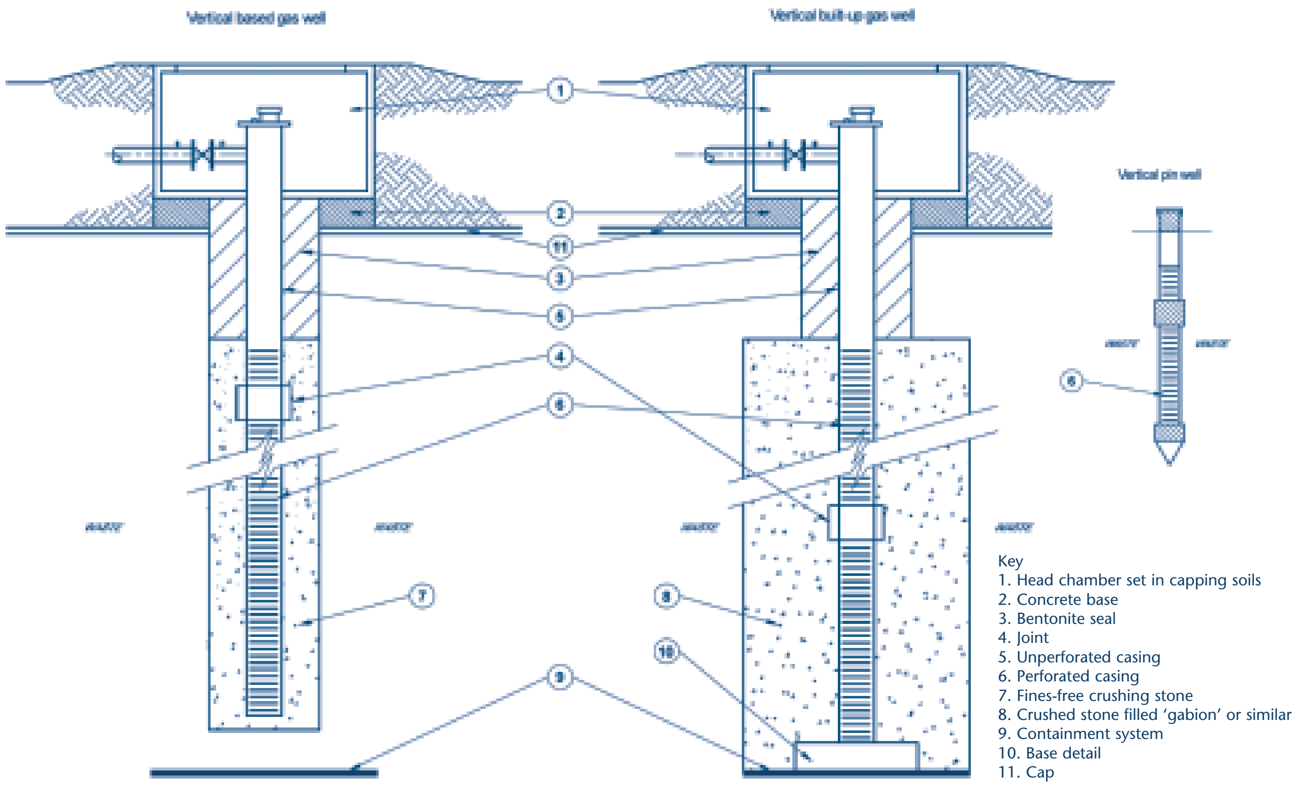
The diameter and spacing of collection wells can vary and will depend on a number of site-specific factors. The layout should therefore be designed using a risk-based approach. Although there are no absolute rules for the spacing of gas wells, it should be typically no more than 40 metres. Closer spacing of collections wells may be necessary to improve control in particularly sensitive areas; this will vary depending on site-specific conditions, the effective zone from which the well will draw gas and the operating protocol for the site. The spacing is also determined by the depth of waste; for instance, in deep sites, nests of wells can be installed at different depths to facilitate the effective collection and extraction of gas.

The configuration of the wells and the depth of the site should be considered carefully at the design stage to ensure that gas can be extracted effectively from the waste mass. The depth, spacing and layout will be dictated by the internal geometry of the site, particularly in land raise or deeper landfills. In such instances, it may be necessary to install wells to a range of depths to provide facilities for collection of the gas from the site at a number of levels. Schematics for some collection well arrangements are shown in Figure 7.1.

The configuration of the gas collection wells must consider the requirements for perimeter collection in relation to lateral migration. This should be balanced with the need to control surface emissions and recover landfill gas from the lower parts of deep landfills.

Where deemed appropriate, the design and layout should incorporate the use of a gas drainage layer. In addition, the design must ensure that migration control is not compromised by the utilisation of landfill gas. Alternative or separate systems may be required to overcome this problem.

Careful consideration must be given to the location of collection wells in relation to the proximity of other engineered features and the requirements for the placement and compaction of waste in these areas. The need to provide measures for the balancing and maintenance of collection wells is another important issue.



Key
1. Head chamber set in capping soils
2. Concrete base
3. Bentonite seal
4. Joint
5. Unperforated casing
6. Perforated casing
7. Fines-free crushing stone
8. Crushed stone filled ‘gabion’ or similar
9. Containment system
10. Base detail
11. Cap

Figure 7.2 Examples of collection well arrangements

Design of wells

General arrangements for examples of gas well types are shown in Figure 7.2. Careful consideration should be given to the selection of well types in relation to the well's function and the collection strategy. This will necessitate designing the collection system and layout for site-specific conditions such as site geometry, operational phasing, waste characteristics etc. – which may vary throughout the operation of the site.

The head of the well, which provides the point of connection to the gas collection pipework and access for monitoring and maintenance, can be constructed using different arrangements depending on the afteruse and/or requirements for access. Typical monitoring facilities at the well head allow for gas sampling, flow rate/pressure measurement and dipping of the well.

Control valves should be incorporated to allow automated or manual adjustments to each well. This can be achieved either at the well or, in the case of manifold systems, through the connection of several wells to a control chamber.

The well head chamber is often incorporated within the restoration layers (i.e. the well head is below the restored ground surface) because of afteruse and/or visual requirements.

At some sites and especially those that have not ceased landfilling, the well head can be built above ground level. This has the advantage of providing simple access for adjustment and monitoring, although it must be protected against accidental damage and vandalism. Alternative arrangements for the connections within the well head chamber and a number of proprietary systems are also available which provide adequate monitoring and control of the gas well. An example of a well head arrangement is given in Figure 7.3.

Constructing collection wells vertically or horizontally during landfilling allows gas to be collected before a particular phase is completed, thus providing greater flexibility in the control of landfill gas at an earlier stage in the site's development.

When designing built up wells, consideration should be given to the instability of the well as a result of waste placement and settlement, which may lead to a deterioration in performance. Proprietary built-up well systems are available in a variety of diameters and can provide an effective solution to settlement difficulties.

Consideration should also be given to the base detail of collection wells, where the interface with the containment system can potentially cause damage.

Retrofitting collection wells by drilling from the surface of the site following waste placement can present a number of potential difficulties in terms of physically installing the well due to obstructions in the waste, the likelihood that point source emissions will be generated during installation, and the need to provide temporary control prior to installation.

Care is also required during the retrofitting of collection wells to ensure that the containment system is not compromised. A distance of at least 1–2 metres should be maintained between the base of the well installation and the containment system. Retrofitted wells should be installed in accordance with code of practice published by the British Drilling Association (2002).

The design detail of the interface between the cap and well should be considered carefully as the integrity of the cap can often be compromised in areas where differential settlement and failure of the cap occurs. Regular inspection for settlement in these areas should be undertaken as part of routine site operations.

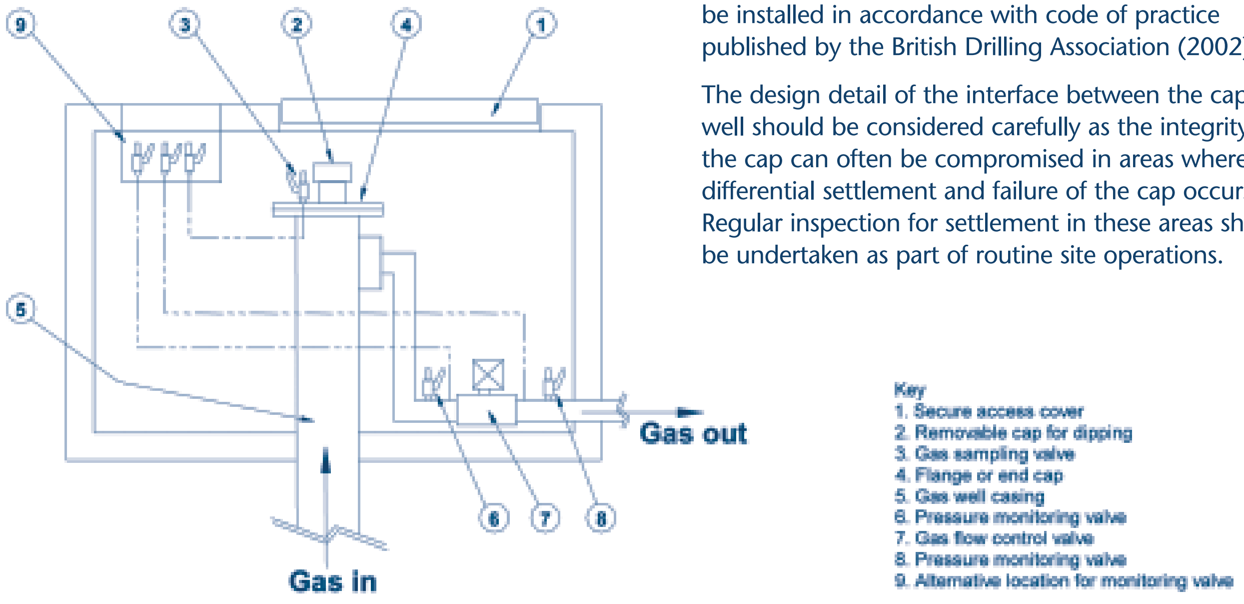


Figure 7.3 An example of a well head arrangement

Operation of wells

In general, gas collection wells should not be used for leachate recirculation due to local saturation of the waste, which can lead to a reduction in the effective (i.e. unsaturated) length of the perforated casing of the well.

The potential deterioration in gas well performance is particularly important. This can arise for a number of reasons, including:

- reduced gas conductance of the waste and stone fill surrounding the perforated casing caused by silting (i.e. the pores become progressively obscured with fines);
- blockage of the perforations in the casing by sediments and bacterial growth;
- overdrawing of gas wells by inducing excessively high flow rates;
- mechanical disruption of the gas well by ground movement or settlement causing a reduction in the cross-sectional area available for gas flow.

It is important to ensure that adequate monitoring and inspection of the wells is undertaken to detect if any of these problems have occurred. In addition, gas well design should make allowance for these various modes of failure. This can be achieved by adopting a pragmatic design based on the following criteria:

- maximising the effective length of the gas well, i.e. by controlling leachate accumulation within the waste mass possibly by extraction from the gas well and, in the case of retrofitted wells, by drilling as deep as practicable without compromising the basal containment system;
- providing contingency measures to maintain consistent operation (e.g. built-in slip-joints or flexible connections at the well head) while allowing for the effects of site settlement on the gas well.

7.3.2 Collection layers

Drainage layers, which can form an integral part of the gas control measures, assist the collection of landfill gas through the incorporation of:

- aggregate layers (sand, gravel, crushed stone);
- geocomposite layers such as geo-nets.

However, the guidance on capping requirements given in Landfill Regulatory Guidance Note 6 (Environment Agency, 2003c) states that the Landfill Directive recommendations for capping can be changed on the basis of a risk assessment. Consequently, a gas drainage layer may not be required at non-hazardous landfills.

When considering the incorporation of the gas collection layer, it is necessary to examine its compatibility with other elements of the gas control measures in relation to:

- how gas will be collected and removed from the layer;
- interface with the cap (protection and deterioration);
- the potential to draw air into the collection system;
- interface and compatibility with other features of the landfill gas collection system;
- settlement of the waste;
- the potential drainage of perched leachate through the drainage layer;
- access for monitoring.

7.3.3 Collection pipework

Connection pipes link the gas collection wells with the treatment system. They provide a controllable means for gas extraction, thus promoting acceptable and reliable gas management. This is normally achieved using various sizes of collection pipes in either HDPE, MDPE or PP. Manufactured lengths of pipes are connected together to form runs to suit the site geometry. Connections can be made using a number of techniques (including butt fusion welding or the use of either electro-fusion or flexible band seal couplings), depending on the function of the pipework, e.g. temporary or permanent.

The layout design should allow for:

- gas monitoring
- prevention of blockage and disruption (by water, leachate or condensates and waste movement)
- routine operations and maintenance tasks.

Provision for the de-watering of pipelines and plant and the management of landfill gas condensate should be considered as part the design of the control system. This should be addressed within the Gas Management Plan.

Undisturbed ground (no settlement) is the preferred location for major or principal pipe runs. During the operational phase, however, collection pipework is often laid temporarily over the filled surface prior to the installation of permanent collection systems, which are normally laid in trenches in the site restoration soils above the capping layer. Measures to protect these temporary arrangements from damage should be incorporated. These may include physical protection such as cones or concrete blocks, and markers such as warning tape or signs. Surface laid pipelines may be exposed to a higher potential for damage arising from high winds and expansion/contraction induced by ambient temperatures. This is likely to necessitate more frequent integrity testing and inspection.

The key factors determining pressure distribution include:

- surface roughness
- gas density
- length
- cross-sectional area
- flow velocity (i.e. the flow rate, in m^3/s, divided by the cross-sectional area of the pipe in m^2).

Compressors and boosters are discussed in Section 7.3.4. Practical experience with existing systems has shown that for ‘long legs’ (i.e. greater than about 5 metres), the flow velocity should not exceed about 10 m/s. This ‘rule of thumb’ results in the selection of 50–100 mm nominal bore (NB) for spurs connecting to well heads, up to 300 mm NB for headers linking multiple wells and up to 450 mm NB for larger headers and ring mains. The operational effectiveness of the connection pipework is related to the integrity of the system, which must be confirmed before commissioning by means of pressure testing as part of the CQA requirements.

Options for connection patterns for gas well fields and well arrangements are shown in Figure 7.4. The most appropriate layout for a particular site will depend upon a range of factors including:

- the availability of undisturbed ground
- the geometry of the site
- the restoration profile and local topography
- environmental constraints that may dictate the location of the processing and treatment plant, e.g. visual intrusion.

The number of variables means that there will be no single solution to the collection layout. Therefore, the approach should be to identify several layouts, which

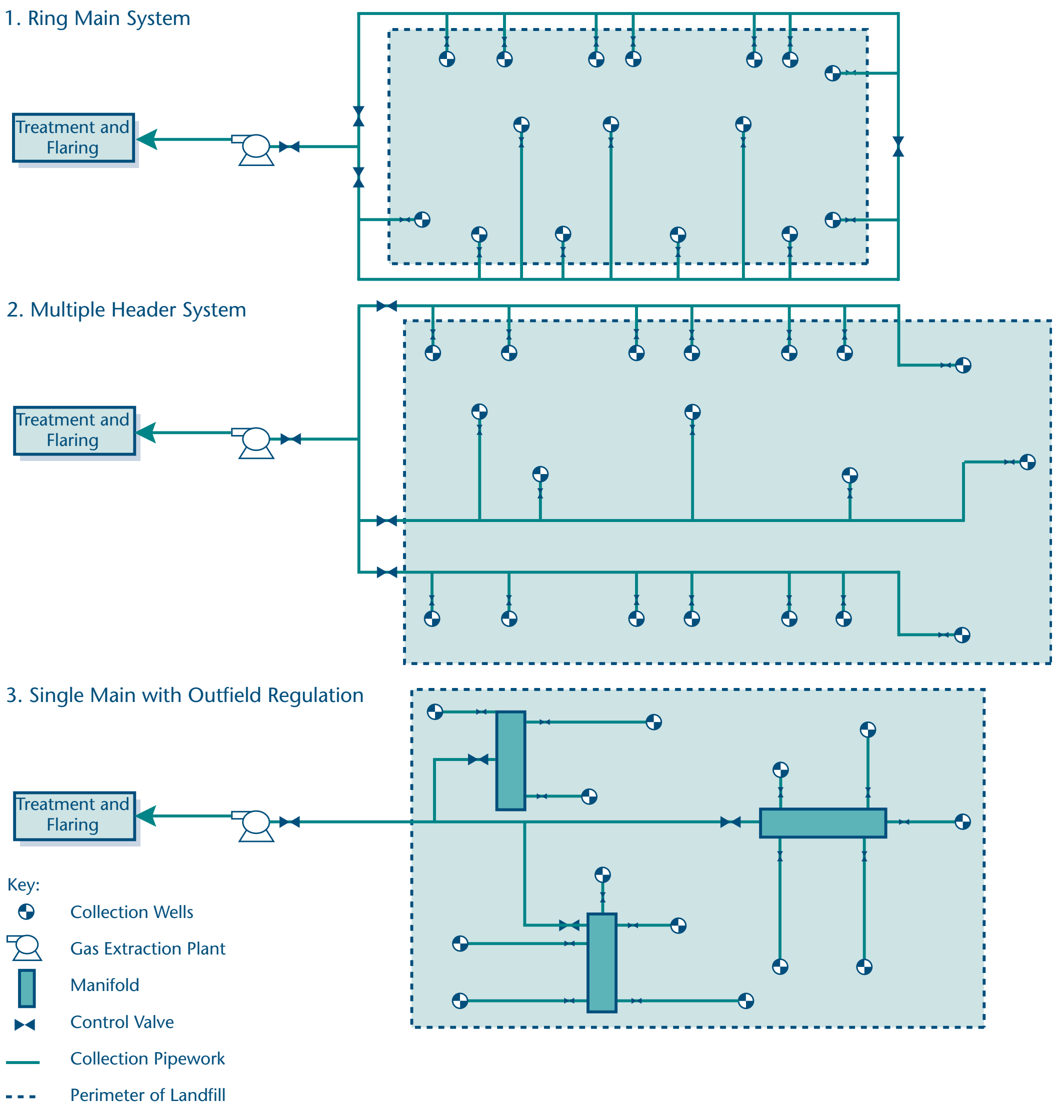


Figure 7.4 An example of landfill gas collection system options

should be reviewed in consultation with site operational engineers before making the final choice. Detailing of the pipe runs in terms of pipe size selection and trench depth can then begin. At this point, the requirement to minimise accumulation of water (condensate) in the pipework should be addressed by incorporating de-watering features such as gravity drains into the site or gas wells. Alternatives include in-line knockout vessels and de-watering manifolds, both of which may either be gravity-drained or pump-discharged.

Consideration must also be given to the well head type and arrangement. In terms of appearance and security (particularly on closed sites), the preference is for below ground designs. However, it will be necessary to provide access at key points for monitoring, maintenance and adjustment.

7.3.4 Extraction plant

Gas must be drawn through the collection pipework to the point of treatment. This is normally achieved by incorporating compressors or boosters to generate a pressure differential, which are capable of overcoming the total pressure loss from the gas wells.

Pressures losses that occur up to the inlet of the compressor are known as 'suction' losses and those from the exit of the compressor to the point of treatment as 'delivery' losses. The magnitude of the suction and delivery losses is a function of the:

- gas flow rate
- length and internal diameter of the pipes
- smoothness of the pipes
- connection arrangements
- viscosity of the gas mixture.

The design strategy should be to select values for suction and delivery pressures from a given compressor or booster type within their range of performance characteristics, and then specify pipework for the required landfill gas flow rate.

A variety of compressors or boosters with individual uses are available in a range of capacities, allowing selection to suit the site's needs. Table 7.1 gives details of some commonly available compressors and boosters.

Centrifugal and regenerative machines are commonly used as they are well suited to typical requirements for landfill gas extraction. Incorporating other processes prior to utilisation or flaring (e.g. deliquescent dryers or filters) introduces additional pressures, thus increasing the requirement for suction capacity. In this case, it may be appropriate to use higher pressure rated machines such as roots blowers and, less frequently, reciprocating compressors.

Care should be taken when selecting both the extraction equipment and the type of collection control systems to prevent over extraction as this can draw air in to the waste and present a fire hazard. Fires can also be caused by damaged or poorly functioning gas collection systems that permit air to be drawn into the waste. The gas collection system and the cap should be well engineered and maintained to prevent fires.

Table 7.1 Examples of types of compressors and boosters

Type	Typical flow rate (Nm^3/hour)	Typical pressure rise (mbarg)	Comments
Single-stage centrifugal booster	2,000	130	Well suited to landfill gas extraction and by far the most common machine used. Low maintenance costs and tolerant of 'dirty' gases.
Two-stage centrifugal	2,000	200	Well suited to landfill gas extraction and supply to booster consumer. Frequently used to supply electricity generating sets.
Regenerative booster	1,000	200	Suitable for landfill gas, although much less frequently used than centrifugal boosters.
Roots blower	1,000	1,500	Occasionally used for landfill gas to supply generators. Positive displacement machine that does not tolerate liquid water.
Sliding vane rotary compressor	1,000	1,000	Similar to Roots machines. Relatively high operating and maintenance costs.
Reciprocating compressor	1,000	>50,000	Capable of very high supply pressures. Have been used to feed gas processing systems. High operating and maintenance costs.

Regular monitoring of the gas collection system will also facilitate the prevention and early detection of fires, enable balancing of the gas field and ensure that landfill gas is being extracted efficiently with due regard for migration.

7.3.5 Condensate management

The conditions which lead to the formation of landfill gas give rise to a gas mixture at a temperature typically in the range 30°C to 40°C, with a relative saturation at or approaching 100 per cent. When the gas stream cools, water vapour condenses to form 'condensate' which can accumulate in collection pipework. In addition, actively drawing landfill gas from a gas well can, under certain conditions, give rise to liquid entrainment, usually in the form of a froth or foam.

Liquid condensate or leachate in gas pipelines reduces their effectiveness and can even lead to complete blockages and major disruptions. Therefore, measures should be incorporated into the gas management system to reduce and control liquid accumulations.

The basic approach to condensate management focuses on eliminating liquid directly from the gas collection pipework using a combination of:

- well head de-watering
- low point drainage through water-sealed traps
- collection and disposal at either a knock-out vessel or at one of a series of drained manifolds/points.

Details of a typical condensate drainage point are shown in Figure 7.5.

Effective design relies on setting pipe runs to fall towards drainage points typically with a minimum gradient of 2 per cent. If such falls cannot be achieved due to the constraints of either the restoration profiles or available land, then the pipework can be stepped to give a 'saw-tooth' alignment. In this case, a 'drop-leg' is incorporated at appropriate intervals along the pipework from which water can be drained.

A typical arrangement for incorporating condensate drainage in gas collection pipework is shown in Figure 7.6.

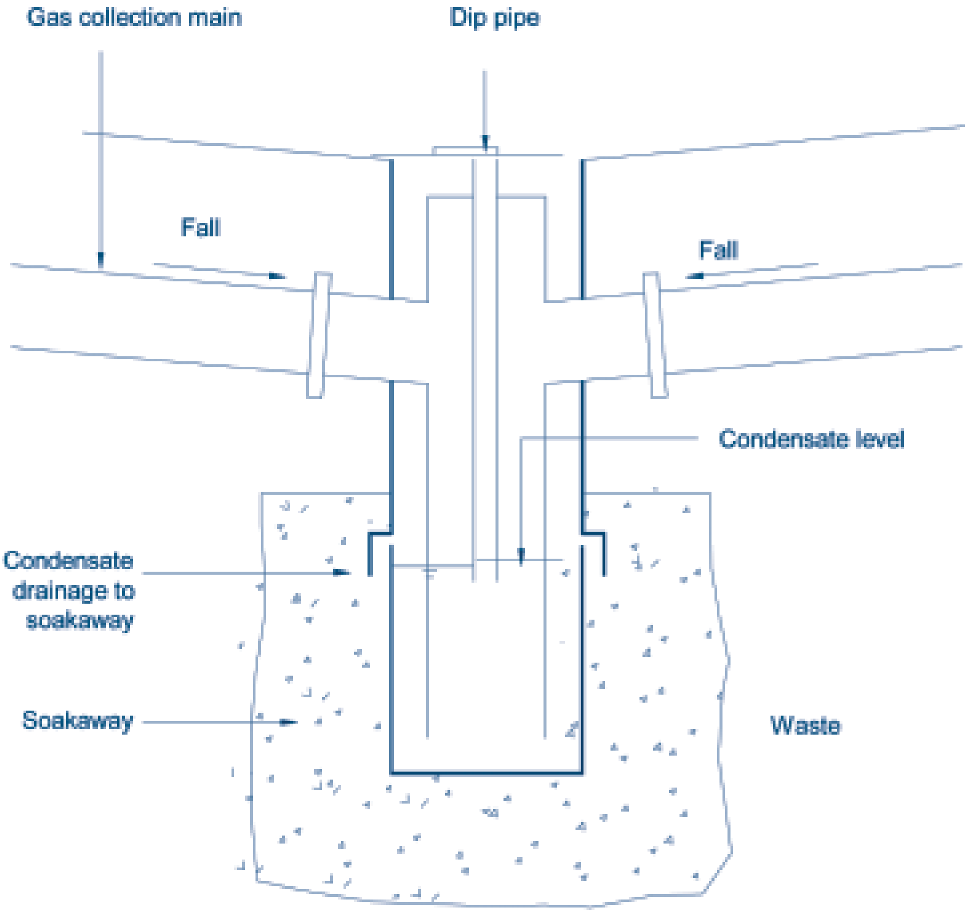


Figure 7.5 Typical condensate drainage point

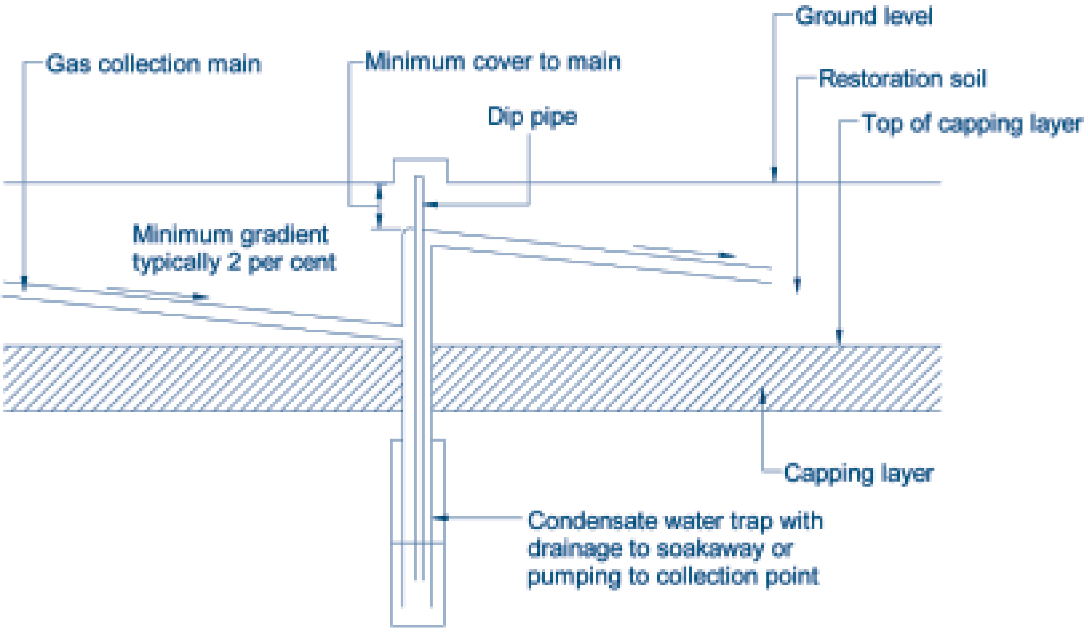


Figure 7.6 Typical condensate drainage collection pipework

Note: water traps may be equipped with pumps for condensate collection where soakaways are not used

If the condensate is removed on-site, then it can be recirculated within the waste (if this is allowed). If the condensate is taken off-site for disposal as a controlled waste, it should be handled and managed according to its properties.

Due to its potentially corrosive nature, the properties of the condensate should also be considered when designing and specifying elements of the control and treatment system. This presents a number of difficulties in terms of system performance/failure, e.g. the deterioration of valves and other plant, and/or the leakage/loss of lubricating oils into the gas stream due to the failure of seals. The properties of the condensate should also be considered in terms of health and safety, particularly in relation to dermal contact during maintenance.

Typical properties of landfill gas condensate are given in Table 7.2.

Table 7.2 Typical characteristics of landfill gas condensates*

	Plant/flare		Gas field drains	
Parameter	**Typical upper value**	**Typical lower value**	**Typical upper value**	**Typical lower value**
pH	7.6	4.0	3.9	3.1
Conductivity	5,700	76	340	200
Chloride	73	1	4	<1
Ammoniacal nitrogen	850	<1	15	3
TOC	4,400	222	9,300	720
Chemical oxgen demand (COD)	14,000	804	4,600	4,600
Biochemical oxygen demand (BOD)	8,800	446	2,900	2,900
Phenols	33	3	17	4
Total volatile acids	4,021	141	4,,,360	730

* All values in mg/litre except pH (dimensionless) and conductivity (µS/cm)

Adapted from Knox (1990).

7.4 Utilisation, flaring and treatment

Additional levels of primary treatment/supplementary processing should be introduced when the gas is to be used as a fuel. These can include:

- filtration
- drying (or ‘conditioning’)
- higher pressure boosting
- after-cooling
- gas composition adjustment.

Another consideration is treatment to remove potentially corrosive trace contaminants such as organochlorides, organofluorides and hydrogen sulphide (see Environment Agency, 2004c).

Utilisation and flaring involves the combustion of landfill gas – with recovery of the energy content, where appropriate – to form an off-gas, which is acceptable for direct discharge to atmosphere. At sites producing landfill gas where it is not possible to generate energy, the minimum requirement is flaring – sometimes with the use of time switches to deliver intermittent flaring.

Treatment of the gas stream either pre- and/or post-combustion may be required to meet the emission limits for the processes identified above. This will be a site-specific issue based on the precise composition of the gas stream and will not constitute the norm.

Useful information on the overall approach to landfill gas processing and treatment is given in a report produced by ETSU for Dti (ETSU, 1996).

7.4.1 Gas treatment and supplementary processing

Larger or more complex landfill gas management systems, and especially those supplying gas to a consumer, require additional treatment to provide greater control of the condition of the delivered gas. There is no single standard system and the nature of the treatment will generally be defined in the form of a specification covering the following issues:

- a minimum supply pressure;
- the target calorific value or Wobbe index (see Glossary);
- the supply temperature, dew point or specific moisture content;
- entrained particle size limits;
- gas composition restrictions (e.g. proportions of corrosive gases such as hydrogen sulphide);
- combustion characteristics such as oxygen content and flame speed.

Further details on gas treatment and supplementary processing are given in Environment Agency (2004c).

7.4.2 Process control

The aim of a process control system is to ensure that the design ratings and parameters of the control system are adequately achieved and maintained. In the context of primary processing, the key variable is the flow rate of landfill gas, which in turn is governed by the values of the suction and delivery losses. The principal control variable is pressure, for which there is a range of measurement equipment options.

Pressure control can be achieved using several different valve types and may be either manual or automatic (balancing). For small and relatively simple gas management systems, manual control can be adopted. Automatic pressure control relies on a spring-controlled diaphragm to adjust the position of the valve seat in response to continuous sensing of the supply pressure.

The most commonly used valves are of the butterfly type, although the use of ball valves and gate valves may also be appropriate.

A key requirement for any control valve in a landfill gas management system is an appropriate level of corrosion protection. In practice, this has led to the use of an all-plastic (polyethylene) construction or stainless steel/aluminium–bronze discs and spindles and polymer-coated bodies.

The use of automated control reduces operational input and these systems when linked, via telemetry, can provide an effective means of systems monitoring. There is, however, a need to ensure appropriate levels of regular monitoring, inspection and maintenance when such systems are used and these should be clearly set out in the Gas Management Plan.

7.4.3 Utilisation

Key factors that should be considered during the design of the utilisation plant include:

- composition of the raw gas extracted/used from the landfill;
- level and type of pretreatment or conditioning applied to the gas prior to its supply to the combustion equipment (e.g. water removal and filtration);
- type of combustion equipment used (e.g. internal combustion engines with wet or dry manifolds, gas turbines, etc.);
- temperature of combustion;
- set-up and maintenance of the combustion equipment;
- fuel to air ratio applied during combustion (which will affect the amount of excess air, if any, available and hence the completeness of oxidation reactions);

- use of secondary or quenched air;
- potential post-combustion treatment of emissions and recirculation of exhaust.

Although direct use of the thermal energy is technically relatively straightforward, there are few situations where a consumer is located close enough to the source of the landfill gas to justify cost-effective supply. Utilisation schemes in which the thermal energy is used to generate electricity, which is then exported, are much more common. Another option for utilisation is the clean-up and storage of landfill gas for use as a vehicle (or mobile plant) fuel. Other applications for landfill gas utilisation are given in Table 7.4.

Utilisation of landfill gas for electricity generation has proved popular owing to the incentive provided by the Non Fossil Fuel Obligation (NFFO) and, more recently, by the policy on new and renewable energy as laid down by the Renewables Obligation (Dti, 2000) and the Renewables Obligation (Scotland) Order (Scottish Executive, 2002b).

The most common technology employed in the UK for electricity generation is the spark ignition engine. This type of engine accounts for over 86 per cent of recent landfill gas to energy schemes in the UK.

The processing and treatment of landfill gas intended to fuel electricity generators is broadly the same as for other thermal utilisation processes. However, the specification for moisture content may be tighter, requiring careful design of gas conditioning and prevention of downstream cooling (which could give rise to condensation). This requirement is especially relevant to turbocharged spark ignition engines fitted with fuel–air control devices.

A further requirement may be the control of potentially corrosive compounds or components, which can have an adverse effect on lubricating oil characteristics. Hydrogen sulphide, organofluorides and organochlorides all fall into this category. The acceptable limits for concentrations of such components have generally been determined through operating experience. Engine manufacturers frequently list values in fuel specifications for their particular machines and offer warranties based on defined gas compositions. This issue should be given careful consideration when selecting the plant and equipment, as it may give rise to operational limitations and should be established during gas production trials. Typical upper limits of selected trace compounds in gas utilisation plant are given in Table 7.3.

Table 7.3 Typical upper limits for some trace compounds in landfill gas utilisation plants

Parameter/component	Typical upper limit
Sulphur dioxide	0.1 mg/m^3
Hydrogen sulphide	25 mg/m^3
Total organosulphur compounds	150 mg/m^3
Total organofluorine compounds	25 mg/m^3
Total organochlorine compounds	60 mg/m^3
Supply temperature	T_{sat} + 5°C
Particles	7 µm

Note: T_{sat} = temperature at saturation

Treatment options for reducing the concentration of corrosive components in landfill gas are available. The most common approach taken by operators is to implement a carefully formulated monitoring protocol and relate the findings to planned maintenance of the engine. For example, monitoring and frequent changing of lubricating oil can be adopted to overcome the effects of corrosive volatile compounds (Fisher, 1992).

Further guidance on the technologies associated with the clean-up of landfill gas are given in Environment Agency (2004c). Consideration should be given to the location of utilisation plant; the impact of exhaust gases needs to be evaluated through risk assessment before finalising its design and location.

7.4.4 Flaring

The final stage of processing in the absence of utilisation is thermal oxidation of the landfill gas in a flare. Flares are also used as a standby process to treat gas in periods of utilisation downtime.

The capacity of the flare system must be compatible with the operational parameters of the site over time. This is particularly important where flares are used in conjunction with utilisation as a standby or control for excess gas. The operating rationale should be clear and risk-based in relation to such scenarios.

Historically, open diffusion type flares have been used to flare landfill gas. These types of flares are no longer acceptable as they do not ensure consistent combustion and cannot be monitored. More sophisticated designs must be adopted in order to achieve permanent control, enhance thermal destruction efficiency and minimise the formation of secondary pollutants. Technical guidance on landfill gas flaring has been produced by the Agency (Environment Agency, 2002d), which sets out the requirements for flare selection and design. Monitoring methods and emission standards can be found in other Agency guidance (Environment Agency, 2004b).

Maximising the thermal destruction efficiency and minimising the yield of NO_x can be achieved by careful control of combustion air and imparting a high level of turbulence upstream of the flame front. Flares are manufactured using a range of proprietary designs with varying capacities and with appropriate monitoring facilities. The use of low calorific thermal oxidation systems provides a method of providing gas control during the early and the later stages of gas production at landfill sites with as little as about 1 per cent methane.

Other design elements that should be considered include the height of the stack, the requirement for appropriate retention times and the incorporation of appropriate sampling ports. Current practice (often governed by planning constraints) is normally based on minimising the visual intrusion of the unit without sufficient consideration of the plume dispersion characteristics or noise.

These are key matters that must be addressed and further guidance on noise is provided by IPPC Horizontal Guidance Note H3 (Environment Agency, 2002g). The optimal stack height will depend on the:

- exit velocity
- pollutant loading
- retention time required (typically 0.3 seconds at 1,000°C)
- location of the flare in relation to receptors
- surrounding topography.

Dispersion modelling should be performed before finalising the design and location of the flare.

7.4.5 Methane oxidation

Microbial populations in soils can oxidise a proportion of the methane passed through them. This has been shown in both field and laboratory studies (DoE, 1991b; 1991c). The Agency is undertaking research into the role and practicalities of methane oxidation at landfill sites (Environment Agency, 2002h).

The percentage of methane oxidised depends very much on the residence time of landfill gas in the soils and the volume of landfill gas fluxing through the surface. Availability of oxygen to the site of oxidation is the rate-limiting step for the process.

The microbial population responsible for methane oxidation can develop in the capping/restoration layers or in the host lithology and soil surrounding the site. The factors that can influence the extent of microbial oxidation include:

- ability of oxygen to permeate soil to reach site of oxidation, i.e. the permeability of the cover soils and host lithology;
- thickness and condition of the cover soils above any engineered cap (or waste if there is no engineered capping layer);
- rate of landfill gas flux through the soil;
  design of the lateral and capping liners, and the types and distribution of defects in those lining systems;
- presence or absence of cracks in the cover soils, or fractures in the host lithology;
- biochemical factors such as nutrient availability, soil pH, temperature and moisture content.

Methane oxidation will have a role in the management of landfill gas control where the following conditions exist:

- the landfill is toward the end of its gassing life and active gas collection is unable to collect a gas of sufficient quality for flaring, even using low calorific thermal oxidation systems;
- soil cover is well aerated;
- soil cover can be inspected regularly to ensure cracks are absent and the soil structure is maintained to a good standard.

Biological methane oxidation as the sole management tool for controlling methane emissions is, therefore, only potentially suitable for those sites which are significantly beyond the peak of their gassing life or where other active forms of gas control will not perform effectively. However, the benefits of methane oxidation should not be ignored at any site.

7.4.6 Other mechanisms for treatment and utilisation

Although uses of landfill gas are generally limited to electricity and heat generation there are others. Forbes *et al.* (1996) describe two processes used in the USA for the clean-up of landfill gas to yield methane for use as a vehicle fuel. One process produces a compressed form of methane and the other produces liquid methane. These novel uses, together with other uses are summarised in Tables 7.4 and 7.5.

7.4.7 Support fuels

It may be necessary to use a support fuel that can be injected either intermittently (on demand) or continuously into the flare in situations where:

- it is critical to maintain extraction, collection and flaring of landfill gas;
- the gas composition is insufficient to sustain efficient combustion.

In such cases, the use of liquefied petroleum gas (LPG) or natural gas or, exceptionally, light gas oil, can be used.

Consideration should be given to the gas control strategies, the cost of operation and sustainable development issues when gas production is low. The use of support fuels may not be the most appropriate solution to sustaining gas control, and options such as intermittent extraction and flaring (which are often preferred), or the use of low calorific flares and methane oxidation provide other alternatives.

Table 7.4 Other options for landfill gas utilisation

Utilisation option	Technology	UK application	Applications elsewhere
Current applications			
Space heating	Boilers	Limited	Limited
Industrial process energy and heat	Kilns Furnaces Boilers	Moderate	Limited
Electricity generation	Internal combustion engines	Very common	Very common
	Dual fuel compression engines	Moderate	Moderate
	Gas turbines	Limited	Common
	Steam turbines	Limited	Moderate
Pipeline and gas grid use	Gas purification	Limited	Moderate
Future applications			
Electricity generation	Fuel cells	No commercial application known	Pilot-scale
Vehicle fuels	Purified compressed fuel	No commercial application known	Pilot-scale

Table 7.5 Other landfill gas products and processes

Product/process	Description/comments	Project yield (m^3/hour)
Compressed methane	Three stage compression to 35 barg. Trace components removed by absorption on carbon. Carbon dioxide removed by cellulose acetate membrane separation. Methane product compressed to 245 barg	Sufficient for fuelling 13 municipal vehicles
Liquefied methane	Initial compression to 34 barg followed by removal of trace components (as above). Carbon dioxide, water, oxygen and nitrogen removed by polyimide membrane separation. Product cooled and compressed to liquefy the methane.	1.6
Fuel cell	Complex pretreatment of landfill gas to remove sulphur compounds and halides. The cleaned gas is fed to phosphoric acid fuel cell producing direct current electricity and process heat.	0.2 MW_e
Reticulation	Process of gas clean-up stripping non-methane components to provide gas with higher calorific value.	No information available
Solid carbon dioxide	Uses the triple point crystallisation process.	1.0 tonne/hour

MW_e = MW electricity
Barg = Bar gauge

7.4.8 Operation and maintenance

The operational procedures of a landfill gas management system should be set out in the Gas Management Plan (see Chapter 3). The procedures should include:

- reference to the conceptual model providing justification for system as built;
- a system description including full as-built drawings together with a record of all subsequent changes to the as-built design, which should include:
  - location specification and construction details of all collection wells, collection pipework, manifolds, valves, etc.;
  - details and process description of gas extraction, utilisation, supplementary processing and flaring plant;
  - operational parameters for all elements of the gas control system;
- a complete set of all commissioning measurement data;
- operating instructions for each element of the gas management system;
- commissioning into service and out of service procedures for each element of the gas management system;
- a specification for routine operational monitoring for each element of the gas control system including details of the parameters to be measured, the measurement precision required and the frequency of measurement (see Chapters 5 and 8);
- a register of all routine adjustments, e.g. control valves;
- a record of all non-routine incidents;
- health and safety instructions for routine operation and further guidance on procedures to adopt in the event of accident or emergency (see Chapter 2).

The successful operation of the system relies on routine monitoring and inspection. Therefore, all measurement data should be subject to careful inspection, checking and interpretation on an ongoing basis. In addition, the measurement data should be subjected periodically to a detailed appraisal and the results compared with the conceptual model and the objectives of the monitoring plan. Any inconsistencies should be investigated in consultation with the regulator and the conceptual model, and the Gas Management Plan should be modified to provide the necessary protection of the environment and human health.

The effectiveness of a landfill gas management system relies on consistent and thorough ongoing maintenance. Failure to adopt a planned preventative maintenance programme may lead to deterioration in the performance of the management system and unacceptable emissions. A fully documented monitoring, inspection and maintenance programme should therefore be included in the Gas Management Plan. The programme should include:

- detailed inspection programme with inventories and frequencies including:
  - responsibilities for monitoring, inspection and maintenance;
  - daily, weekly, monthly requirements, etc. for monitoring, inspection and maintenance;
  - procedures for documenting and reporting of faults;
  - procedures for implementing corrective actions;
- a register of fault conditions and the corrective actions taken to overcome the faults;
- details of routine repairs and replacements;
- review requirements for fault conditions and repairs;
- an inventory of all replacement parts and contact details for relevant suppliers and manufactures.

Personnel responsible for the operation and maintenance of the gas management system should be fully conversant with operational procedures, and safety and maintenance programmes.

Monitoring

This chapter sets out specific measures and techniques for the monitoring of landfill gas, based on the regulatory requirements identified in Part A. A monitoring and sampling plan should be developed as a result of the conceptual site model as part of the Gas Management Plan as outlined in Section 3.3.3. Landfill gas monitoring should be undertaken for the following main components:

- source
- emissions
- air quality
- meteorology.

8.1 Source monitoring

The aim of source monitoring is to characterise the quantity and quality of the gas in each section of the landfill. Routine monitoring to determine the composition of this gas is typically undertaken using portable hand-held instruments. These instruments measure the bulk components within the landfill gas and associated physical parameters. Information on the techniques that can be used for this routine monitoring is given in guidance on the monitoring of landfill gas published by the Institute of Wastes Management (IWM, 1998).

Two different types of source monitoring points are found on landfill sites: collection wells and monitoring wells. These are discussed below.

As well as monitoring gas concentration, composition and pressure, gas flow rates should also be monitored in order to achieve sufficient control over gas extraction and utilisation systems. Flow rates from active gas extraction wells can range from a few to several hundred cubic metres per hour.

8.1.1 Collection wells

Collection wells and associated manifolds are monitored to determine the effectiveness of the gas extraction and collection system. Monitoring also facilitates the balancing of the gas collection and extraction system. The recommended frequencies and determinands for monitoring collection wells are given in Table 5.4 (in Chapter 5).

Collection well monitoring is essential for the efficient management of an extraction system. If monitoring results show that the expected performance is not being achieved, the system should be balanced and/or actions set out in the contingency plans implemented.

8.1.2 Monitoring wells

Monitoring wells are those constructed within the landfill for the purpose of monitoring landfill gas concentrations and fluxes within the waste mass. This is a requirement of the Landfill Regulations and should enable the landfill gas to be characterised for each section of the landfill.

These wells are independent of the gas collection and extraction system, and are used as dedicated monitoring points solely for the purpose of ascertaining the composition of landfill gas and how it responds to environmental conditions.

Leachate monitoring or extraction wells may also be used for gas monitoring purposes and assisting with the establishment of gas production rates. If such monitoring points are used, however, they cannot be regarded as comparable with, or even a substitute for, specifically designed gas monitoring points within the waste mass. At depth, the measurements obtained may be affected by partial or complete blockages of perforations originally provided within the well. Where these perforations are covered by leachate, the measurement may only be the concentration of gas within the headspace.

Care should be exercised during the installation and maintenance of gas monitoring points to ensure that these are appropriately sealed and do not provide routes through which air ingress can occur.

8.1.3 Pressure monitoring

Atmospheric pressure is an important parameter to consider when checking source monitoring points. Atmospheric pressure should be measured regularly in order to aid understanding of gas pressure readings within the waste body. Rapid drops in atmospheric pressure can result in the pressure of landfill gas being significantly above that of ambient atmospheric pressure, resulting in possible migration. The monitoring of pressures within the waste mass gives an indication of the likelihood of gas migration occurring.

The rate of change of pressure, both within the waste mass itself and atmospheric pressure, can significantly affect the migration of landfill gas. Monitoring of gas pressure within the waste mass provides a way of measuring the following parameters.

- **Total pressure** – the pressure of landfill gas within the pores of the waste fill. Trends in total pressure can be used to ascertain whether the gas collection system is managing the gas generation within the fill. Total pressure within the waste mass can be subject to wide variations.
- **Rate of change of total pressure** – this depends on the rates of formation and dispersion of the gas, along with the changes in atmospheric pressure. A rapid positive rate of change indicates that the gas collection system does not have the capacity to manage the gas generated under falling atmospheric pressure conditions. A falling rate of change of total pressure, coupled with air ingress, indicates that the gas field is being over pumped.

Pressure and composition monitoring within the waste requires the installation of permanent sampling points distributed at selected locations. Infrequent measurement of gas concentrations and a failure to take barometric pressure readings at the time of sampling will make it difficult to demonstrate whether the gas readings were taken over falling, rising or steady atmospheric pressure conditions. Atmospheric pressure should be monitored constantly or regularly (e.g. hourly) to make proper use of the pressure data. This can be achieved using an automated weather station.

The required pressure monitoring frequencies are given in Table 8.3. Both the parameters to be monitored and the frequency of monitoring should be set out in the Gas Management Plan.

8.1.4 Trace components

A large number of substances are present at trace levels in landfill gas. These compounds contribute significantly to the potential odour and health impacts of the landfill gas. The regulator has identified a number of priority compounds that should be measured in landfill gas and has issued guidance on appropriate sampling and analytical methods for these compounds (Environment Agency, 2004f).

Much of this monitoring involves laboratory analysis of samples taken from the gas collection system. The monitoring is undertaken far less frequently and from fewer locations than the measurement of the bulk gases. The sampling point must be selected so that the gas is representative of the landfill or a particular section of the landfill, e.g. taken from the gas main line. The sample should also be taken at a time when the gas collection system is at or near steady state conditions.

8.2 Emissions monitoring

Emissions monitoring on landfill sites will typically consist of:

- surface emissions
- lateral emissions
- combustion emissions.

8.2.1 Surface emissions

Monitoring of methane gas emissions from the surface of the landfill is undertaken to:

- identify faults in the gas management system and to prioritise the remediation required,
- measure the total emissions from the site of methane, an important greenhouse gas involved in global warming.

A qualitative estimate of methane emissions through a surface cap can be made using a hand-held instrument such as a flame ionisation detector (FID). However, very low flux cannot normally be detected and localised on a landfill cap. Extensive research suggests that the flux box is currently the most cost effective technique for the verification of the range of surface emission sources typically found on a landfill site. Flux boxes are enclosed chambers (see Figure 8.1) used to measure the rate of change in methane concentrations above a specific, small area of the landfill surface. By measuring the flux at a number of representative sampling points, an estimate can be made of the total emissions from a zone.

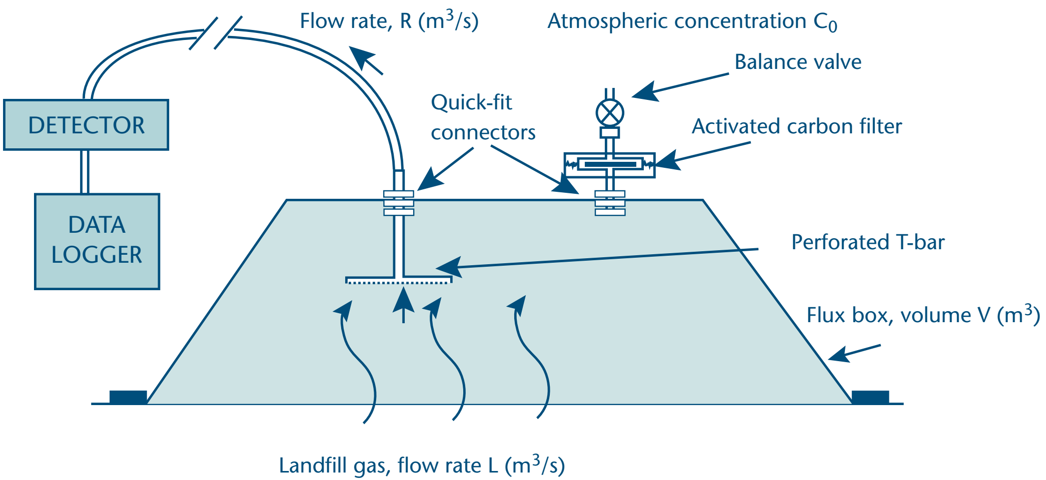


Figure 8.1 Schematic of a flux box for surface methane emissions measurement (adapted from Environment Agency, 2004d)

Table 5.4 gives typical frequencies at which surface emissions of landfill gas should be monitored. A method for the measurement of landfill methane emissions using a flux box is set out in the guidance for monitoring landfill gas surface emissions (Environment Agency, 2004d). The key steps for surface emissions monitoring are shown in Figure 8.2.

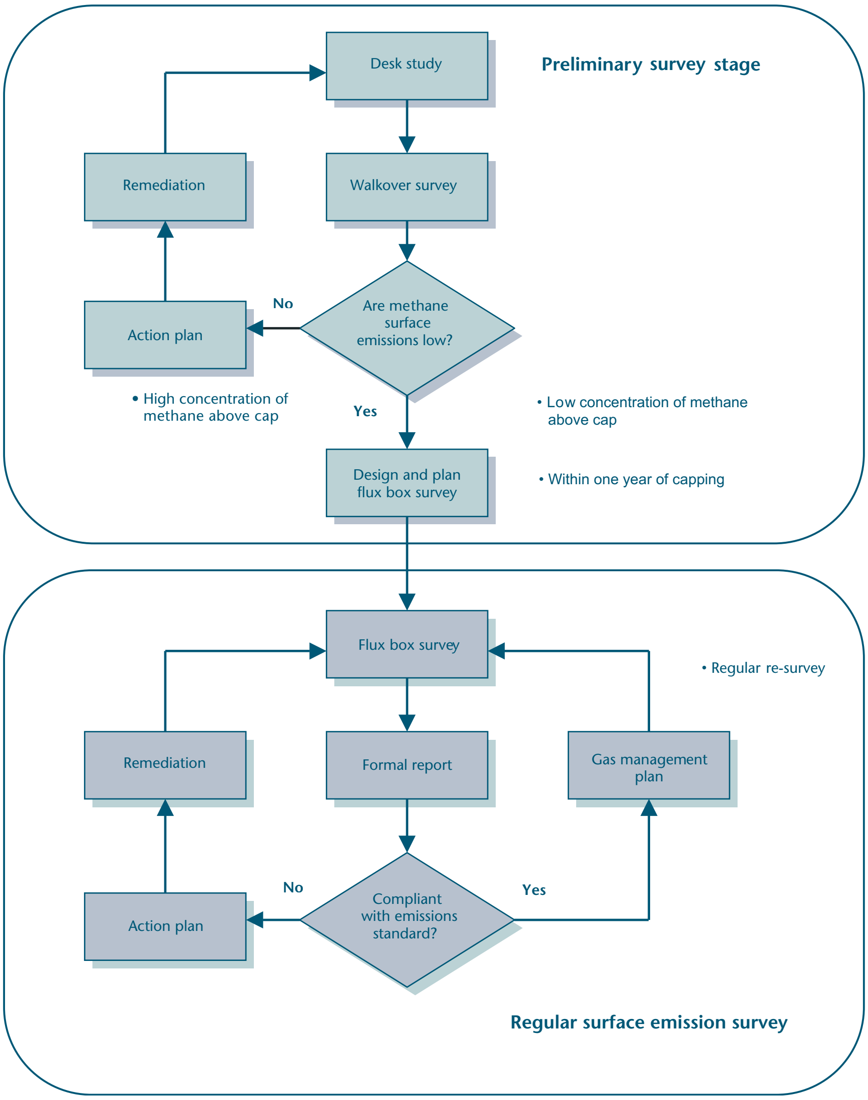


Figure 8.2 Process of surface emissions monitoring

Source: Environment Agency, 2004d

The first step is a desk study to obtain the history of the waste disposal activities at the site and details of the capping and gas control measures. Appendix 4 of the monitoring guidance (Environment Agency, 2004d) contains a proforma which gives a comprehensive guide of the parameters to assist in the characterisation of a site.

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

- A preliminary stage using a portable FID to identify inadequacies in the gas containment and collection system.
- A quantitative survey stage when the flux of methane emitted through the intact cap is measured using an array of flux boxes.

Using information from the desk study, a walkover of the site is conducted to identify any zones or features where a relatively high concentration of methane can be detected. The zones should then be traversed in a systematic manner using a FID, held as close to the surface of the landfill as possible. A global positioning system is frequently used to assist in the mapping of the zones. High concentrations of methane at locations on the cap indicate inadequacies in the gas containment and collection system. Only when these deficiencies have been remedied and there is a low concentration of methane above the surface is it appropriate to begin a quantitative survey of the surface flux.

The information from the FID survey is then used in conjunction with the results of the desk study to divide the site into monitoring zones where the surface characteristics are similar. A matrix of monitoring points is specified for each zone so that the quantitative survey is representative of the total surface of the site.

Flux boxes are then placed at the selected locations and sealed against the ground surface. The rate at which methane enters the confined space is measured using a FID and a flux for that location is calculated. The individual measurements from all the locations are aggregated to estimate the emission rate for the whole site or for a specific zone within the site.

Field research has shown that low surface flux emissions can be achieved by following current practice for site capping and gas abstraction systems. The emission standards reflect best practice conditions for permanently and temporarily capped zones (Environment Agency, 2004d). Where zones do not meet the emission standards, further remediation or improvement of the gas management system must be undertaken and the surface re-surveyed.

8.2.2 Lateral emissions

The monitoring of lateral emissions is undertaken using gas monitoring boreholes outside the perimeter of the deposited waste. These boreholes can be located both on-site and off-site. They provide information on the movement of landfill gas below the surface of the landfill from the waste mass. The monitoring of external boreholes is essential to demonstrate the efficient management of gas within the site and to detect any gas migrating from the site. The key features of off-site monitoring boreholes are shown in Figure 8.3.

Monitoring boreholes should remain sealed at all times to avoid the dilution of landfill gas with air. They should have a security cover to ensure that the valves cannot be tampered with.

The background concentrations for methane and carbon dioxide need to be established in consultation with the regulator before landfilling begins. Details of these levels and the appropriate action/trigger levels should be set out in the Gas Management Plan. If the results of monitoring are at or above the appropriate trigger levels, the regulator must be informed immediately and remedial action implemented within an appropriately defined timescale.

The location and spacing of landfill gas monitoring boreholes is site-specific and depends on the likely risks posed by off-site gas migration. The risk varies with:

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

The spacing of monitoring points must be considered as part of the risk assessment for the site and should be based on the conceptual model. Off-site monitoring boreholes have historically been located relatively close to the edge of the waste fill. It is recommended that boreholes are sited at least 20 metres from the boundary of the waste. Guidance on the spacing of monitoring boreholes is given in Table 8.1. However, the distances presented in Table 8.1 are only a guide, as the risk assessment is the primary tool for determining the minimum required borehole spacing (this may be less than the minimum indicated).

Table 8.1 Guidance on typical off site monitoring borehole spacing

Site description	Monitoring borehole spacing (m)	
	Minimum	Maximum
Uniform low permeability strata (e.g. clay); no development within 250 metres	50	150
Uniform low permeability strata (e.g. clay); development within 250 metres	20	50
Uniform low permeability strata (e.g. clay); development within 150 metres	10	50
Uniform matrix dominated permeable strata (e.g. porous sandstone); no development within 250 metres	20	50
Uniform matrix dominated permeability strata (e.g. porous sandstone); development within 250 metres	10	50
Uniform matrix dominated permeability strata (e.g. porous sandstone); development within 150 metres	10	20
Fissure or fracture flow dominated permeable strata (e.g. blocky sandstone or igneous rock); no development within 250 metres	20	50
Fissure or fracture flow dominated permeable strata (e.g. blocky sandstone or igneous rock); development within 250 metres	10	50
Fissure or fracture flow dominated permeable strata (e.g. blocky sandstone or igneous rock); development within 150 metres	5	20

Note: The maximum spacings given in relation to the development relate to the zone of development and not the entire boundary.

The monitoring frequencies required for off-site gas monitoring boreholes are shown in Table 5.4, but are subject to site-specific considerations (see Chapter 5).

Before sampling using portable instruments or other techniques, atmospheric pressure and borehole pressure should be measured. If the pressure differential is large, it is an indication that gas is likely to be moving under advective pressure. If landfill gas is detected in a monitoring borehole, it is also likely that landfill gas will have migrated beyond the monitoring point. The lack of a positive pressure reading (relative to atmospheric pressure) when landfill gas is present in the borehole may indicate that landfill gas is migrating off-site through diffusive flow.

The trigger levels for methane and carbon dioxide permitted in any off-site gas monitoring borehole, without remedial intervention, are given in Table 8.2. Trigger levels are compliance levels and, in order to meet them, action levels should be set at a level at which the operator can take action to remain compliant. Trigger levels form part of the PPC permit.

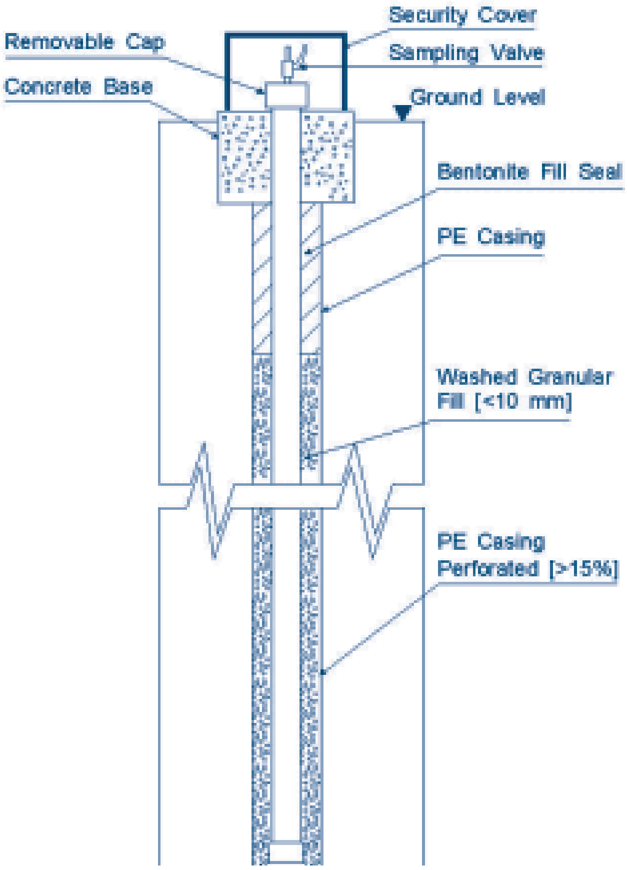


Figure 8.3 The features of a landfill gas monitoring borehole (adapted from IWM, 1998)

Table 8.2 Trigger levels for gas monitoring boreholes

Parameter	Trigger concentrations (% v/v)
Methane	1 per cent above agreed background concentrations[1]
Carbon dioxide	1.5 per cent above agreed background concentrations[2]

[1] Based on 20 per cent of the LEL

[2] Based on 20 per cent of the 8-hour UK Occupational Exposure Standard (OES)

8.2.3 Combustion monitoring

The Regulator has developed a series of guidance documents that specify the requirements for monitoring landfill gas flares and engines (Environment Agency, 2004b; 2004e). The guidance provides a standard set of monitoring methods that allow for the collection of emissions data in a transparent and consistent manner. Further information on monitored emissions from enclosed landfill gas flares is presented in Appendix D of this document.

The Agency guidance documents also provide a tiered approach to the formation of emission standards for landfill gas engines and flares. These standards comprise of a generic emission requirement based on best practice, combined with a stricter site-specific risk based standard, where appropriate.

8.3 Monitoring air quality

The monitoring of air quality within and around landfill sites is becoming increasingly important. The Agency has produced a number of Technical Guidance Notes, which provide important reference information relating to the monitoring of air quality (applicable in England and Wales), including:

- M1 *Sampling requirements for monitoring stack emissions to air from industrial installations* (Environment Agency, 2002i);
- M2 *Monitoring of stack emissions to air* (Environment Agency, 2002j);
- M8 *Environmental monitoring strategy – ambient air* (Environment Agency, 2002k);
- M9 *Monitoring methods for ambient air* (Environment Agency, 2000d);
- M17 *Monitoring of particulate matter in ambient air around waste facilities* (Environment Agency, 2004g).

IPPC Horizontal Guidance Note H1 (Environment Agency, 2002c) provides a comprehensive list of EALs for assessing the releases to air from a variety of processes. The EAL for an airborne compound relates to the concentration below which the substance in question is considered to have no significant environmental impact. Most levels have been calculated as fractions of the values provided in HSE guidance on occupational exposure limits (OELs) (HSE, 2002).

Air quality monitoring on landfill sites will typically consist of:

- odour monitoring
- particulate matter monitoring.

8.3.1 Odour monitoring

Odour is defined in the Agency's technical guidance for the regulation of odour at waste management facilities (Environment Agency, 2002a) as:

- that characteristic property of a substance which makes it perceptible to the sense of smell;
- a smell whether pleasant or unpleasant; fragrant or stench.

The perceptibility of an odour depends on the concentration of that substance or mixture of substances in the atmosphere and, for each pure substance, there is a limiting concentration in air below which the odour is not perceptible. This is known as the odour threshold of that substance.

Mixtures of more than one substance such as landfill gas are more complex as the constituent gases can interact; the odour threshold of the mixture is less than (hypo-addition), greater than (hyper addition) or equal (complete addition) to the sum of the gases individual intensities.

An odour can be described by four interlinked sensory characteristics:

- odour concentration, i.e. the amount of odour present in the air;
- hedonic tone, i.e. relative pleasantness or unpleasantness;
- quality, qualitative attribute e.g. fruity;
- intensity, i.e. the perceived strength of the odour.

The offensiveness of an odour is highly subjective. The judgement of the offensiveness of an odour is dependent upon factors such as race, gender, age, occupation, health and previous history of odour experiences. Odours are often expressed in odour units (ou/m^3), with one odour unit being the concentration at which 50 per cent of an odour panel detect the odour.

The monitoring of odour is undertaken to fulfil a number of differing objectives including:

- the development of input data for risk assessment and predictive dispersion modelling
- development of gas monitoring plan
- prioritisation of odour sources for mitigation or abatement
- selection of odour abatement measures
- assessment of the effectiveness of odour abatement and mitigation measures.

The Agency's technical guidance for the regulation of odour at waste management facilities in England and Wales (Environment Agency, 2002a) details how odour monitoring should be undertaken at a landfill site. Most of this guidance is relevant to sites regulated under the PPC regime.

On-site odour assessments should be carried out, as far as possible, in a distal to proximal direction, i.e. from the furthest point away from the site relative to the wind direction towards the site boundary or onto the site itself, downwind of the site and in a proximal to distal direction up wind of the site. The persistence of the odour, together with its location from the site boundary, should be noted.

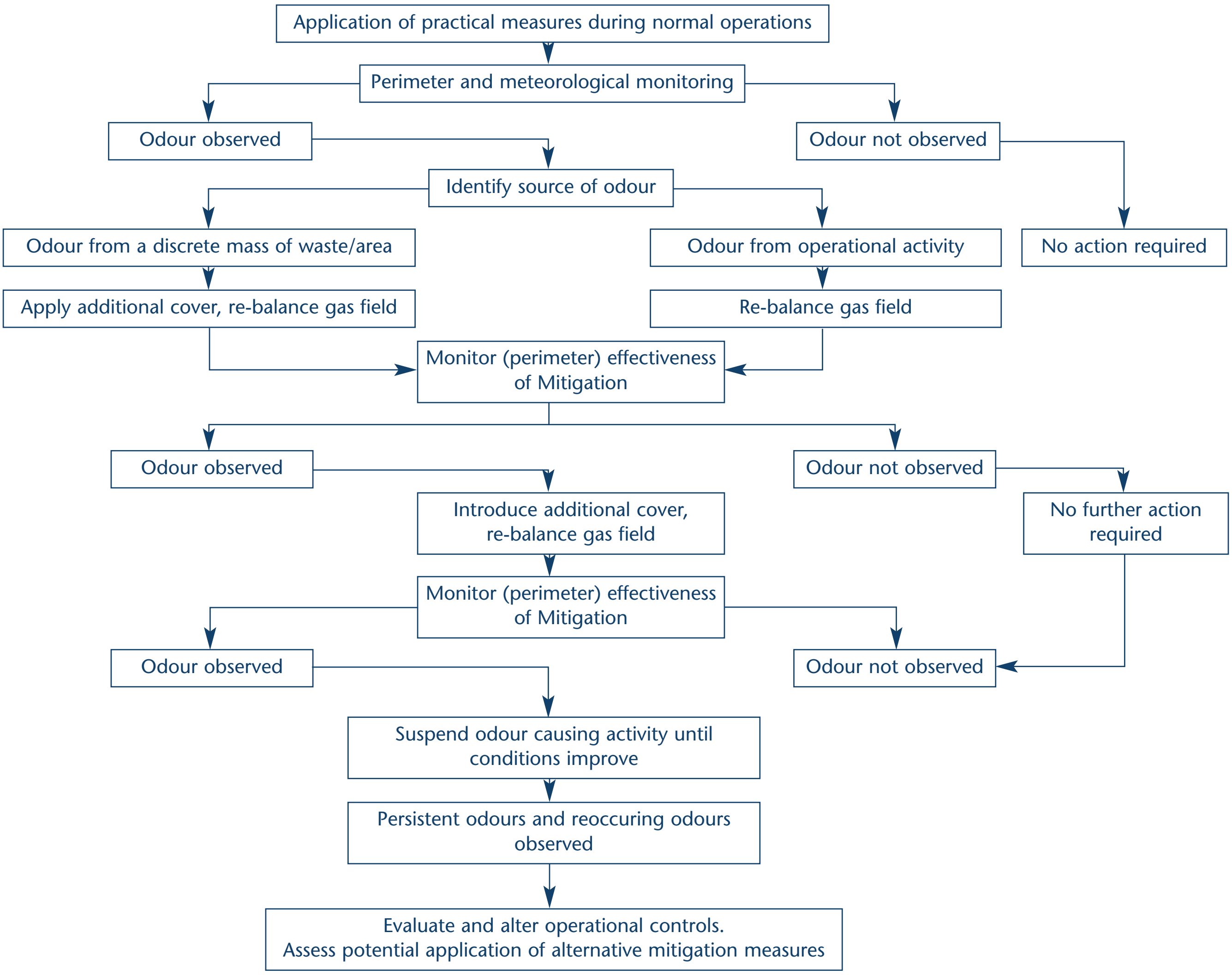


Figure 8.4 Typical odour action plan

Subjective monitoring can be supported by techniques such as olfactometry, gas chromatography and mass spectrometry. Collected samples of air should be assessed for the strength of an odour and the potential source. Olfactometry involves the presentation of the samples of air at various levels of dilution to an odour panel. These methods are covered in more detail in Horizontal Odour Guidance H4 (Environment Agency, 2003b).

As an alternative to olfactometry, measurement of a selected 'marker' compound in the atmosphere (e.g. hydrogen sulphide) may be used as a surrogate measure for odour. Portable monitoring instruments are available that can measure hydrogen sulphide down to parts per billion concentrations and a large area can be covered in a relatively short time. This technique has been used successfully to pinpoint odour and landfill gas escapes on a number of UK landfills. It is also possible to select specific organic components to be monitored, e.g. VOCs, organosulphur compounds and aromatic hydrocarbons. Measuring the concentration of the carrier gas (methane) can also be an effective way of identifying the extent of the odour plume.

Odour action plans should be developed to engage a series of specific actions or odour mitigation measures in response to a particular event or anticipated result. An example schematic diagram of an odour action plan is shown in Figure 8.4.

8.3.2 Particulate monitoring

Particulates can be present in the landfill gas and are also generated by landfill gas combustion plant.

Further information on monitoring of particulate matter in ambient air around waste facilities is given in Technical Guidance Document M17 (Environment Agency, 2004g).

8.4 Meteorological monitoring

Annex III of the Landfill Directive requires that meteorological data is collected at the frequencies given in Table 8.3. This requirement will typically be included in a PPC permit and the suggested meteorological monitoring in the Landfill Directive is required by the Agency. The UK is required to report on a three-yearly basis to the European Commission on the methods used to collect these data.

Meteorological data should ideally be collected using an on-site weather station with an automated logging capability. In some circumstances, it may be appropriate to obtain some or all of these data from a local meteorological station.

8.5 Monitoring procedures

Sampling and analytical methods used in monitoring must be selected to ensure reliable and accurate results. A description of the measurement techniques and sampling strategy, in addition to the analytical and testing schedules, should be included in the monitoring section of the Gas Management Plan. Table 8.4 summarises the relationship between the monitoring purpose and the type of instrument to be used.

Table 8.3 Meteorological monitoring suggested by the Landfill Directive

Landfill Directive Requirements	Operational and restored phases	Aftercare phase
Volume of precipitation	Recorded daily, reported monthly.	Monthly average based on the sum of daily records.
Maximum and minimum temperature, recorded at 15:00 GMT	Recorded daily at 15:00 GMT, reported monthly	Monthly average maximum and minimum temperatures based on daily measurments taken at 15:00 GMT
Wind speed and direction	Recorded continuously, reported yearly as a wind rose.	Not required.
Evaporation	Daily	Monthly average based on the sum of daily records.
Barometric pressure	Daily	Monthly average based on the sum of daily records.
Atmospheric humidity, recorded at 15:00 GMT	Daily	Monthly average based on the sum of daily records.

GMT = Greenwich Mean Time

Table 8.4 The relationship between monitoring purpose and instrument types (adapted from IWM, 1998)

Purpose	Monitoring location	Measured parameters	Instrument type
Monitoring for gas during a surface survey	Ground surface services services manholes, search bar holes	Flammable gas (methane), carbon dioxide and oxygen concentration Pressure, temperature and flow.	Portable
Monitoring for gas outside the waste	Gas monitoring borehole or probe	Flammable gas (methane), carbon dioxide and oxygen concentration Pressure, temperature and flow.	Portable OR Fixed for continuous monitoring with telemetry (optional)
Monitoring the gas in the waste or within a gas collection system	Gas or leachate extraction well, Knock-Out-Pot (gas de-watering plant), gas collection pipes	Flammable gas (methane), carbon dioxide and oxygen concentration Pressure, temperature, flow calorific value and moisture	Portable OR Fixed for continuous monitoring with telemetry (optional)
Monitoring in a gas thermal destruction unit	Gas flare	Temperature (continuous) Flammable gas (methane), arbon dioxide and oxygen oncentration Pressure, temperature and flow (periodic)	Fixed for continuous monitoring with telemetry (optional)
Monitoring in a gas utilisation plant	Engine	Flammable gas (methane), carbon dioxide and oxygen concentration Pressure, temperature, flow, calorific value and moisture	Portable OR Fixed for continuous monitoring with telemetry (optional)
Detailed gas analysis[1]	Sample of gas	Gas composition and concentration of its components (including priority trace components) Moisture	Fixed or transportable laboratory instruments (e.g. GC–MS)

[1] The Landfill Directive requires that any analysis must be undertaken by a competent laboratory.

Landfill gas sampling errors often occur due to dilution of the gas source – either because gas volumes are too small or due to leaks in the sampling system.

Sampling pipework must be flushed with the gas mixture to be analysed before sampling to ensure air dilution during sampling does not occur. However, if the sampling of small volumes is unavoidable, this fact must be recorded.

Surface openings of any monitoring points should be kept sealed before and during sampling to avoid dilution with air. When the volume of gas to be sampled is small compared with the amount of gas being drawn through the instrument, a peak reading will be obtained which will fall to a steady reading, proportional to the effectiveness of the seal of the sampling system and the volume of gas entering the sampling volume. Both the peak and steady state concentrations should therefore be noted. An instrument should be set at zero when in use and in the absence of landfill gas.

The range of instruments that can be used to monitor landfill gas is extensive and increasing as new detection systems are developed and old systems refined. Such instruments generally fall into three categories:

- portable hand-held instruments with a self-contained power supply
- semi-portable instruments which are battery or mains driven
- in situ monitoring units (usually mains powered).

When taking field measurements with portable instruments, it is important to:

- record the location and conditions in which the measurements are being carried out (IWM, 1998);
- train staff to take field measurements
- adhere to site health and safety requirements.

Portable instruments tend to be relatively light, robust under most field conditions, possess integral pumps or are aspirated by hand, and provide a direct readout. However, portable instruments are often confined to a limited range of parameters with varying degrees of sensitivity. Several portable instruments, including thermal conductivity and catalytic detectors, are equipped with more than one detection system. When taking field measurements with portable instruments, the equipment should have in-line filters installed to enable any condensate, moisture and dust to be trapped. These should be checked regularly.

Semi-portable units may measure a wider range of parameters at a greater sensitivity than portable instruments. However, these units tend to be cumbersome and fragile, and often need an external power source. In situ instruments have dedicated functions and combine some of the attributes and drawbacks of both portable and semi-portable instruments.

Sensors used to measure the concentrations of landfill gas include infra-red, catalytic oxidation, thermal conductivity, flame ionisation, semi-conductor, paramagnetic and electrochemical gas detectors. More detailed information about these analysers is given in Appendix F. Any equipment used in the monitoring of landfill gas must be calibrated and serviced in accordance with the manufacturer's recommendations to ensure that accurate measurements are taken. Records must be kept of the services and calibration for each instrument.

Check samples of gas should be analysed by a laboratory on an occasional basis to confirm the results of on-site analysis.

8.6 Data analysis and reporting

Operators are typically required to provide the regulator with annual reports of the data obtained monitoring landfill gas. These reports should:

- contain raw and aggregated data, charts and trends;
- demonstrate compliance with the conditions of the landfill permit;
- provide an interpretation of the data, including comparison with the objectives of the Gas Management Plan and a periodic review of the conceptual site model;
- include proposed revisions of the Plan and the model in light of this review.

The data will form part of the public register and should be supplied in electronic format.

Interpretation of data should include exception reports to highlight where deviations are occurring. Should any values at or above the agreed action/trigger levels be recorded, then the regulator must be informed and a previously agreed course of remedial action – as set out in the Gas Management Plan – implemented.

Technical Guidance Note M8 (Environment Agency, 2002k) details the statistical analysis and reporting of results required for air quality data in England and Wales. It emphasises the importance of summarising data in such a way as to allow meaningful interpretation. The raw monitoring data can be manipulated to produce simple tables and graphs to display the data.

When reporting large amounts of raw data, the use of statistics is recommended so that the data are described by a limited set of numerical values. Common statistical analyses include:

- **ranking** the raw data –- placing the data set in order from the lowest to the highest value obtained;
- obtaining the **range** of the raw data – the difference between the highest and lowest ranked data values;
- obtaining the **median** value – the middle value of the ranked data;
- obtaining the **quartile** values –- by dividing the ranked data into four;
- obtaining the **decile** value – by dividing the ranked data into ten;
- use of **frequency distributions** – group ranking of the data to enable their distribution to be plotted as a frequency curve or a histogram;
- measures of **central tendency** – common measures include the arithmetic mean (average), the median (middle number of a ranked data set), the mode (the most frequently occurring number) and the geometric mean (logarithmic mean).

Data can also be reported in a time-series plot, which is a useful method for showing fluctuations of different pollutants at the same site due to diurnal (daily) or seasonal effects and for showing possible anomalous results within the data set.

Detailed information relating to the use of statistics in analysing air quality data is given in Section 12 of Technical Guidance Note M8 (Environment Agency, 2002k).

Guidance on the management of landfill gas

Appendices

Appendix A:

Identified trace components in landfill gas

Chemical	Chemical	Chemical
(1-methylethyl)benzene	1,2,4-trimethylcyclohexane	1-butene
(1-methylethyl)cyclohexane	1,2,4-trimethylcyclopentane	1-chloro-1,1-difluoroethane
1-(ethenyloxy)-butane	1,2-dichloro-1,1,2,2-tetrafluoroethane	1-chloro-1-fluoroethane
1-(ethylthio)-butane	1,2-dichloro-1-fluoroethane	1-chloropropane
1,1,1,2-tetrachloroethane	1,2-dichlorobenzene	1-decene
1,1,1,2-tetrafluorochloroethane	1,2-dichloroethane	1-ethenyl-3-ethylbenzene
1,1,1-trichloroethane	1,2-dichloroethene	1-ethyl-2,3-dimethylbenzene
1,1,1-trichlorotrifluoroethane	1,2-dichlorotetrafluoroethane	1-ethyl-2-methylbenzene
1,1,1-trifluoro-2-chloroethane	1,2-dimethyl-3-(1-methylethyl)	1-ethyl-2-methylcyclohexane
1,1,1-trifluorochloroethane	1,2-dimethylcyclohexane	1-ethyl-2-methylcyclopentane
1,1,2,2-tetrachloroethane	1,2-dimethylcyclopentane	1-ethyl-3-ethylbenzene
1,1,2,2-tetrafluoroethane	1,2-dimethylcyclopropane	1-ethyl-3-methylcyclohexane
1,1,2-trichloro-1,2,2-trifluoroethane	1,3,5-trimethyl cyclohexane	1-ethyl-3-methylcyclopentane
1,1,2-trichloroethane	1,3,5-trimethylbenzene	1-ethyl-4-methylcyclohexane
1,1,2-trifluoro-1,2,2-trichloroethane	1,3,5-trimethylcyclohexane	1-heptene
1,1,2-trifluoro-1,2-dichloroethane	1,3-butadiene	1-hexene
1,1,2-trifluoro-1-chloroethane	1,3-dichlorobenzene	1-methyl-2-propylbenzene
1,1,3-trimethylcyclohexane	1,3-dimethylcyclohexane	1-methyl-2-propylcyclopentane
1,10-undecadiene	1,3-dimethylcyclohexane (cis)	1-methyl-3-propylbenzene
1,11-dodecadiene	1,3-dimethylcyclohexane (trans)	1-methyl-4-(1-methylethyl) benzene
1,1-chlorofluoroethane	1,3-dimethylcyclopentane	1-methyl-4-(1-methylethyl)
1,1-dichloroethane	1,3-dimethylcyclopentane (trans)	1-methyl-4-propylbenzene
1,1-dichloroethene	1,3-dioxolane	1-methylpropylbenzene
1,1-dichlorotetrafluoroethane	1,3-pentadiene	1-octene
1,1-difluoro-1-chloroethane	1,4-dichlorobenzene	1-pentanethiol
1,1-dimethylcyclopropane	1,4-dimethylcyclohexane	1-pentene
1,1-thiobispropane	1,4-pentadiene	1-phenyl-1-propanone
1,1-trichloroethane	1,6-dimethylnaphthalene	1-propanethiol
1,2,3,4,6,7,8-HpCDD	1,6-heptadiene	1-propanol
1,2,3,4,6,7,8-HpCDF	1,8-nonadiene	1-undecene
1,2,3,4,7,8,9-HpCDF	1,9-decadiene	2 ethynyl phenol
1,2,3,4,7,8-HxCDD	1234678 H7CDF	2(2-hydropropoxy)propan-1-ol
1,2,3,4,7,8-HxCDF	1234679 H7CDD	2(methylthio)propane
1,2,3,4-tetrachlorobenzene	123478 H6CDD	2,2-difluoropropane
1,2,3,6,7,8-HxCDD	123478 H6CDF	2,2-dimethylbutane
1,2,3,6,7,8-HxCDF	1234789H7CDF	2,2-dimethylpentane
1,2,3,7,8,9-HxCDD	123678 H6CDD	2,2-dimethylpropanoic acid
1,2,3,7,8,9-HxCDF	123678 H6CDF	2,3,3-trimethylpentane
1,2,3,7,8-PeCDD	12378 P5CDF	2,3,4,6,7,8-HxCDF
1,2,3,7,8-PeCDF	123789 H6CDD	2,3,4,7,8-PeCDF
1,2,3-trichlorobenzene	123789 H6CDF	2,3,4-trimethylhexane
1,2,3-trimethylbenzene	12379 P5CDD	2,3,4-trimethylpentane
1,2,4-trichlorobenzene	1-butanethiol	2,3,7,8-TCDD
1,2,4-trimethylbenzene	1-butanol	2,3,7,8-TCDF

Chemical	Chemical	Chemical
2,3-dimethylheptane	3-(ethylthio)propanal	butyl acetate
2,3-dimethylpentane	3,3-dimethylpentane	butyl benzene
2,4,4-trimethylpentane	3,5-dimethyloctane	butyl butyrate
2,4,6-trimethylheptane	3-carene	butyl cyclohexane
2,4-dimethylheptane	3-ethyl-4-methylheptane	butyl ester
2,4-dimethylhexane	3-ethylhexane	butyl ethanoate
2,5-dimethylheptane	3-ethylpentane	butyl ethyl trisulphide
2,5-dimethylhexane	3-methyl butan-2-ol	butyl formate
2,5-dimethylpentene	3-methyl pentan-2-ol	butyl methyl trisulphide
2,6-dimethylheptane	3-methyl-1-butanol	butyl propyl trisulphide
2,6-dimethylnonane	3-methyl-2-butanone	butyl trisulphides
2,6-dimethyloctane	3-methyldecane	butylbenzene
2,6-dimethynonane	3-methylheptane	butylpropyldisulphide
234678 H6CDF	3-methylhexane	butynes
23478 P5CDF	3-methylnonane	butyric acid
2379 T4CDD	3-methyloctane	camphene
2379 T4CDF	3-methylpentane	camphor
2-butanethiol	3-methypentane	carbon disulphide
2-butanol	3-pentanol	carbon monoxide
2-butanone	4-carene	carbonyl sulphide
2-butene	4-methyl-1-hexene	carene
2-butoxy ethanol	4-methyl-2-pentene (e)	chlorobenzene
2-chloro-1,1,1-trifluoroethane	4-methyldecane	chlorodifluoromethane
2-ethyl-1,3-dimethylbenzene	4-methylheptane	chloroethane
2-ethyl-1-butanol	4-methylnonane	chloroethene (vinyl chloride)
2-ethyl-1-hexanol	4-methyloctane	chlorofluoromethane
2-ethyl-cycloheptanone	5-methyldecane	chloromethane
2-furanmethanol	acenaphthene	chloromethylbenzene
2-hexanone	acetaphenone	chloropropene
2-methyl-1,3-butadiene	acetone	chlorotrifluoroethene
2-methyl-1-butane	acetonitrile	chlorotrifluoromethane
2-methyl-1-butene	a-chlorotoluene	chlorotrifluoromethene
2-methyl-1-pentene	amyl acetate (mixed isomers)	chrysene
2-methyl-1-propanethiol	amyl alcohol	cis-1,2-dichloroethene
2-methyl-1-propanol	amyl mercaptan	cyclobutane
2-methyl-1-propene	anthracene	cycloheptane
2-methyl-2-propenoic acid	arsenic	cyclohexane
2-methylbutane	benzealdehyde	cyclohexanone
2-methyldecane	benzene	cyclopentane
2-methylheptane	benzo(a)anthracene	cyclopentanone
2-methylhexane	benzo(a)pyrene	cyclopentene
2-methylnonane	benzo(b)fluoranthene	decahydro-4,8,8-trimethyl-9-methylene- (1a,3aß,4a,8aß)]-1,4-methanoazulene
2-methyloctane	benzo(ghi)perylene	
2-methylpentane	benzo(k)fluoranthene	
2-methylpropane	benzoic acid	decahydronaphthalene
2-methylpropylbenzene	benzothiazole	decamethylcyclopentasiloxane
2-methylpropylcyclohexane	biphenylene	decanal
2-pentanone	bromochlorodifluoromethane	decanhydronaphthalene
2-pentene	bromochlorofluoromethane	dibromochloromethane
2-propanethiol	bromodichloromethane	dibutyl sulphide
2-propanol	bromoethane	dibutyl trisulphide
2-propenal	butanal	dichlorobenzene (mixed isomers)
2-propene-1-thiol	butane mercaptan	dichlorobutene
2-propyl thiophene	butanoic ethyl ester	dichlorodifluoromethane
3 ethynyl phenol	butene	dichlorofluoromethane

Chemical	Chemical	Chemical
dichloromethane	ethylmethyl trisulphide	methyl ether
diethyl disulphide	ethylmethylcyclohexane	methyl ethyl butanoate
diethyl phthalate	ethylpentane	methyl ethyl disulphide
diethyl sulphide	ethylpropyl disulphide	methyl ethyl ketone
diethylbenzene	ethylpropyl trisulphide	methyl ethyl propanoate
di-isooctyl phthalate	ethylvinyl benzene	methyl furan
dimethoxy methyl propanoate	ethyne	methyl isobutyl carbinol
dimethyl cyclohexane	fluoranthene	methyl isobutyl ketone
dimethyl cyclopentane	fluorene	methyl isobutyrate
dimethyl disulphide	formic acid	methyl isopropyl disulphide
dimethyl ether	furan	methyl isopropyl ketone
dimethyl ethyl methanoate	furfural	methyl isovalerate
dimethyl furan	HA1334	methyl naphthalene
dimethyl pentan-3-one	HA1335	methyl pentanoate
dimethyl styrene	HA1343	methyl propanoate
dimethyl sulphide	HA1344	methyl propyl disulphide
dimethyl tetrasulphide	HA1352	methyl propyl ethanoate
dimethyl trisulphide	HA1353	methyl vinyl ketone
dimethylbutane	heneicosane	methyl-4-isopropenylbenzene
dipropyl ether	heptachlorodibenzodioxin	methylal
dipropyl sulphide	heptadecane	methylcyclobutane
dipropyl trisulphide	heptadibrodibenzofuran	methylcyclohexane
dodecamethylcyclohexasiloxane	heptyl mercaptan	methylcyclopentane
dodecene	hexachlorobenzene	methylcyclopropane
eicosane	hexachlorodibenzodioxin	methylenecyclohexane
ethanal (acetaldehyde)	hexadecane	methylethyl cyclohexane
ethane	hexadibrodibenzofuran	methylethyl sulphide
ethanethiol	hexadiene	methylpropyltrisulphide
ethanoic acid (acetic acid)	hexamethylcyclotrisiloxane	methylthioethane
ethanol	hexamethyldisiloxane	naphthalene
ethene	hexanal	n-butane
ether	hexyl methanoates	n-butanol
ethyl 2-methyl butyroate	hydrogen	n-butyl disulphide
ethyl acetate	hydrogen chloride	n-butyl propionate
ethyl alcohol	hydrogen cyanide	n-decane
ethyl butyrate	hydrogen fluoride	n-decene
ethyl caproate	hydrogen sulphide	n-dodecane
ethyl cyclohexane	indeno(123cd)pyrene	n-heptane
ethyl cyclopentane	isobutane	n-hexane
ethyl dimethyl propanoate	isobutyl formate	n-hexanol
ethyl ethanoate	limonene	n-hexyl mercaptan
ethyl isopropyl disulphide	l-propanol	n-nonane
ethyl isovalerate	m-cresol	n-octane
ethyl methyl ether	mercury	nonadecane
ethyl n-propyl disulfide	methanal (acetaldehyde)	nonanal
ethyl pentanoate	methanethiol	nonene
ethyl propionate	methanol	n-pentane
ethyl toluene	methyl 2-methyl butanoate	n-propane
ethylbenzene	methyl 2-methyl propenoate	n-propyl acetate
ethylcyclohexane	methyl acetate	n-propyl butyrate
ethylcyclopentane	methyl butyl disulphide	n-tetradecane
ethylcyclopropane	methyl butyrate	n-tridecane
ethylene oxide	methyl caproate	n-undecane
ethylisobutyldisulphide	methyl cyanide	n-undecene
ethylmethyl disulphide	methyl cycloheptane	OCDD (octachlorodibenzodioxin)

Chemical	Chemical
OCDF	propyl propionate
o-cresol	propylbenzene
octabromodibenzofuran	propylthiophene
octadecane	propyltoluene
octadiene	pyrene
octamethylcyclotetrasiloxane	sec-butyl alcohol
octanal	sec-butylbenzene
PCB 101	styrene
PCB 118	sulphur dioxide
PCB 126	sulphuric acid
PCB 138	t-butyl alcohol
PCB 153	t-butylbenzene
PCB 169	terpenes
PCB 180	tetrachlorodibenzodioxin
PCB 28	tetrachloroethane
PCB 52	tetrachloroethene
PCB 77	tetrachloromethane
p-cresol	tetradecane
p-cymenyl	tetradibrodibenzofuran
pentachlorobenzene	tetrafluorochloroethane
pentachlorodibenzodioxin	tetrahydro-2-furanmethanol
pentadecane	tetrahydrofuran
pentadibrodibenzofuran	tetramethylbenzene
pentanal	tetramethylcyclohexane
pentene	thiophene
pentyl benzene	thujene
pentyl methanoate	toluene
pentyl trisulphide	trans-1,2-dichloroethene
phellandrene	tribromomethane
phenanthrene	trichloroethene
phenol	trichlorofluoromethane
pinene	trichloromethane
propadiene	trifluorobenzene
propan-2-one	trimethyl cyclopentane
propanal	trimethylhexane
propanoic acid	trimethylsilanol
propene	vinyl toluene
propionic acid	xylene
propyl butyl disulphide	α-pinene
propyl cyclohexane	ß-cymene
propyl methyl propanoate	ß-pinene
propyl methyl trisulphide	γ-terpinene

Source: revised from Environment Agency, 2002e

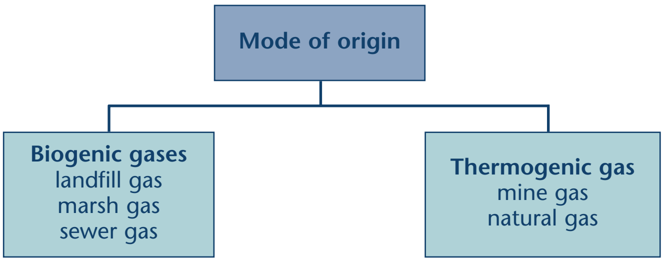
Appendix B:

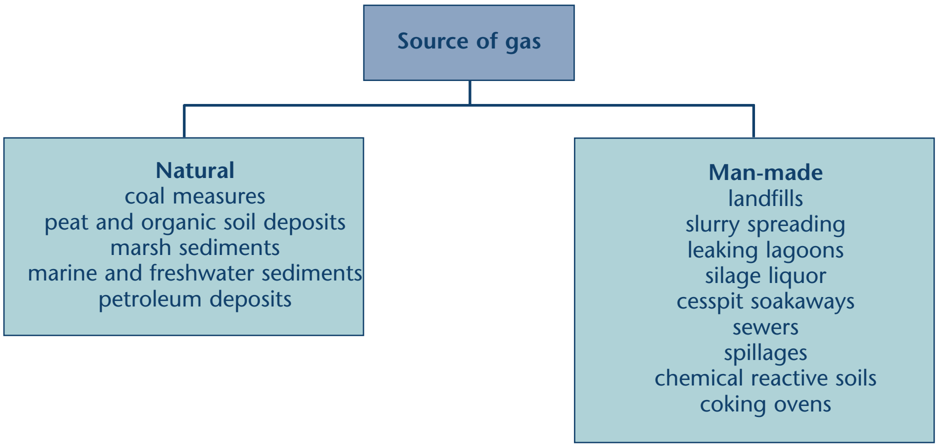
Compositional comparison of gas sources

A compositional comparison of typical landfill gas with other gas sources

Compound	Landfill gas	Marsh gas	Natural gas	Mine gas
Methane	20–65	11–88	17–97	22–95
Ethane	Trace		0.7–16	3–8
Propane	Trace		0.4–7.9	1–4
Butane	Trace		0.1–3.4	0–1
Carbon dioxide	16–57		0–9.5	0.2–6.0
Carbon monoxide			4.7	0–10
Nitrogen	0.5–37	3-69	0.1–22	1–61
Helium/argon			Often removed	Present

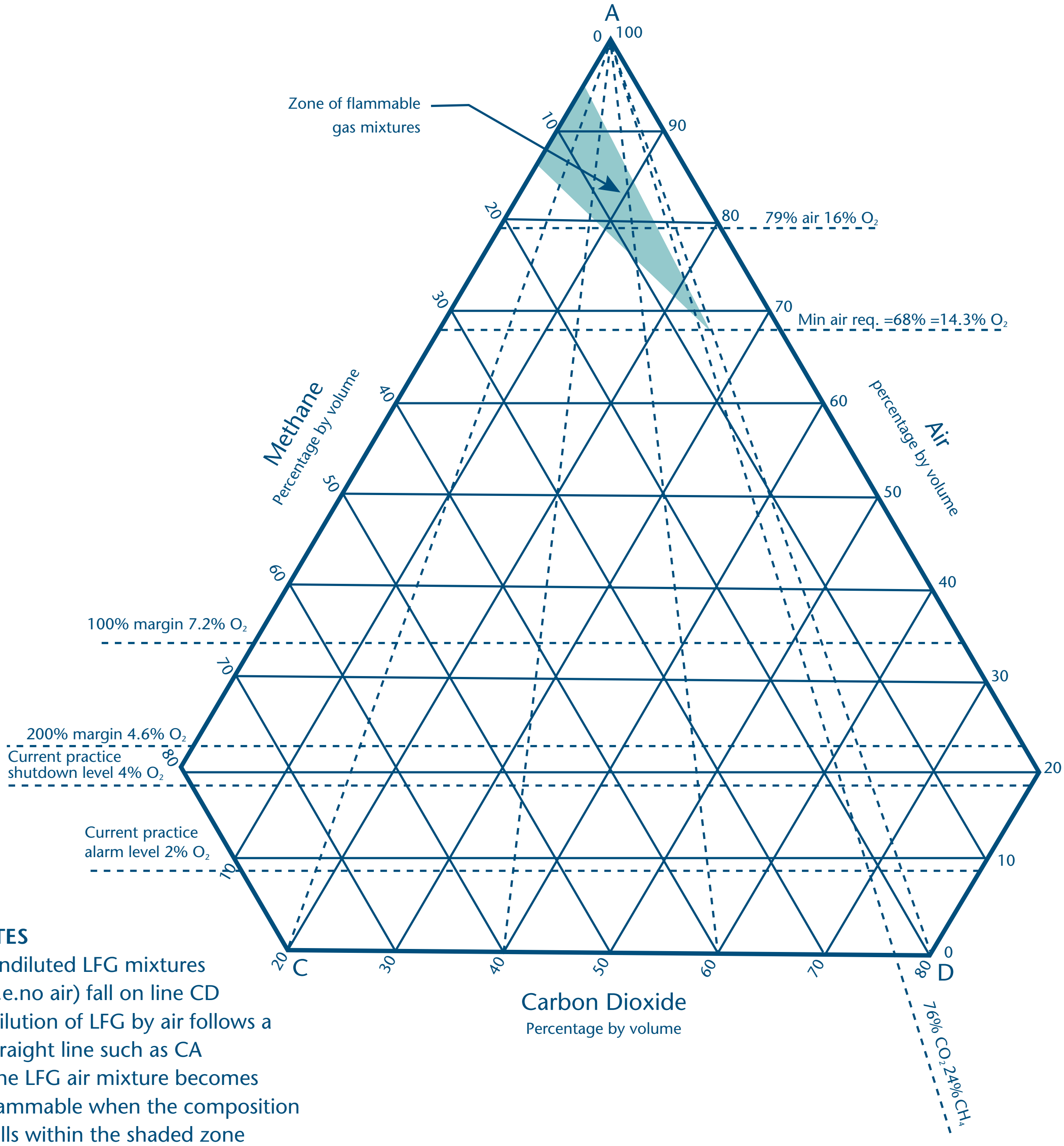
Source: Latham, 1998.
Note: Figures are based on %v/v.





Appendix C:

Effects of CO_2 on the flammable limits of methane



NOTES

1. Undiluted LFG mixtures (i.e.no air) fall on line CD
2. Dilution of LFG by air follows a straight line such as CA
3. The LFG air mixture becomes flammable when the composition falls within the shaded zone

Source: Cooper *et. al.*, 1993

Appendix D:

Average flare emissions data

Averaged emissions data from a range of landfill gas flares (all mg/Nn^3)

Determinand	Measured value									
	Site									
	A	B	C	D	E	F	G	H	I	J
Inlet gas										
Methane (%)[b]	55	56	45	44	33	54	36	39	36	46
Carbon dioxide (%)[b]	39	41	31	32	30	43	30	34	23	37
Oxygen (%)[b]	0.4	<0.1	0.2	4.4	7.0	0.9	6.2	0.6	7.0	1.8
Nitrogen (%)[b]	5.0	3.2	24	20	30	1.9	28	21	34	15
Hydrogen sulphide (ppm)[b]	<5	587	23	30	85	1416	33	89	5	18
Carbon monoxide (ppm)[b]	<2	11	24	45	786[a]	40	530[a]	56	36	194
Emissions										
Temperature (°C)[b]	513	956	588	986	1208	1162	992	849	738	862
Oxygen (%)[b]	17.3	12.6	15.3	11.0	5.1	6.4	11.5	12.4	14.3	11.5
Carbon dioxide (%)[b]	2.6	5.7	4.1	8.6	14.7	12.4	8.3	5.8	5.3	8.3
Moisture (%)[b]	3.1	5.6	3.6	15.0	13.0	16.3	8.4	15.3	7.2	12.2
Carbon monoxide (mg/m^3)[c]	1,042	617	2178	27	32	34	253	34	99	<2
Oxides of nitrogen (as NO_2) (mg/m^3)[c]	75	111	43	92	99	149	82	59	63	14
Total VOCs (as C) (mg/m^3)[c]	21	3	2	<2	2	<2	10	6	17	<2
Hydrogen chloride (mg/m^3)[c]	36	9.5	4.6	7.4	11	4.2	36	7.4	4.9	16.2
Hydrogen fluoride (mg/m^3)[c]	21	2.5	0.4	2.5	0.7	1.6	7.8	2.5	0.5	0.5
Sulphur dioxide (mg/m^3)[c]	482	239	63	30	43	359	181	61	58	83

[a] Denotes the result may be affected by possible interference due to the presence of hydrogen.

[b] On-site measurement

[c] Averaged emission by laboratory analysis (at reference conditions of 3% O_2, 273K, 101.3kPa, dry).

Source: Environment Agency, 2004b

Appendix E:

Example emergency procedures

Example emergency procedures: methane (flammable gas)

Level of methane	Location	Action to be taken by the person undertaking the monitoring	Action to be taken by landfill manager
At 100 ppm (0.2% LEL)	Monitoring boreholes	No action	No action
At 100 ppm (0.2% LEL)	In buildings or services within 250 meters	Immediately inform landfill manager. Take gas sample(s) as soon as practicable for confirmatory gas chromatography analysis.	Review monitoring frequency and prepare for additional monitoring measures.
At 1,000 ppm (2% LEL)	Monitoring boreholes	Immediately inform landfill manager	Inform the regulator. Review control measures.
At 1,000 ppm (2% LEL)	In buildings or services within 250 meters	Immediately inform landfill manager. Take gas sample(s) as soon as practicable for confirmatory gas chromatography analysis.	With regard to detection in buildings, inform the regulator and other appropriate authorities. Immediately review building monitoring frequency.
At 5,000 ppm (10% LEL) and rising	Monitoring boreholes	Immediately inform landfill manager. Take gas sample(s) as soon as practicable for analysis by confirmatory gas chromatography.	Inform the regulator. Assess the landfill gas risk. Consider a revised programme for landfill gas control. Increase frequency of monitoring probes.
At 5,000 ppm (10% LEL) and rising	In buildings and services within 250 meters	Immediately inform landfill manager. Take gas sample(s) as soon as practicable for confirmatory analysis by gas chromatography.	Inform regulator and other relevant authorities. Implement continuous monitoring. Prepare for implementation of evacuation procedure. Consider the installation of audible alarms.
At 9,000–10,000 ppm (18–20% LEL)	In buildings and services within 250 meters	Immediately inform landfill manager. Receive instructions on carrying out evacuation procedure, ventilating building(s) and switching off sources of ignition.	Instruct monitoring personnel on evacuation/ventilation/isolation of ignition sources, etc. Immediately inform regulator and other relevant authorities. Send out additional assistance to site. Prepare for rapid implementationof evacuation procedures.
At 10,000 ppm (20% LEL)	Monitoring boreholes	Immediately inform landfill manager. Take gas sample(s) as soon as practical for confirmatory analysis by gas chromatography.	Immediately inform regulator and other relevant authorities. Assess the risk Immediately consider the monitoring of adjacent buildings.
Above 10,000 ppm (20% LEL)	In buildings and services within 250 meters	Immediately inform landfill manager and follow evacuation procedure.	Immediately inform regulator and other relevant authorities. Immediately send out additional assistance to site. Immediately follow evacuation procedures.

Example emergency plan: carbon dioxide			
Level of carbon dioxide	**Location**	**Action to be taken by the person undertaking the monitoring**	**Action to be taken by landfill manager**
0.4% v/v	In buildings and services within 250 metres	Immediately inform landfill manager. Carry out an immediate check on the environmenta conditions within the building, e.g. has a poorly ventilated room been occupied by people or animals, or has a gas appliance been used without a fume extraction (if it has, the occupier must be immediately told not to use the gas appliance and the gas supplier informed as soon as practicable). Immediately ventilate the building. Take gas sample(s) as soon as practicable for confirmatory gas chromatography analysis.	Inform regulator and other relevant authorities. Make preparations for evacuation.
0.5% v/v	In buildings and services within 250 metres	Check on environmental conditions as for 0.4% CO_2 level. Vent building and check gas concentrations again. Leave gas monitors in building for 24 hours to give audible warning of gas build up. Take gas sample(s) as soon as practicable for confirmatory gas chromatography analysis.	Inform regulator and other relevant authorities. If CO_2 levels reach 0.5% v/v within 24 hours, then follow evacuation procedure.
1.5% v/v	Monitoring boreholes	Immediately inform landfill manager. Take gas sample(s) as soon as practical for confirmatory gas chromatography.	Inform the regulator and other relevant authorities. Assess monitoring date against background levels. Undertake a gas survey of neighbouring buildings. Increase the monitoring frequency for the monitoring boreholes to daily, as necessary.
1.5% v/v	In buildings and services within 250 metres	Immediately inform landfill manager and follow evacuation procedure.	Immediately inform the regulator and other relevant authorities. Immediately send out additional assistance to site. Immediately follow evacuation procedures.

Appendix F:

Characteristics of various gas sensors

Type	Gas	Advantages	Disadvantages
Infra-red	Methane, carbon dioxide and other hydrocarbons	Fast response Can be used to measure specific gases in gas mixtures. Simple to use Wide detection range (ppmv to 100% v/v) Less prone to cross interference with other gases than other sensors. Cannot be 'poisoned'. Can be incorporated into intrinsically safe instruments. Gas sample passes unchanged through the sensor.	Prone to zero drift. Pressure sensitive Temperature sensitive Moisture sensitive Majority of instruments sensitive to hydrocarbon bond only, not specifically to methane – in presence of specific organic compounds can cause interference. Optics sensitive to contamination (condensate, particulates)
Flame ionisation	Methane Flammable gases and vapours	Highly sensitive (usual range 0.1–10,000 ppmv) Fast response	Will not work in oxygen-deficient environment. Accuracy is affected by presence of other gases such as carbon dioxide, hydrogen, minor constituents of landfill gas, and water vapour. 'Blind test' – responds to any flammable gas. Limited detection range Gas sample destroyed
Electrochemical	Oxygen, hydrogen sulphide and carbon monoxide	Low cost Usual detection range 0–25% v/v against various gases	Limited shelf life Requires frequent calibration. Can lose sensitivity due to moisture, corrosion and poisoning. Poor performance against crosscontamination with other components of landfill gas
Paramagnetic	Oxygen	Accurate Robust No interference from other gases	Prone to drift and gas contaminants. Expensive Responds to partial pressure and not to concentration.
Catalytic oxidation (pellistor)	Methane Flammable gases and vapours	Fast response Low detection range (0.1–100% LEL) Responds to any flammable gas.	Accuracy affected by presence of other flammable gases. Readings inaccurate in oxygen-deficient environment (<12% v/v) Prone to ageing, poisoning and moisture. Not possible to notice sensor deterioration Gas sample destroyed during measurement.

Type	Gas	Advantages	Disadvantages
Thermal conductivity	Methane Flammable gases and vapours	Fast response to any flammable gas Full detection range (0–100% v/v) Independent of oxygen level Can be combined with other detectors.	Accuracy affected by the presence of other flammable gases, carbon dioxide and other gases with the same thermal conductivity. Sensitivity too poor for use in safety checks Errors at low concentrations
Semiconductor	Mainly toxic gas	Good selectivity for some toxic gases (e.g. hydrogen sulphide) Less susceptible to poisoning High sensitivity to low concentration of gases Long-term stability	Lack of sensitivity to combustible gases Not specific to any one material Accuracy and response depend upon humidity.
Chemical (indicator tubes)	Carbon dioxide Carbon monoxide Hydrogen sulphide Water vapour Other gases	Simple in use Inexpensive	Crude identification of specific landfill gas Prone to interference effects. Should really be used for indication only.
Photo-ionisation	Most organic gases	Very sensitive	Susceptible to cross-contamination High cost

Source: IWM, 1998

Infra-red detectors

Infra-red (IR) absorption forms the basis of a range of monitoring instruments of varying sophistication. The most common devices used for landfill gas monitoring are relatively simple devices tuned to measure IR absorption at specific wavelengths that are unique to the compound of interest (usually CO_2 and CH_4). These conventional analysers comprise an IR source, a cell with a defined path length over which the measurement is made, a reference cell and an IR detector. These analysers are generally capable of providing measurements in the range of 0.5 ppm to 100 per cent CO_2 and/or CH_4.

Flame ionisation detectors (FIDs)

These detectors operate on the principle of maintaining a voltage between two electrodes located across a small hydrogen flame burning in air. Organic compounds present in the gas drawn into the instrument pass through the flame, producing an increase in the number of free electrons. This registers as an increase in the current flowing between the electrodes. FIDs are unsuitable for monitoring in an oxygen-deficient environment as their flame requires oxygen to support combustion. Although intrinsically safe FIDs have been introduced, the flame poses a potential ignition source where flammable and explosive atmospheres are encountered.

Electrochemical analysers

These analysers usually comprise an electrochemical cell made up of two electrodes immersed in a common electrolyte held within an insulated container. The cell is isolated by a gas permeable membrane or capillary diffusion barrier that allows the component of interest to pass into the cell while retaining the electrolyte. When the component comes into contact with the electrolyte, the electrical characteristics of the cell are altered resulting in a voltage/current. The magnitude of this electrical change in the cell is proportional to the concentration of the component, allowing this to be measured. Electrochemical sensors require careful calibration prior to use to ensure reliability.

Paramagnetic analysers

Paramagnetic analysers offer an alternative to electrochemical sensors for oxygen measurement. They utilise the positive magnetic susceptibility of oxygen to determine changes in the partial pressure of the gas (equated to a concentration). All other gases, with the exception of nitric oxide, exhibit a negative magnetic affinity.

Catalytic analysers

These have been widely used on landfill sites for the measurement of low methane concentrations. Gas is drawn into the detector and oxidised on a small heated element (usually a platinum resistance thermometer) embedded in a pellet (usually comprised of ThO_2 and Al_2O_3) covered by a porous catalytic layer (also known as a pellistor). The oxidation reaction on the catalytic surface increases the temperature of the pellet, causing the temperature of the platinum element to rise and increases its resistance. Catalytic detectors respond to any flammable gas and oxygen concentrations in the sampled gas are required to exceed 12 per cent by volume to ensure the complete oxidation of flammable components.

Thermal conductivity detectors

These detectors operate by comparing the thermal conductivity of the sampled gas to an electronic standard (based on the thermal conductivity of normal atmospheric air). Gas is drawn into the detector over a catalytically inactive element heated to a constant temperature (in air). The element is contained within a wheatstone bridge circuit, and any changes within the element are registered as a voltage change. This is then compared to the unit's internal standard. This detector will respond to any gas that has a different thermal conductivity to air. Where the instruments are primarily used to measure methane concentrations, the presence of carbon dioxide may produce falsely low results. It is thus important to calibrate the instrument using CH_4 and CO_2 mixtures.

Semiconductor

Semiconductor sensors operate on the principle of the interaction of gases on the surface of the semiconductor, which causes a change in the electrical conductivity. The change in conductivity can be displayed as a concentration reading or trigger an alarm. This type of sensor lacks selectivity for combustible gases and is more often used to detect toxic gases such as hydrogen sulphide.

Chemical

Chemical sensors were in common use before the advent of electronic meters and are usually in the form of detector tubes. The gas sample is drawn over a specifically formulated chemical and, if the compound of interest is present, produces a colour change. These tubes can be used only once, and are subject to interference by other gases and chemical vapours. They can be used for a wide range of gases and vapours. Tubes can vary for the same species, depending on the detection range.

Photo-ionisation detectors (PIDs)

Photo-ionisation detectors use a sealed light source to emit photons of sufficient energy to ionise most organic components of landfill gas. The detector consists of a pair of electrodes within a detector chamber. The sample in the chamber is bombarded by photons, which ionise organic components in the sample. The ions are collected on one of the electrodes. The current this induces in the electrode is measured and processed to give a meter reading. Detection limits for methane are approximately 0.1 per cent, but the detectors can suffer from interference from other organic components being ionised.

Other monitoring

Gas pressure can be measured using either hand-held or fixed manometers utilising pressure transducers or dial pressure gauges, or using analysers that incorporate pressure monitors. The flow of gas is measured by instruments reading differential pressure, vortex shedding devices, positive displacement meters, mass flow transducers, and van and hot wire anemometers.

Greater analytical scope can also be introduced using more sophisticated and expensive instruments including:

- *Fourier transform infra-red spectroscopy (FTIR)* – these are fast, highly sensitive instruments, capable of measuring absorption phenomena at all wavelengths simultaneously. They are capable of producing detection limits below 1ppm for a wide range of compounds within minutes.
- *Long-path monitoring using tuneable lasers* are eminently suitable for various forms of gas detection as the tuneable infra-red, ultra-violet and visible lasers posses a number of properties as radiation emitters, including the generation of radiation over a wide spectral range and the emission of high intensity radiation with narrow band width.
- *Other long-path monitoring systems* use low-energy, non-laser radiation sources, but suffer from poorer sensitivity, provide more limited scope of detection and are operated over much reduced path lengths (up to 500 metres).

Glossary

Acetogenic phase
The period during the decomposition of refuse in a landfill when the conversion of organic polymers such as cellulose to simple compounds, such as ethanoic (acetic) and other short chain fatty acids dominates and little or no methanogenic activity takes place.

Admixture
Anything added to form a mixture, or the mixture itself.

Adsorption
The uptake of one substance on to the surface of another.

Advection
Molecular movement from a region of high pressure to one of lower pressure due to the difference in pressure.

Aerobic
In the presence of air.

Anaerobic
In the absence of air.

Best Available Techniques (BAT)
The most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing, in principle, the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole.

Bentonite
A group of clay minerals that swell on wetting.

Biogas
Gas formed by the digestion of organic materials.

Biogenic
Resulting from the actions of living organisms.

BOD (biochemical oxygen demand)
A measure of the amount of material present in water which can be readily oxidised by micro-organisms and is thus a measure of the power of that material to take up the oxygen in aqueous media (mass/litre^3).

Borehole
A hole drilled outside wastes for the purposes of monitoring or sampling.

Capping material
A landfill covering, usually having a low permeability to water. Permanent capping is part of the final restoration following completion of landfill/tipping. Temporary capping is an intermediate cap, which may be removed on the resumption of tipping.

Carburation
The mixing of air with a volatile fuel to form a combustible mixture for use in an internal combustion engine.

Catalytic oxidation
The chemical reaction of oxidation accelerated by a catalyst.

Cell
The compartment within a landfill in which waste is deposited: The cell has physical boundaries, which may be a low permeability base, a bund wall and a low permeability cover.

Coal gas
Gas produced in the old towns gas works by subjecting coal to heat and pressure: The resultant gas was collected, purified and distributed through a pipe network.

COD (chemical oxygen demand)
A measure of the total amount of chemically oxidisable material present in liquid (mass/litre^3) .

Cohesive soils
Soils that are primarily composed of clays and can be moulded.

Compliance
The process of achieving conformity with a regulatory standard.

Condensate
Forms when warm landfill gas cools during transport or processing (such as compression).

Consolidated
Compacted soft material that has been converted to a hard material. For example, sandstones are consolidated sands or soils which have been subject to prolonged overburden pressure by overlying strata or mechanical load application.

Cover
Material used to cover solid wastes deposited in landfills. Daily cover may be used at the end of each working day to minimise odours, wind-blown litter, insect or rodent infestation, and water ingress. Final cover is the layer or layers of materials placed on the surface of the landfill before its restoration.

Construction Quality Assurance (CQA)
A planned and systematic application and recording of methods and actions designed to provide adequate confidence that items or services meet contractual and regulatory requirements, and will perform satisfactorily in service.

Decomposition
Natural breakdown of materials by the action of micro-organisms, chemical reaction or physical processes.

Degradation
See decomposition.

Differential pressure
A difference between the pressures at two distinct points within a system.

Diffusive flow
Molecular movement from a region of high concentration to a more dilute region of low concentration due to random, free movement of the molecules.

Emission
The direct or indirect release of substances, vibrations, heat or noise from individual or diffuse sources in an installation into the air, water or land.

Endogenous
Developing or originating within an organism, or part of an organism.

Environmental impact
The total effect of any operation on the environment.

Faults
Fractures in rock along which relative displacement has occurred.

Flame ionisation detector (FID)
Detector based on the conduction by ions produced when the analyte is ionised in a hydrogen/air flame. The resulting voltage change is proportional to the concentration of the analyte.

Flame ionisation
Method of detection that measures flammable gas by ionising a sample in a hydrogen flame.

Flammable substance
A substance supporting combustion in air.

Flow velocity
The flow rate (litre^3/time) divided by the cross-sectional area of the pipe (in litre^2).

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.

Gas chromatography
Analytical technique for separating gas mixtures, in which the gas is passed through a long column containing a fixed absorbent phase that separates the gas mixture into its component parts.

Gas drainage layer
An engineered layer of high gas permeability immediately underlying an artificially established cap that is designed to facilitate the collection of landfill gas.

Geomembrane/synthetic
An engineered polymeric material fabricated to a low hydraulic permeability.

Geotextile
A geosynthetic material normally from man-made fibres which is fabricated to be permeable.

Groundwater
All water that is below the surface of the ground and in direct contact with the ground or subsoil.

Hydrocarbon
A chemical compound containing only hydrogen and carbon atoms.

Hydrolysis
A chemical reaction in which water reacts with another substance and gives decomposition or other products.

Inert
Strictly, material or wastes that will not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter which comes into contact in any way likely to give rise to environmental pollution or harm to human health. The total leachablity and pollutant content of waste and the ecotoxicity of the leachate must be insignificant and, in particular, not endanger the quality of surface and/or groundwater

Infra-red detector
An instrument that measures adsorption in the infra-red range of spectrum.

Installation (as defined by the PPC (England and Wales) Regulations 2000) (PPC Scotland Regulations 2003)
A stationary technical unit where one or more activities listed in Part 1 of Schedule 1 are carried out.

Any other location on the same site where any other directly associated activities are carried out which have a technical connection with the activities carried out in the stationary technical unit and which could have and effect on pollution.

And, other than in Schedule 3, references to an installation include references to part of an installation.

Interstitial
Occurring in the interstices (spaces) between other material.

Intrinsically safe
Said of apparatus that is designed to be safe under dangerous conditions – usually refers to equipment that can be used in an explosive atmosphere because it will not produce a spark.

Joints
Cracks within a block of rock along which there has been little or no movement of the rock.

Landfill gas
All the gases generated from the landfilled waste.

Leachate
Any liquid percolating through the deposited waste and emitted from or contained within a landfill.

Leachate recirculation
The practice of returning leachate to the landfill from which it has been abstracted.

LEL (Lower Explosive Limit)
The lowest percentage concentration by volume of a flammable substance in air which will allow an explosion to occur in a confined space at 25°C and normal atmospheric pressure, and where an ignition source is present (units: %).

Liner
A natural or synthetic membrane material, used to line the base and sides of a landfill site to reduce the rate of leachate and gas emissions.

Lithology
The study and description of the general, gross physical characteristics of a rock.

Mains gas
A commercial methane-rich gas distributed through underground pipes to domestic, commercial and industrial customers.

Marsh gas
Gas produced from marshes and bogs.

Methane
The hydrocarbon of the highest concentration typically found in landfill gas (CH_4).

Methanogenesis
The process leading to the production of methane.

Moisture content
Percentage of water contained in a sample of waste or soil, usually determined by drying the sample at 105°C to constant weight.

Monitoring
A continuous or regular periodic check to determine the ongoing nature of the 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.

Odorants
Strictly, chemical compounds added to mains gas to impart odour or, more widely, particularly odorous volatile organic compounds in landfill gas.

Odour threshold value (odour detection threshold)
The concentration of an odorous gas, detected by 50 per cent of an odour panel.

Partial pressure
In a mixture of gases or vapours, each constituent can be considered to contribute to the total pressure that pressure it would exert if it were present alone in a vessel of the same volume as that occupied by the mixture (units: %).

Permeability
A measure of the rate at which a gas will pass through a medium (litre^2). The coefficient of permeability of a given fluid is an expression of the rate of flow through unit area and thickness under unit differential pressure at a given temperature (litre/time).

pH
An expression of hydrogen ion concentration, specifically, the negative logarithm of the hydrogen ion concentration. The range is from 0 to 14, with 7 as neutral, 0–7 as acidic, and 7–14 as alkaline.

Phase (of a landfill)
A prepared operational, temporarily restored or restored area.

Pollution, pollutant
The addition of materials or energy to an existing environment system to the extent that undesirable changes are produced directly or indirectly in that system: a pollutant is a material or type of energy whose introduction into an environmental system leads to pollution.

Polycyclic
Organic chemical compound where the atoms form more than one ring structure.

Potentiation
The capacity of a compound to act as precursor for sensory or toxic effects from other compounds without causing such effects itself.

ppb
Parts per billion, method of expressing concentration. 1 ppb is a thousandth of a ppm (see below).

ppm
Parts per million, method of expressing concentration. 10,000 ppm v/v equates to 1 per cent gas at standard temperature and pressure (STP) by volume.

ppmv
Part per million by volume.

Protocol
A formal or customary procedure.

Putrescible
A substance capable of being readily decomposed by bacterial action. Offensive odours usually occur as by-products of this decomposition.

Retention time
The time at which the gases stay within the shroud at, or above, a specific temperature (also known as residence time) (measured in units of time).

Settlement
The amount by which a landfill surface sinks below its original level due to ravelling, compaction by its own weight, and degradation of the waste, e.g. a tipped waste thickness of 40 metres settling by 8 metres would have undergone 20 per cent settlement.

Sewer gas
Gas produced by the decomposition of organic compounds in sewerage.

Soft development
The re-use of land that avoids domestic, industrial or commercial property.

Specific moisture content
Specific moisture content of air is the ratio of the mass of water to the mass of dry air in a given volume of moist air (units: %).

Spike survey
Measurement of methane gradient with one data point at the base of the spiked hole and an assumed zero concentration at the surface.

Stabilisation
As applied to landfill, this term includes the degradation of organic matter or the leaching of inorganic matter to stable products and the settlement of the fill to its rest level. It also refers to the use of plants and/or geotextiles to prevent soil erosion from the surface of a landfill or spoil heap.

Stratification
Formation of distinct layers due to ineffective mixing of gases.

Stoichiometric
The exact proportions in which substances react. For combustion, a theoretical minimum amount of air or oxygen required to consume the fuel completely.

Synergism
An interaction of elements such that their combined effect is greater than the sum of their individual effects.

Time-weighted average
The resultant value averaged over a period of time.

Transitory
Not permanent, short lived.

Trigger/action levels
Trigger levels are compliance levels and, in order to meet trigger levels, action levels should be set at a level at which the operator can take action to remain compliant. These may form part of the PPC permit.

UEL (Upper Explosive Limit)
The highest concentration of mixture of a compound and air which will support an explosion at 25°C and normal atmospheric pressure, and in the presence of a flame.

v/v
By volume (as in % v/v or ppm v/v); usually applied to gases.

Well head
The top portion of a well, usually containing a valve, and various monitoring parts.

Well
A hole drilled within wastes for the purposes of sampling, monitoring, gas or leachate extraction.

Wobbe index
Ratio of the corresponding calorific value of a gas per unit volume and the square root of its relative density under the same reference conditions. It is dimensionless.

Working area
The area or areas of a landfill in which waste is currently being deposited.

w/w
By weight (as in % w/w).

Zone
Part of the site surface deemed to be of generally uniform character such that the area concerned is assumed to be suitably homogenous in the context of surface emissions.

Acronyms

ATP	Adenosine triphosphate
BAT	Best Available Technique
BES	Bentonite-enhanced soil
BMW	Biodegradable municipal waste
BOD	Biochemical oxygen demand
CFC	Chlorofluorocarbon
COD	Chemical oxygen demand
COSHH	Control of Substances Hazardous to Health
CQA	Construction Quality Assurance
DAC	Dense asphaltic concrete
Defra	Department for Environment, Food and Rural Affairs
DETR	Department of the Environment, Transport and the Regions
DoE	Department of the Environment
Dti	Department of Trade and Industry
EAL	Environmental Assessment Level
EIA	Environmental Impact Assessment
EPAQS	Expert Panel on Air Quality Standards
EQS	Environmental Quality Standard
ETSU	Energy Technology Support Unit (now part of Future Energy Solutions, AEA Technology)
FID	Flame ionisation detector
GCL	Geosynthetic clay liner
GC–MS	Gas chromatography–mass spectrometry
GDPO	General Development Procedure Order
GLC	Ground level concentration
GRT	Gas retention time
GWP	Global warming potential
HCl	Hydrogen chloride
HCFC	Hydrochlorofluorocarbon
HDPE	High density polyethylene
HF	Hydrogen fluoride
HRT	Hydraulic retention time
HSE	Health and Safety Executive
IPPC	Integrated Pollution Prevention and Control
IWM	Institute of Wastes Management (now Chartered Institute of Wastes Management)
LEL	Lower Explosive Limit
LLDPE	Linear low density polyethylene
LPA	Local planning authority
LPG	Liquefied petroleum gas
MDPE	Medium density polyethylene
NB	Nominal bore
Netcen	National Environmental Technology Centre
NFFO	Non-fossil Fuel Obligation
NMVOC	Non-methane volatile organic compound
NO_x	Nitrogen oxides
ODPM	Office of the Deputy Prime Minister
OEL	Occupational Exposure Limit
OES	Occupational Exposure Standard
PAH	Polycyclic aromatic hydrocarbon
PC	Predicted concentration
PCB	Polychlorinated biphenyl
PCDD	Polychlorinated dibenzo-*p*-dioxin
PCDF	Polychlorinated dibenzofuran
PEC	Predicted Environmental Concentration
PID	Photo-ionisation detector
PP	Polypropylene
PPC	Pollution Prevention and Control
PPG	Planning Policy Guidance
SEPA	Scottish Environment Protection Agency
SO_x	Sulphur oxides
SSSI	Site of Special Scientific Interest
TOC	Total organic carbon
TWA	Time-weighted average
UEL	Upper Explosive Limit
VOC	Volatile organic compound
WHO	World Health Organization

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