LFTGN 08

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Guidance for monitoring landfill gas engine emissions

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Published by:

Environment Agency
Rio House, Waterside Drive, Aztec West
Almondsbury, Bristol BS32 4UD
Tel: 08708 506506

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Dissemination Status
Internal: Released to Regions
External: Public Domain

Research Contractor
This document is based on research undertaken as part of R&D Project P1-406 by Entec.

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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) to 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. Environment Agency and SEPA officers, servants or agents accept no liability whatsoever for any loss or damage arising from the interpretation or use of the information, or reliance on views contained herein. It does not constitute law, but officers may use it during their regulatory and enforcement activities. Any exemption from any of the requirements of legislation is not implied.

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Acknowledgements
The Environment Agency would like to acknowledge the contribution made by the members of the Biogas Association and Eb Nationwide in the development of this guidance. The Environment Agency would also like to thank the operators who allowed access to their sites and the monitoring of equipment.

Executive summary

The Environment Agency and the Scottish Environment Protection Agency have produced this document to assist officers in the regulation of emissions from landfill gas engines. This report is mainly concerned with emissions from spark ignition engines and, in general, does not consider emissions from other forms of landfill gas utilisation such as dual-fuel engines and gas turbines. These other types of engines should be considered on a site-specific basis, drawing upon the principles contained within this guidance. A separate document is available on the monitoring of emissions from landfill gas flares.

This technical guidance draws upon information from collaborative research undertaken by the Environment Agency and the Biogas Association.

Tables A and B summarise the emission testing requirements for landfill gas engines installed and commissioned:

- between January 1998 and 31 December 2005
- post 31 December 2005.

Engines commissioned and installed before December 1997 should be considered on a site-specific risk basis, but with regard to the emissions standards specified in Table A. For each parameter, the analytical technique and reference method used are identified, along with the required testing frequency and emission limits.

These emission limits are a maximum value and may require adjustment or additional parameters, subject to a risk assessment being undertaken of local parameters.

Alternatives to the reference methods given in Tables A and B can be used as long as they are shown to be fit-for-purpose and a suitable justification is presented before sampling is undertaken.

Table A Summary of emissions testing requirements for landfill gas spark ignition engines commissioned between 1 January 1998 and 31 December 2005

Emission	Reference method [a]	Sampling and analytical technique	Minimum testing frequency	Emission limit [b]
NOx [c]	ISO 10849: 1996	Extractive sampling and chemiluminescence	Annually	650 mg/m^3
CO	ISO 12039: 2001	Extractive sampling and non-dispersive infra-red (NDIR) analysis	Annually	1,500 mg/m^3
Total VOCs	BS EN 12619: 1999 [d] BS EN 13526: 2002 [e]	Extractive sampling and flame ionisation detector (FID) analysis	Annually	1,750 mg/m^3
NMVOCs	BS EN 13649: 2002	Extractive sampling onto sorbent, thermal desorption and analysis by gas chromatography	Annually	150 mg/m^3

[a] Technical Guidance Note M2 (Environment Agency, 2002d)

[b] These standards are based on normal operating conditions and load (temperature: 0°C (273K); pressure: 101.3 kPa; and oxygen: 5 per cent (dry gas). For more information, see Section 5.5. Site-specific risk assessments may require a stricter emission standard to be applied.

[c] NOx expressed as nitrogen dioxide (throughout this document).

[d] At sites with low total VOC concentrations.

[e] At sites with low to moderate total VOC concentrations.

In addition to the numerical emission limits given in Table A, the following apply:

- Discharges must be vertically upwards and unimpeded by cowls or any other fixture on top of the exhaust.
- Sampling sockets must be fitted to all new installations and it is recommended that are fitted to existing installations.
- The management of crankcase emissions to minimise their release to the environment is recommended.
- Continuous assessment of methane and flow in the inlet gas is recommended.
- Continuous assessment of NOx and CO in the emission is recommended.

Table B Summary of emissions testing requirements for landfill gas spark ignition engines commissioned after 31 December 2005

Emission	Reference method[a]	Sampling and analytical technique	Minimum testing frequency	Emission limit[b]
NOx[c]	ISO 10849: 1996	Extractive sampling and chemiluminescence	Annually	500 mg/m^3
CO	ISO 12039: 2001	Extractive sampling and non-dispersive infrared (NDIR) analysis	Annually	1,400 mg/m^3
Total VOCs	BS EN 12619: 1999[d] BS EN 13526: 2002[e]	Extractive sampling and flame ionisation detector (FID) analysis	Annually	1,000 mg/m^3
NMVOCs	BS EN 13649: 2002	Extractive sampling onto sorbent, thermal desorption and analysis by gas chromatography	Annually	75 mg/m^3

[a] Technical Guidance Note M2 (Environment Agency, 2002d)

[b] These standards are based on normal operating conditions and load (temperature: 0°C (273K); pressure: 101.3 kPa; and oxygen: 5 per cent (dry gas). For more information, see Section 5.5. Site-specific risk assessments may require a stricter emission standard to be applied.

[c] NOx expressed as nitrogen dioxide (throughout this document).

[d] At sites with low total VOC concentrations.

[e] At sites with low to moderate total VOC concentrations.

In addition to the numerical emission limits given in Table B, the following apply:

- Discharges must be vertically upwards and unimpeded by cowls or any other fixture on top of the stack.
- Sampling sockets must be fitted to all new installations.
- Crankcase emissions must be managed to minimise their release to the environment.
- Continuous assessment of methane and flow in the inlet gas must be undertaken.
- Continuous assessment of NOx and CO in the emission is recommended.

Contents

Setting the scene

The Environment Agency and the Scottish Environment Protection Agency (SEPA) have produced this document to assist officers in the regulation of emissions from landfill gas engines. A standard set of monitoring methods has been produced to allow the collection of emissions data in a transparent and consistent manner. This document provides emissions standards to be met by all landfill gas spark ignition engines.

This guidance is concerned primarily with emissions from spark ignition engines and, in general, does not consider emissions from other forms of landfill gas utilisation. Other types of engines should be considered on a site-specific basis, but the aim should be to apply the principles contained within this guidance.

1.1 Structure of this document

This is one of a series of linked documents that support the overarching document, *Guidance on the management of landfill gas* (Environment Agency, 2004a). The full series comprises:

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

This document is divided into the following sections:

- Section 1 discusses the generation, combustion and utilisation of landfill gas.
- Section 2 discusses different types of landfill gas engines, their operation and maintenance and the emissions released, and outlines the clean-up technologies available.
- Section 3 reviews the relevant legislation and summarises international emission standards applicable to landfill gas engines.
- Section 4 details site-specific issues that may be encountered during emissions testing of landfill gas engines and incorporates health and safety considerations.
- Section 5 describes the monitoring methods including the frequency of testing and emission limits, the reference methods for analysis, the necessary correction factors and uncertainty, and how to assess the compliance of actual monitoring data.
- Section 6 sets out the sampling equipment, methodologies and analysis required to test the parameters.

1.2 Landfill gas - the issues

Landfill gas is an inevitable by-product of the anaerobic decomposition of organic waste and, because of its high content of combustible gases, it is a potentially valuable energy source. To overcome concerns relating to public health and environmental protection, landfill operators should collect and dispose of landfill gas in an environmentally safe manner.

Collection of the gas has been traditionally undertaken using collection wells within the landfill. When not utilised as a fuel, landfill gas is usually flared at high temperatures – a process that destroys most of the toxic and odorous components. Passive venting of landfill gas to atmosphere is no longer acceptable. At all landfills, some landfill gas does escape to atmosphere through the surface and lining of the site. The percentage of fugitive gas escaping will depend primarily on the collection efficiency on-site, the design of the lining, the capping of the site and the volume of gas generated.

1.2.1 The Landfill Directive

Annex I of the Landfill Directive (Council of the European Union, 1999) sets out a clear obligation to safely manage and minimise landfill gas emissions. The technical requirements of the Landfill Directive have been implemented in England and Wales via the Landfill Regulations (England and Wales) 2002 and in

Scotland via the Landfill (Scotland) Regulations 2003. The Regulations 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;
- 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;
- landfill gas which cannot be used to produce energy must be flared.

1.2.2 Renewables Policy

In 2000, the UK Government set a target of obtaining 10 per cent of the UK's energy from non-fossil sources by 2010. Its renewables policy has two main strands.

Non-Fossil Fuel Obligation (NFFO)
The Non-Fossil Fuel Obligation (NFFO) framework was established as part of the Electricity Act 1989 to ensure that renewable energy sources could compete in the open market. Under this Act, the Secretary of State made five Orders requiring the regional electricity companies (RECs) to contract for certain amounts of electricity-generating capacity from renewable sources (including wind, water and waste materials). There have been five NFFO Orders to date. The first two Orders, NFFO 1 and NFFO 2 started in 1990 and 1992, respectively, and terminated at the end of 1998. Contracts under the remaining three Orders, NFFO 3 (1995), NFFO 4 (1997) and NFFO 5 (1998), will continue for many years, with the last such contract terminating in 2018.

Renewables Obligation
As part of its revised policy for renewable energy in the UK, the Government introduced the Renewables Obligation for England and Wales (known as Renewables Obligation (Scotland) for Scotland) as a successor to the NFFO. This Obligation, which was introduced by the Utilities Act 2000, requires power suppliers to derive a specified proportion of the electricity they supply to their customers from renewable resources. It also introduced transitional arrangements for NFFO 3, 4 and 5. Table 1.1 sets out the percentage obligation against the year of achievement.

Compliance with the Renewables Obligation is demonstrated by presenting Renewables Obligation Certificates (ROCs) to the Office of Gas and Electricity Markets (Ofgem) at the end of each compliance period. Suppliers may also fulfil all, or part, of their obligation by paying Ofgem a buyout price for each kWh they are short of their target. The buyout price is linked to the retail price index (RPI), with the revenue raised being returned to the suppliers in proportion to the number of ROCs they have presented to discharge their obligation. This approach is intended to provide a strong financial incentive for suppliers to fulfil the Renewables Obligation through ROCs rather than simply buying out.

Further information on the Renewables Obligation and UK renewables policy can be found on the Department of Trade and Industry's website (http://www.dti.gov.uk/energy/renewables/).

Table 1.1 Percentage of total sales of electricity from renewable sources

Year	Percentage of total sales of electricity from renewable sources
2002	3
2003	4.3
2004	4.9
2010	10.4*

* Maintained at this level until 2027.

1.3 Landfill gas composition and energy recovery plant

1.3.1 Landfill gas constituents

The Landfill (England and Wales) Regulations, 2002 define landfill gas as: 'all the gases generated from the landfilled waste'.

The chemical composition of landfill gas is variable, but mature landfill gas is commonly a mixture predominantly made up of methane (CH_4; generally 60 to 35 per cent volume/volume) and carbon dioxide (CO_2; 35 to 60 per cent v/v). It will also contain trace concentrations of a range of vapours and gases.

Landfill gas is generally considered to consist of two distinct fractions:

- The **bulk fraction** is a mixture of methane, carbon dioxide, hydrogen, nitrogen and oxygen. These are measured in terms of percentage by volume.
- The **trace fraction** is a wide range of volatile and semi-volatile organic compounds that are measured in terms of parts per million (ppm) or parts per billion (ppb). Over 500 trace components have been identified in landfill gas, comprising up to one per cent of the gas by weight (about 0.1 to 0.35 per cent by volume) (Environment Agency, 2002a).

Only a limited number of studies have been undertaken to investigate the emissions from landfill gas combustion processes. However, it is apparent that emissions can be highly variable from plant to plant and at different periods of operation within the same plant. Primary emissions are nitrogen, carbon dioxide, sulphur dioxide (SO_2), oxides of nitrogen and water vapour. In the case of sulphur dioxide, emission concentrations depend primarily on sulphur-containing compounds in the landfill gas. Hydrogen sulphide (H_2S) may be a significant component and this may have implications for local air quality. Dual-fuel engines that utilise diesel in combination with landfill gas often emit higher concentrations of hydrogen sulphide and sulphur dioxide than spark ignition engines.

In addition to the compounds indicated above, a number of trace components will be emitted including heavy metals and volatile organic compounds (VOCs). Trace quantities of metals will be present in both the elemental and compound form (As, Cd, Cr, Cu, Pb, Mn, Hg, Ni, Sn, Zn). Trace quantities of a number of compounds with potential health impacts may be emitted, with dioxins and furans of particular interest (Fielder, 2001).

1.3.2 Generation of landfill gas during landfill life

The five phases in the generation of landfill gas are discussed in detail in *Guidance on the management of landfill gas* (Environment Agency, 2004a).

- Phase I results in the liberation of carbon dioxide, water and heat.
- Phase II results in alcohol formation.
- Phase III results in acetate formation.
- Phase IV sees methane and carbon dioxide evolving in a ratio of approximately 3:2.
- Phase V is where the gaseous content of the landfill will gradually assume that of atmospheric air.

These phases can last many years and typically will extend into the period well after the site has stopped taking waste. Landfill gas is suitable for use in landfill gas engines during phases IV and V.

1.3.3 Factors affecting the constituents of landfill gas

The composition of landfill gas will vary from one site to another and from one cell of a landfill to another. It will also change with time.

The important factors controlling the rates and amounts of gas likely to be evolved include:

- site characteristics
- moisture content
- waste type
- pH
- age of the waste
- temperature
- site operations
- ingress of oxygen
- density of waste
- gas management system.

1.4 Landfill gas combustion

Combustion is the chemical reaction between fuel and oxygen, resulting in the liberation of heat. Once the fuel is ignited, it must supply sufficient heat to raise the temperature and establish continuous combustion.

During combustion processes, fuel is premixed and reacted with an oxidant to produce heat and light. In landfill gas engines, 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:

$$CH_4 + 2O_2 + 7.52N_2 \longrightarrow CO_2 + 2H_20 + 7.52N_2 + \text{heat} + \text{light}$$

This stoichiometric mixture represents the precise amount of air needed to completely burn one mole of methane. If more air is supplied than required for stoichiometric combustion, the mixture is termed lean and oxidising. If, however, too little air is supplied, the mixture is rich and reducing. In practice, more air is added to ensure that nearly complete combustion takes place within the engine; therefore, the engine runs lean.

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 abstraction and engine system and their combustion products
- contaminants present in the air used in combustion.

The thermal yield of complete combustion of methane is 35.9 MJ/m^3. Typically, landfill gas containing 50 per cent methane will have a thermal yield of approximately 18 MJ/m^3.

1.5 Landfill gas utilisation

The technology for converting landfill gas into a useful source of energy has improved continuously during the successive tranches of the NFFO. With a careful maintenance programme, landfill gas collection and use can be optimised to turn a potential liability into an asset.

The utilisation of landfill gas as a fuel has certain limitations, including:

- the gas field produces continuously (utilisation is best suited to continuous use applications rather than collection and storage);
- climatic and seasonal changes will cause variations in supply;
- the gas is generated at fixed sites with a limited life-span (the supporting infrastructure can be expensive);
- the gas contains a wide range of compounds (e.g. corrosive and acidic materials, which can be detrimental to certain applications).

However, in practice landfill gas can be used for a number of different applications, including:

- combined heat and power (CHP) plant for industrial facilities including brick and cement manufacture and space heating of greenhouses;
- electricity generation – use of landfill gas as a fuel in spark ignition internal combustion (IC) engines, turbines or boilers to produce electricity, which is then either sold to the national grid or used locally at industrial or domestic sites;
- mains gas pipeline use – after upgrading to saleable fuel for introduction into the gas grid or the production of bottled fuel;
- vehicle fuel substitution.

2

Landfill gas engines

2.1 Introduction

The types of landfill gas engine used to convert landfill gas into energy include:

- gas turbines
- dual-fuel (compression ignition) engines
- spark ignition engines.

Engines are available in varying sizes, from a few hundred kilowatts to several megawatts.

There are approximately 150 sites in the UK currently generating electricity for the grid. The UK landfill gas resource is estimated to be equivalent to around 6.75 TWh/year (around 2 per cent of the current UK electricity demand) (DTI, 2002). Beyond 2005, the number of landfill gas utilisation schemes may decline as implementation of the Landfill Directive results in the diversion of biodegradable municipal waste away from landfill sites, thus reducing the potential for methane generation.

The following review of landfill gas engine characteristics is based on a typical lean-burn spark-ignition engine. These are the most commonly used landfill gas engines in the UK.

2.1.1 Operational design intent

The commonest landfill gas engines are lean-burn spark ignition gas engines that have been modified to run on a biogas fuel. Traditionally, these engines are based on a heavy fuel oil/diesel engine, which they have many technical and operational design similarities. Some landfill gas engine units in the UK are dual-fuelled to operate on a combination of landfill gas and pilot diesel fuel oil, which provides the ignition source.

The principle of lean-burn combustion offers a combination of high power, high efficiency and reduced exhaust emissions. This is achieved through the controlled combustion of a homogenous and lean mixture of gas and air in a compact combustion chamber. The gas feed pressure can be varied to keep the energy supply to the engine constant. Some control systems use exhaust oxygen sensors to maintain optimal operating conditions for the engine and to maximise power output.

The engines are designed to operate for base load power generation under varying conditions and can operate for significant periods between scheduled overhauls. A typical power station compound will include a flare to safely combust any landfill gas collected in excess of the maximum requirements of the engines and to ensure effective gas management during anticipated engine downtime. The engine generators and ancillary equipment are housed in buildings or container units that are acoustically designed for noise reduction.

Figure 2.1 shows the basic process flow for landfill gas. Because differing landfill sites will produce gas of differing composition, gas collection systems will require slightly different methods of separation and treatment.

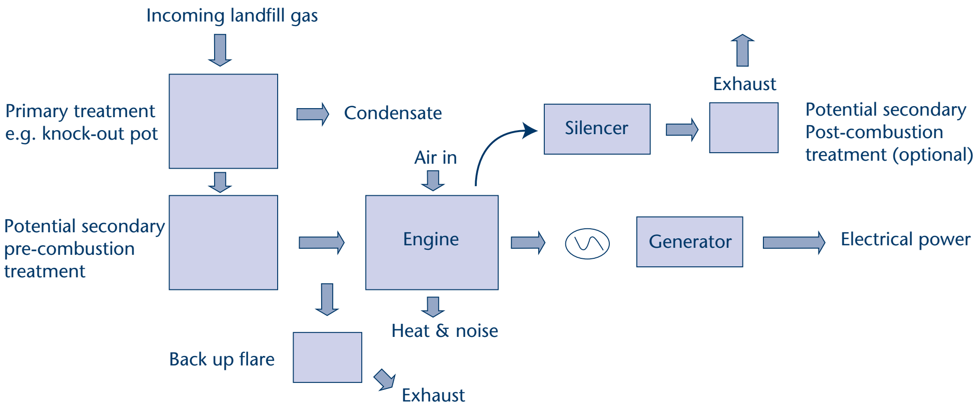
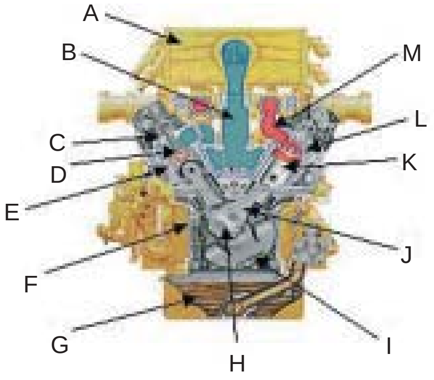


Figure 2.1 Process flow diagram for landfill gas

2.1.2 *Operation of an engine*

A typical internal combustion engine for landfill gas is shown in Figure 2.2. A brief description of the main components is given below.



A	Intercooler/Turbo Charger
B	Inlet (Air & Fuel)
C	Rocker Arms, Valves & Springs
D	Spark Plug
E	Cylinder
F	Engine Block
G	Oil Sump
H	Crankshaft
I	Balance Weight
J	Connecting Rod
K	Piston
L	Coolant
M	Exhaust

Figure 2.2 Parts of an engine

Turbo charger
The majority of engines are fitted with a turbo charger, which significantly boost the engine's power without increasing the size or number of cylinders. The turbo charger is fitted on the exhaust manifold of the engine and uses the energy in the exhaust gas to spin the compressor turbine. This is a type of forced induction system for the air flowing into the cylinder. Compressing the air has the advantage that it lets more air into the cylinder; more air means that more fuel can be added, thus generating more power from each explosion in the cylinder. More power in each explosion will generate more power from the generating set. The turbo charger increases the temperature of the air due to its compression. A water-cooled heat exchanger, the intercooler, is fitted to remove the heat from the compressed air before it is introduced into the cylinder.

Inlet
Most types of lean-burn, spark-ignition gas engines mix the combustion air and fuel before the turbo charger so that the air/fuel mixture is compressed and the intercooler removes most of the heat of compression. On dual fuel engines the compressed air from the turbo charger is mixed with the landfill gas fuel as it enters the cylinders via the inlet valves or via a direct injection system.

Cylinder
The cylinder is the core of the engine and consists of the piston, valves and spark plugs. Once the air/fuel mixture enters the cylinder, the piston moves up and compresses the gas. At a predetermined point in the cycle the spark plug operates and causes the mixture to explode. This explosion forces the piston down. Once the piston reaches the bottom of its stroke, the exhaust valves open and the exhaust gas is discharged via the exhaust manifold and turbo charger. A 4-stroke engine has the following stages:

- induction
- compression
- ignition
- exhaust.

Connecting rod and crankshaft
The connecting rod connects the piston to the crankshaft. It oscillates to convert the vertical movement of the pistons to a rotary motion on the crankshaft. The crankshaft is connected to the generator to generate electricity.

Sump
The sump surrounds the crankshaft. It collects oil, which has lubricated and cooled the crankshaft, connecting rods and other engine components.

Coolant
A jacket of water surrounds the cylinders in the engine block. The water ensures that the engine block does not get too hot; the radiator dissipates the heat from the engine.

2.1.3 *Operating profiles*

Landfill gas plants differ from site to site in both operation and characteristics. In the UK, the most commonly used engines in operation are units made by Caterpillar and Jenbacher. Other engine suppliers include Deutz, Ruston Mirlees, Perkins and Waukesha. The size and output energy producing capacity of these engines is between 300 kW and 3.6 MW for an individual unit. The combined output from engines installed on a single landfill site can vary greatly from 300 kW to a site with a potential production of 20–30 MW.

Many factors can affect the operating profiles and efficiency of landfill gas engines operating in the UK. These include:

- physical and chemical characteristics of the waste
- gas management systems
- site characteristics (e.g. age of the landfill, remaining capacity of the landfill).

Landfill gas production from landfilled waste will vary over time in terms of both production rate and composition. However, an efficient gas management and engine control system will be able to determine and respond to the typical characteristics of the landfill gas fuel input for a specific site engine, such that an efficient engine operating profile can be established. Engine management systems are used to adjust and reduce nitrogen oxide (NOx) emissions, but any reduction must be balanced with the likely increase in other emissions, most notably carbon monoxide (CO) (Environment Agency, 2004b).

Many sites operate a primary pretreatment system to remove moisture and particulates from the landfill gas. The need for secondary systems (e.g. full chemical treatment) is less frequently justified and will depend upon site-specific factors such as the aggressiveness of the gas. Engine components can be damaged by certain components (e.g. siloxanes) within the landfill gas. Untreated aggressive gas constituents will reduce engine efficiency and reliability, and necessitate more regular servicing and engine overhauls.

2.1.4 Maintenance schedules

The utilisation of landfill gas is not normally a labour-intensive operation. Operational technology has progressed to such an extent that some schemes can run on sites that are not permanently manned. Remote telemetry links can be deployed to allow several landfill gas engine sites to be controlled centrally. However, the amount of maintenance time that will be required during the early years of a landfill gas utilisation scheme is difficult to predict due to the variability of gas production and potential problems.

Chemical analysis of the engine oil is normally carried out regularly as part of a preventative maintenance regime. This analysis indicates when oils need changing and can show possible wear or defect to engine components.

A regular maintenance scheme should be established for individual engine units, based on guidelines specified by the manufacturer. The engine maintenance schedule should not be a fixed programme, but should depend on many factors such as gas quality and age of engine. Maintenance should generally be carried out as and when required, since some wearing components may require replacement before a scheduled overhaul service.

The advantages of carrying out regular maintenance include:
- maximising engine efficiency and life cycle revenue through increased availability;
- avoiding unscheduled downtime;
- minimising operational costs by maintaining optimum levels of engine operation and planning maintenance schedules in advance;
- maintaining engine exhaust emissions at low levels.

Typical maintenance schedules for a Caterpillar engine is given in Table 2.1. For Caterpillar engines, there are four service categories for engine maintenance: preventive maintenance; top end overhauls; in-frame overhauls; and major overhauls. Schedules will vary between manufacturers and also due to site-specific factors.

Preventative maintenance
Preventive maintenance is designed to avoid unscheduled downtime and to maintain an efficient level of operation between overhaul services. The following measures are included at this level of service:

- replacing parts such as oil filters, air filters, fuel filters and spark plugs;
- setting valve lash;
- measuring valve recession;
- lubrication of linkages such as fuel control rods and actuator link joints;
- changing oil and coolants.

Preventive maintenance may be carried out as routinely as every 400–750 hours.

Top-end overhaul
A top-end overhaul may involve:

- removing, renewing and replacing the cylinder heads;
- servicing the turbocharger;
- inspection and maintenance of other mechanical components.

In-frame overhaul
An in-frame overhaul will include the work carried out during a top-end overhaul plus:

- additional inspection and replacement of piston rings, liners, connecting rod bearings, main crankshaft bearings and seals;
- inspection of other wearing components such as valve lifters, gear train bearings, dampers and seals and the replacement of such components if necessary.

Table 2.1 Typical engine maintenance schedules

Engine model	Design speed	Fuel source	Expected overhaul intervals (hours)			
			Preventive	Top end	In-frame	Major
G3500	1,500	Biogas	500	7,500	22,500	37,500

Source: Caterpillar (1997)

Major overhaul
The major overhaul incorporates the work undertaken during the top-end and in-frame overhauls, plus all of the additional parts and labour needed to completely rebuild the engine.

2.2 Emissions from landfill gas engines

The composition of the exhaust from the landfill gas engine will depend on a variety of factors. These include:

- the composition of the raw gas;
- the pretreatment of the raw gas, e.g. water removal, particulate removal;
- combustion conditions, e.g. temperature, excess air;
- potential post combustion systems.

As a result, the exhaust emissions will contain:

- an unburnt fraction of the raw fuel gas, e.g. methane, etc.;
- products of complete and incomplete combustion, e.g. CO_2, CO, VOCs, etc.;
- contaminants from the engine, e.g. lubricants, metals, VOCs;
- secondary products generated during combustion, e.g. NOx, SO_2, acid gases.

Thus, key emissions that may be of interest from landfill gas engines are:

- combustion gases (NOx, CO, CO_2, SO_2);
- total particulate matter;
- heavy metals (As, Cd, Cr, Cu, Hg, Mn, Ni, Pb, Sn and Zn);
- total volatile organic compounds (VOCs);
- dioxins and furans (PCDDs and PCDFs);
- polycyclic aromatic hydrocarbons (PAHs);
- hydrogen sulphide (H_2S);
- halide gases (HCl, HF);
- nitric acid (HNO_3);
- speciated organic compounds.

2.3 Landfill gas clean-up

Emission-specific abatement technologies are available for both pre-combustion gas and post-combustion exhausts.

Currently, the main reasons for using pre-combustion gas clean-up technologies are to minimise engine damage caused by aggressive components in the raw gas. This in turn minimises essential maintenance and the costs associated with repairing worn engine parts. This also can have the benefit of reducing exhaust emissions.

Guidance on gas treatment technologies for landfill gas engines (Environment Agency, 2004b) explains how appropriate and effective the various technologies are and provides a basis for a cost benefit analysis of these abatement technologies. The need for additional gas clean-up should be identified on a site-specific basis.

2.4 Landfill gas flares

During periods where there is too much landfill gas for the engines to burn or during periods of maintenance, it will be necessary to burn the landfill gas through an enclosed flare. However, the burning of landfill gas through a flare will also result in the release of emissions. *Guidance on the monitoring of landfill gas flare emissions* is available as a separate document (Environment Agency, 2004c).

Review of existing emissions standards

3.1 The need for emissions standards for landfill gas engines

One aim of the Landfill Directive is to reduce methane emissions. This coupled with the UK's renewables policy (see Section 1.2.2) means that the utilisation of landfill gas as a viable source of fuel in combustion processes has become a commercial reality.

Emissions from landfill gas engines have become an important consideration for both local air quality management and health risk assessment due to:

- the advent of commercial-scale plant utilising landfill gas as a fuel source;
- the spread of this energy type;
- the proximity of many landfill sites to residential and business units.

The majority of current standards worldwide are generic to all plant using landfill gas as a fuel source, rather than being specific to a single type of technology (e.g. engines based on diesel engines, attached to generators or boilers). Although this is not itself a problem, the many factors involved in the operation of landfill gas engines will result in distinctly different emissions from different operations.

3.2 International standards

A number of EU countries have adopted standards for emissions from landfill gas powered plants. German (TA Luft) and Swiss (LVR) standards are summarised in Table 3.1, together with the regional standards adopted by Essen in Germany.

Emissions standards are more complex than plain numbers and, thus, a simple comparison is inappropriate. For example, standards can be based on process type approval, best practice or site-specific risk.

Both the EU and USA have statutes for regulating emissions from stationary spark ignition engines, gas turbines and boilers rather than legislation related specifically to those powered by landfill gas (e.g. Council of the European Union, 2002). The maximum emission levels set out in these statutes are applied to equipment fuelled by landfill gas. However, these emission limits are often contained in several different pieces of legislation, reflecting when the legislation was enacted.

The United States Environmental Protection Agency (USEPA) is currently developing protocols for monitoring emissions from stationary internal combustion engines and included in this protocol are the emissions from engines using landfill gas as a fuel source.

The USEPA has adopted a similar style of standards for stationary spark ignition engines. These standards are variable depending on the year of construction of the equipment. The USEPA emission limits (ICCR, 1997) for a capacity ≥225 cc are:

CO	519 g/kWh
hydrocarbon (HC) + NOx	13.4 g/kWh

For comparison purposes, a typical 1 MW site in the UK has a capacity of 47,000 cc (based on a 1 MW Jenbacher engine).

In addition to USEPA and federal government sources, US states and counties can enact local legislation to control of a variety of environmental emissions. For example, Maricopa County in Arizona has issued the following maximum emission levels for non-mobile IC engines.

NOx	213 ppm (470 mg/m^3)
Total VOC	800 ppm (430 mg/m^3 expressed as carbon)
CO	25,344 ppm (31,680 mg/m^3)

In addition to these standards, any new commissioned IC engines combusting landfill gas are required to comply with a NOx emissions limit of 140 ppm (rich burn) and 210 ppm (lean burn).

Table 3.1 European emission levels for landfill gas fuelled plant

	TA Luft (Germany) [a] 2002 [b] Internal combustion engine	HmfUR (Essen) 1989 Engine/boiler	LRV (Switzerland) 1985 (2000)	
			Stationary combustion engine [c]	Waste burning
Dust (mg/m^3)		5	50	20
CO (mg/m^3)	650	100	650	60
NOx (mg/m^3)	500	200	400	80
SO_2 (mg/m^3)	350	500	–	50
HCl (mg/m^3)	–	30	–	20
FHF (mg/m^3)	–	5	–	2
Unburned carbon (mg/m^3)	–	20	–	20
Formaldehyde (mg/m^3)	60	–	–	
Other metals (mg/m^3)	_	_	_	1
PCDD/PCDF (ng/m^3)	–	0.1	–	–

[a] Referenced to 5 per cent oxygen for engines.
[b] TA Luft provides guidance that is implemented as standards at the state level.
[c] Based on > 0.1 MW thermal input.

Table 3.2 Emission limit valves (ELVs) for NOx for new installations set by the Gothenburg Protocol

Equipment		NOx emission (mg/m^3)
Boilers 50-100 MW		400
Gas turbine		50
Spark ignition (IC)	Lean burn engines	250
	All other engines	500

Note: Values are referenced to 5 per cent oxygen and apply to engines running >500 hours/year.

4

Site-specific issues

4.1 Health and safety

Health and safety at work is not regulated by the Environment Agency or SEPA. This guidance is issued as advice to those who will be required by the regulator to carry out the work described in this document. Any health and safety issues should be discussed with the Health and Safety Executive (HSE).

4.1.1 Safety requirements

Consideration of health and safety is of paramount importance when undertaking any engine emissions programme. It is a legal requirement for a health and safety risk assessment to be carried out before any test work is undertaken at a site (see Section 4.1.2). A risk assessment considers the levels of risk from any hazards present on a site and identifies what measures need to be implemented in order to minimise the safety risk. A preliminary site survey should be undertaken before any emissions monitoring exercise.

Each site will have site-specific issues and the risk assessment should assess the risks associated with:

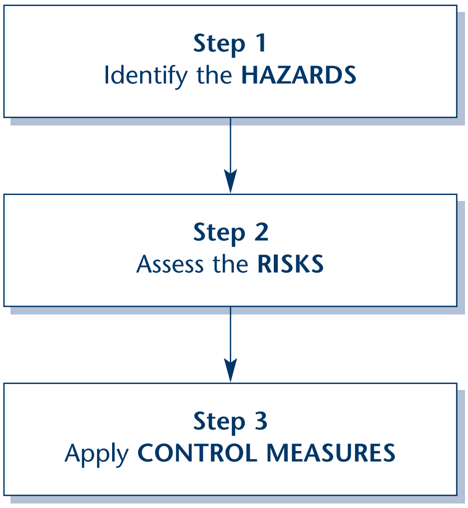
- the testing site location
- sampling positions
- site/test area access
- logistical requirements.

The risk assessment should be updated to account for any changes made to the proposed working plan as set out in the method statement. Safety requirements must take priority over any other factor in the testing programme.

4.1.2 Health and safety guidance and regulations

The Health and Safety at Work Act 1974 places a duty on employers to have a safety policy and to carry out risk assessments for any work programme. Any work being carried out to the Agency's Monitoring Certification Scheme (MCERTS) standards (Environment Agency, 2002e) also requires a risk assessment to be produced. Technical Guidance Note M1 (Environment Agency, 2000b) provides detailed guidance for the assessment of safety requirements on a test site.

The fundamental stages of the risk assessment process can be summarised as:



It is vital to understand the difference between hazard and risk:

- a **hazard** is a substance or physical situation with inherent potential to cause harm;
- **risk** is an estimation of the likelihood of that potential being realised, within a specified period or in specified circumstances, and the consequence.

The Source Testing Association also publishes guidelines on the hazards and risks relating to source testing (STA, 2000a), which describe general hazards and potential risks associated with testing. It has also produced *Example risk assessments for stack sampling operations* (STA, 2000b), which provides guidance on the issues to be aware of when undertaking emissions testing.

The MCERTS performance standard for organisations carrying out manual stack emissions monitoring includes an annex detailing requirements for undertaking a risk assessment prior to stack emissions testing (Environment Agency, 2002c). This guidance should be consulted as part of the risk assessment process.

4.1.3 *Key health and safety issues relating to landfill gas engine exhaust testing*

Prominent hazards to be considered during any landfill gas engine-testing programme are set out in Figure 4.1.

The hazards depicted in Figure 4.1 are an indication of some factors that may be included in a normal risk assessment. However, this list of hazards is not exhaustive; others include work place stress, fire and explosions within the utilisation compound.

An individual risk assessment must be completed for each site test as there will be site-specific issues that need to be accounted for in the assessment.

4.2 Emissions testing

This section provides an overview of the potential practicalities or site-specific issues associated with emissions testing. Significant emphasis must be given to the health and safety issues to be considered during the testing of the landfill gas engines.

4.2.1 *Safe working platform and means of access to the sampling position*

The safety requirements for emission monitoring is considered in Section 4 of Technical Guidance Note M1 (Environment Agency, 2002b). The provision of an adequate sampling platform with safe access is of paramount importance to a successful and safe sampling programme. Under no circumstances is monitoring via a ladder or a cherry picker acceptable.

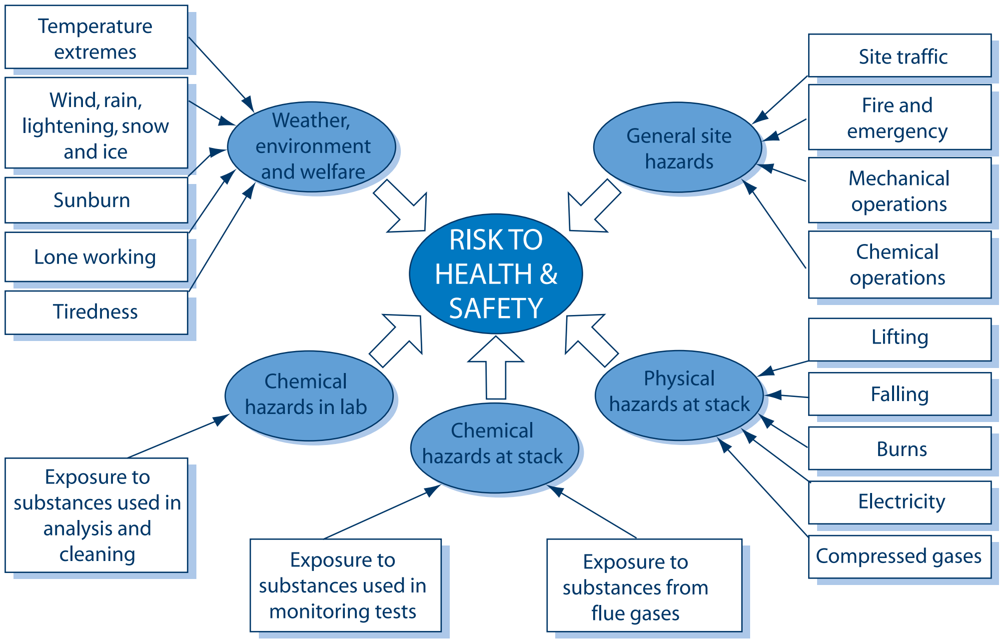
With respect to scaffolding, stack testers need to see evidence that the scaffold has been inspected by a competent person prior to use. This inspection must be documented as a written record such as a properly completed and dated Scaf-Tag accreditation before the test teams operate on the scaffold. A Scaf-Tag certificate requires each scaffolding platform to be inspected by the scaffolding company every seven days or the certificate becomes invalid. The purpose of this inspection is to re-assess platforms that have undergone intensive use, have been modified or have been subject to extreme weather conditions.

However, it is the responsibility of the site management and the test team to ensure that the scaffolding is fit for use on the day in question. This may require a daily inspection of items such as:

- guard rails
- toe boards
- walking areas
- ladders (are they secured at the top)
- access to the working area.

If there is any doubt over the safety of the scaffolding, this must be communicated and work must not progress. For further information, refer to Technical Guidance Note M1 (Environment Agency, 2002b) and relevant health and safety documents.

All platforms must meet the minimum weight criteria required for sampling, defined as 400 kg point load in BS EN 13284-1 (BSI, 2002a). The platform should be provided with handrails and kick-boards that meet the requirements of the Construction (Health, Safety



Source: Technical Guidance Note M1 (Environment Agency, 2002b)

Figure 4.1 Prominent hazards associated with emissions monitoring and Welfare) Regulations 1996. The minimum length in front of the access port must be 2 metres or the length of the probe plus 1 metre (whichever is the greater). The working height of the platform should also be designed so that an individual working on the platform does not have an exhaust exit at or below head height. This is because, if the wind direction were to change, there is a risk that hot exhaust emissions might blow onto the individual.

Figure 4.2 identifies some of the hazards associated with working platforms and emissions testing. For example, the access ladder is not properly secured against the scaffolding and there are numerous trip hazards on the sampling platform, including the location of the sampling equipment and the sampling line cuts across the sampling platform. Figure 4.2 demonstrates that extreme care must be taken when carrying out emissions testing.

Careful consideration must be given to the details shown in Figures 4.3 to 4.6 when planning any emissions testing programme. The working platform should be considered in terms of its size; it should enable a test team to operate safely using often awkward and heavy sampling equipment. Standard platform layouts are provided in Figures 4.3 and 4.4. The surface area of the platform should be no less than 5 m^2.

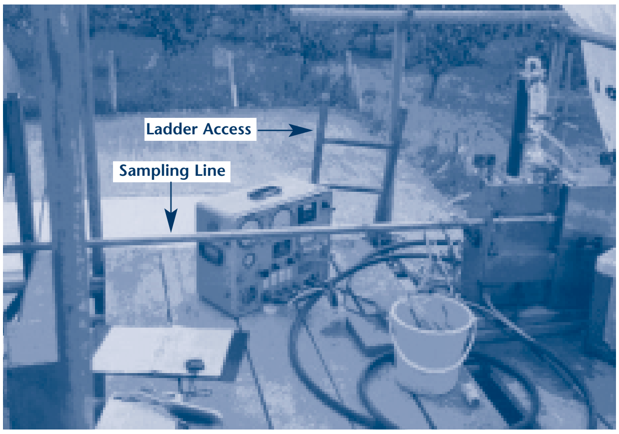
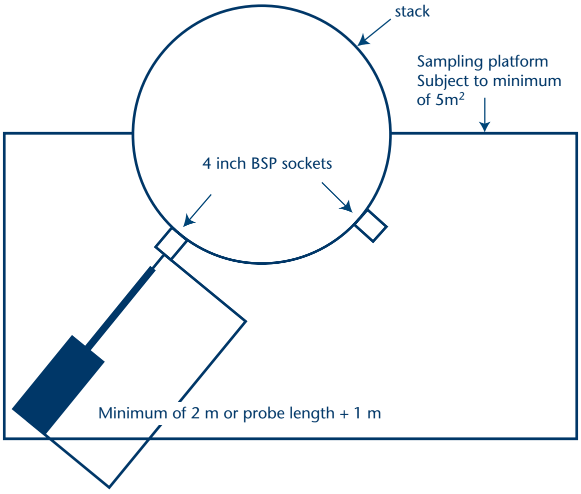
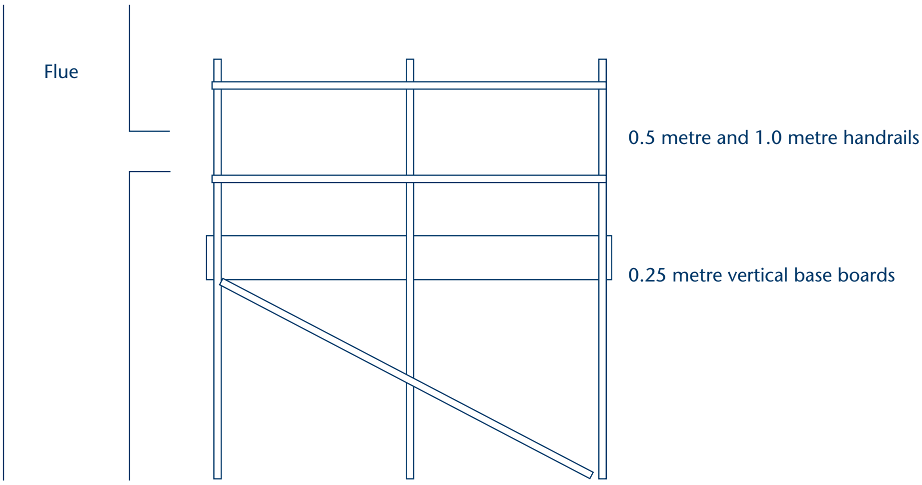


Figure 4.2 Example hazards on a working platform



Source: Technical Guidance Note M1 (Environment Agency, 2002b)

Figure 4.3 Plan view of platform working area and orientation recommendations for small vertical circular stacks (<3.6 metres in diameter)



Note: Handrails must be clear of the sampling holes.

Figure 4.4 Typical scaffolding layout

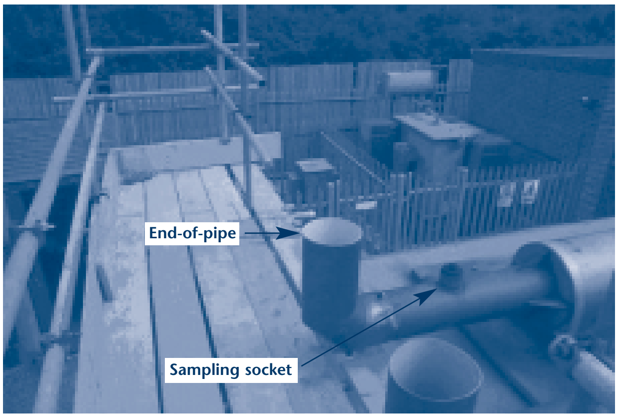


Figure 4.5 Example sampling platform for emissions monitoring

Figure 4.5 shows an actual sampling platform used to monitor the emissions from a landfill gas engine, along with a sampling point and end-of-pipe emissions testing point.

4.2.2 Engine exhausts

The type of exhaust fitted onto the engine unit will determine the sampling methodology required for emissions testing.

Many existing engine units have a short, stub-style exhaust (this may or may not include an elbow bend). These are unsuitable for the installation of sampling ports as there is often not enough length on which to fit the ports. This results in there being insufficient exhaust length on either side of the ports to make the sampling methodology valid. Modified methods of sampling these short stub exhausts (see below) must be agreed with the regulator.

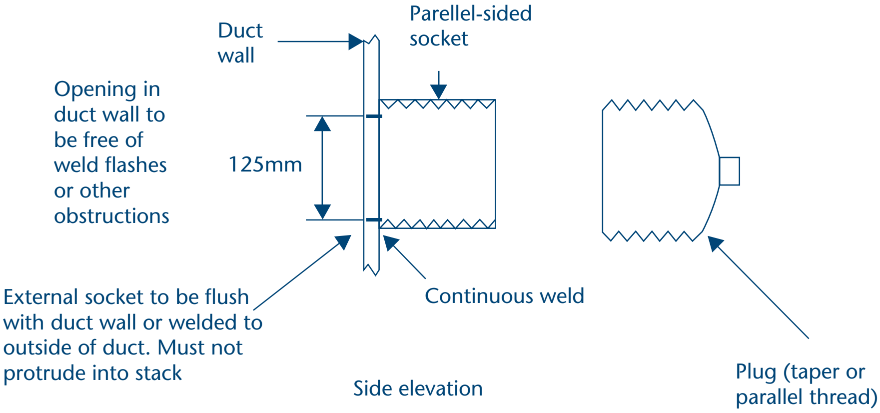
Most engine units have a sampling port immediately after the engine turbine. This may be used by the control system to measure NOx generation and to adjust the air: fuel ratios, and hence the control of the engine. Emissions sampling typically requires sampling ports of a larger diameter. If detailed size analysis of particulate matter is required, a 125 mm diameter access port is essential. For some combustion emissions, sampling ports can be smaller than the 125 mm diameter quoted e.g. a 50 mm sampling port. Alternative sampling port locations and sizes may be acceptable on existing engines, but must be agreed in writing with regulator.

Figure 4.6 sets out a typical access point for sampling purposes, with the dimensions given in millimetres.

If sampling ports are not available or it is not practicable to fit the ports to an exhaust, end-of-pipe sampling can also be undertaken as an interim measure.

All new engines are expected to incorporate suitable sampling ports to meet the requirements of BS EN 13284-1 (BSI, 2002a). The modification of engines at sites remaining within the waste management licensing regime will be prioritised on a site-specific risk basis. In addition, all discharges should be vertically upwards and unimpeded by cowls or any other fixture on top of the exhaust (HMIP, 1993). This modification will significantly improve the dispersion of emissions in the atmosphere and aid emissions monitoring.

Table 4.1 shows the differences between emissions from the sampling socket and from the end-of-pipe. These data come from an actual spark ignition engine test, where each sample period consisted of 120 readings.



Source: Environment Agency (2002c)

Figure 4.6 125 mm socket installed as an access point

The data in Table 4.1 suggest that the differences between the emissions from a sampling port and from the end-of-pipe can be small and within the uncertainty of the sampling techniques. Consequently, it is valid to use end-of-pipe sampling as a representative measure of combustion gas emissions for an interim period while more suitable arrangements are constructed on new installations or on existing ones as a result of re-permitting. Figure 4.7 also compares emissions of the combustion gases recorded in the sampling port and end-of-pipe. Again, this trace shows the similarities between emissions from the sampling socket and end-of-pipe.

When sampling exhaust gases from landfill gas engines, a flow profile is required to ensure that a representative sample is taken. If the ratio of the highest to lowest gas velocities exceeds 3:1, another sampling position should be sought (BSI, 2002a). The flow profile overrides other sampling parameters; sampling ports not on a straight run of ductwork can therefore still be used if the flow profile is acceptable.

Isokinetic sampling (when the sample is extracted from the gas stream at the same velocity as the gas in the duct) should be undertaken with reference to BS EN 13284-1 (BSI, 2002a), although this is largely designed for large diameter exhausts. Isokinetic sampling must be undertaken for particulate-based emissions. For gaseous emissions, it is not essential to sample isokinetically although, for components such as HCl and HF where droplet formation may occur, isokinetic sampling should be considered.

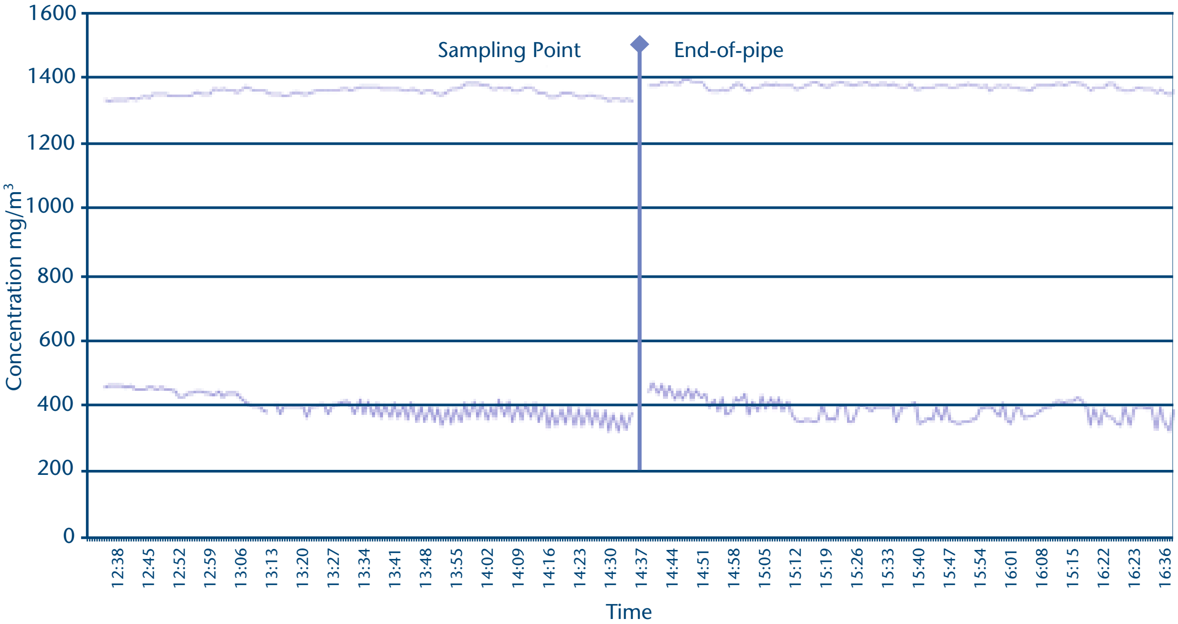
4.2.3 Power supply

A reliable source of power is required for the sampling equipment and continuous gas monitoring instruments. Ideally, a 410 V power supply should be suitable, although 110 V supplies should be used for portable equipment. Different instruments may have alternative requirements for power.

Table 4.1 Comparison between emissions from end-of-pipe and sampling sockets

	Oxygen (%)		Carbon monoxide (mg/m^3)		Nitrogen dioxide (mg/m^3)	
	Sampling port	End-of-pipe	Sampling port	End-of-pipe	Sampling port	End-of-pipe
Maximum	10.3	10.6	1,398	1,398	449	459
Minimum	9.9	9.8	1,326	1,352	307	311
Average	10.1	10.3	1,366	1,377	385	377

Source: Environment Agency (2002d)



Source: Environment Agency (2002d)

Figure 4.7 Comparison of combustion gases in the sampling port and end-of-pipe (at reference oxygen conditions)

5

Emissions monitoring

5.1 List of required test parameters

Tables 5.1 and 5.2 set out the methodologies to be used during emissions testing of landfill gas engines. These methodologies include those taken from Part II of Technical Guidance Note M2 (Environment Agency, 2002d) and other methods that have proved effective when monitoring emissions from landfill gas engines.

There are several British, European and International standards for emission monitoring and the USEPA (USEPA, online 1) is another useful source of emission sampling information. Tables 5.1 and 5.2 set out the reference methodologies given in Technical Guidance Note M2. In the absence of any other guidance, the following order of priority should be used:

- Comité Europeén de Normalisation (CEN)
- International Standardisation Organisation (ISO).

If a substance cannot be measured using one of these standards, methods developed by the following organisations can be used:

- American Society for Testing and Materials (ASTM)
- Association Française de Normalisation (AFNOR)
- British Standards Institution (BSI)
- Deutsches Institute für Normung (DIN)
- United States Environmental Protection Agency (USEPA)
- Verein Deutstcher Ingenieure (VDI).

If the substance cannot be monitored using any of the standards above, then the occupational methods from the following list may be adapted:

- Methods for the Determination of Hazardous Substances (MDHS) published by HSE;
- National Institute of Occupational Safety and Health (NIOSH)
- Occupational Safety and Health Administration (OSHA).

Each landfill gas engine should be assessed on an individual site basis. Monitoring for additional emissions parameters may be required at particular sites, based on a risk assessment and local impact effects. Table 5.2 provides examples of such additional emission parameters.

Many of the reference methodologies were developed for waste incineration plant. The detailed methodologies given in Section 6 are those that have been used successfully to test a number of landfill gas engines. Any methodology chosen for the testing of landfill gas engines must be fit for purpose.

Table 5.1 Primary monitoring parameters: landfill gas spark ignition engine emission tests

Parameter	Performance standard (M2 reference standards)	Alternative methodology
Nitrogen oxides	ISO 10849 (ISO, 1996)	USEPA Method 7E (USEPA online 2)
Carbon monoxide	ISO 12039 (NDIR analysis) (ISO, 2001)	ISO 12039: 2001 (FTIR analysis or electrochemical cell)
Total volatile organic compounds	BS EN 12619 [a] (BSI, 1999) BS EN 13526 [b] (BSI, 2002b)	USEPA Method 25 (USEPA online 3)
Non-methane volatile organic compounds (NMVOCs)	BS EN 13649 (BSI, 2002c)	USEPA Method 18 (USEPA online 4)
Flow	BS 6069 (BSI, 1993)	
Temperature	BS 6069 (BSI, 1993)	

[a] At sites with low VOCs concentrations.
[b] At sites with low to moderate VOCs concentrations.
Source: Environment Agency (2002f)

Table 5.2 Secondary monitoring parameters: landfill gas spark ignition engine emission tests

Parameter	Performance standard (M2 reference)	Alternative methodology
Sulphur dioxide	ISO 11632 (ISO, 1998)	BS 6069-4.1: 1990 (BSI, 1990) BS 6069-4.4: 1993 (various methods) (BSI, 1993)
Particulates	BS EN 13284-1 (BSI, 2002a)	ISO 9096: 2003 (ISO, 2003)
Dioxins (PCDD and PCDF)	BS EN 1948: 1997: Parts 1–3 (BSI, 1997)	USEPA Method 23 (USEPA, 1995)
Heavy metals	BS EN 14385 (BSI, 2004)	USEPA Method 29 (USEPA online 8)
Halides	BS EN 1911* (BSI, 1998)	USEPA Methods 26 and 26A (USEPA online 5, 6)
Hydrogen sulphide	USEPA Method 15 (USEPA, 1996a)	USEPA Method 11 (USEPA online 7)

* Parts 1 and 2 cover sampling. Part 3 covers analysis by three different methods A, B and C. (All halides, excluding HCl, are analysed using Method C, whereas HCl can be analysed using all three methods.)

Source: Environment Agency (2002d)

5.2 Environmental risk assessment

Figure 5.1 provides a framework for a tiered approach to environmental risk assessment and management. This approach ensures that the level of effort put into assessing each risk is proportionate to its priority (in relation to other risks) and its complexity (in relation to an understanding of the likely impacts. *Guidelines for environmental risk assessment and management* (DETR *et al.*, 2000) should be consulted before undertaking any risk assessment. Particular risk assessment issues relating to landfill gas are covered in *Guidance on the management of landfill gas* (Environment Agency, 2004a).

5.3 Testing frequency

The frequency of testing the emissions from an engine should be based upon an individual site assessment. Once an emissions profile has been established, the frequency of monitoring may be reduced, in agreement with the regulator, to a minimum of annual monitoring.

In the time between full emissions testing, the performance of the equipment must be continuously assessed. This will normally require periodic, measurements to be made of emission parameters such as NOx and CO. The frequency of measurement required to assess whether the equipment is performing consistently will be site specific. For instance an engine working close to a sensitive receptor will require more frequent assessment of emission parameters than a unit operating with a stable gas supply at a remote location. In some particularly sensitive locations continuous monitoring of emission parameters may be required.

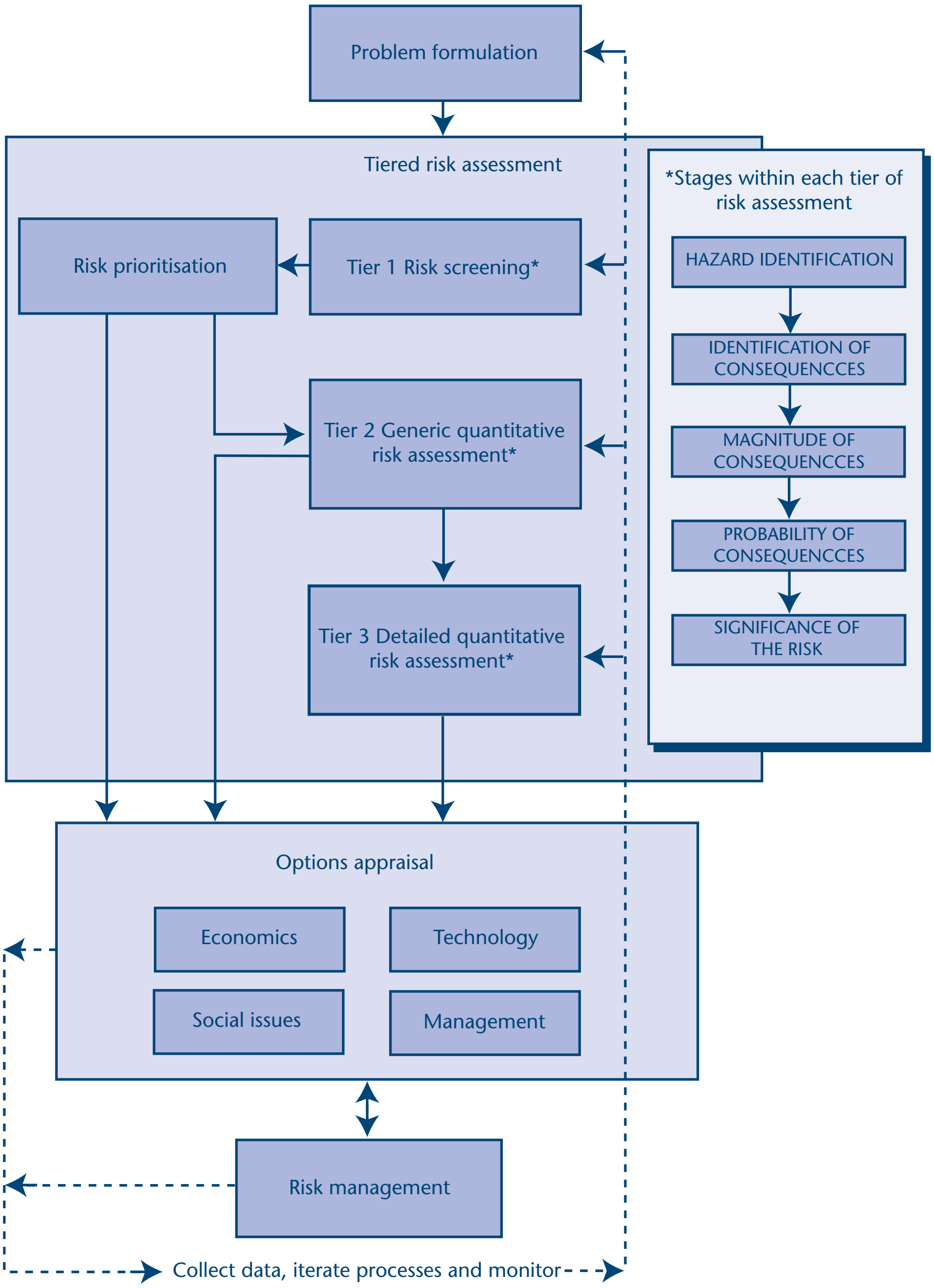
5.4 Emission standards

The regulator has adopted a tiered approach to the formation of emissions standards for landfill gas engines. The standards have been developed from research undertaken by both the Environment Agency and the waste management industry, which has identified the emissions associated with a well constructed, maintained and operated landfill gas spark ignition engine (Biogas Association, 2002; Environment Agency, 2002e). However, the emissions associated with a landfill gas engine are different to those of other spark ignition engines. This is primarily due to the fuel source and this necessitates the application of different emission standards.

Site-specific considerations may necessitate a stricter emission standard based on risk, either in terms of the generic emissions standard stated below (e.g. a reduction of NOx from 500 to 400 mg/m^3) or in terms of additional parameters. These will include consideration of atypical raw landfill gas (e.g. elevated levels of chlorinated compounds) and assessment of dispersion modelling (e.g. a potential breach of a local air quality standard).

Data on priority trace gas composition will be required to undertake a satisfactory risk assessment and to determine a site-specific emission standard (Environment Agency, 2002a). Guidance on carrying out a risk assessment is given in Horizontal Guidance Note IPPC H1 (Environment Agency, 2002f) and Guidance on the management of landfill gas (Environment Agency, 2004a). Factors that may be considered include:

- topography
- location of receptors



Source: DETR *et al.* (2000)

Figure 5.1 A framework for environmental risk assessment and management

- quality of landfill gas
- size, number and age of engine and flare installations
- single or multiple exhausts
- emission height (see Environment Agency 2002a, Appendix B).

Alternative landfill gas utilisation systems such as dual-fuel engines should meet emissions standards that are based on site-specific circumstances and draw upon the principles contained within this guidance. For example, in a dual-fuelled engine, the combustion principle is that diesel promotes the ignition of the landfill gas, which results in increased emissions of SO_2, NOx and particulates. These parameters should be considered as part of the site-specific emissions standard.

5.4.1 Landfill gas engines commissioned before 31 December 1997

All engines should be considered on a site-specific risk basis and the emission standards should be determined based upon the impact that they may have on health, environment or amenity. This determination should be based on the guidance provided in Horizontal Guidance Note IPPC H1 (Environment Agency, 2002f) and the emission standards given Table 5.3a. Recommendations concerning discharges and sampling sockets contained in Section 5.4.3 should also be followed as best practice.

5.4.2 Landfill gas engines commissioned between 1 January 1998 and 31 December 2005

All engines should be designed, operated and maintained to comply with emission standards given in Table 5.3a.

Table 5.3a Emission standards for spark ignition landfill gas engines (commissioned between 1 January 1998 and 31 December 2005)

Parameter	Emission standard *
Nitrogen oxides	650 mg/m^3
Carbon monoxide	1,500 mg/m^3
Total volatile organic compounds	1,750 mg/m^3
Total non-methane volatile organic compounds	150 mg/m^3

* These standards are based on normal operating conditions and load. Site-specific risk assessments may require a stricter emission standard to be applied.

Temperature: 0°C (273K); pressure: 101.3 kPa; and oxygen: 5 per cent (dry gas). For more information, see Section 5.5

In addition to the numerical emission standards given in Table 5.3a, the following apply:

- Discharges must be vertically upwards and unimpeded by cowls or any other fixture on top of the exhaust (see Section 4.2 and HMIP, 1993).
- Sampling sockets (see Section 4.2.2) must be fitted to all new installations and it is recommended that they are fitted to existing installations.
- The management of crankcase emissions to minimise their release to the environment is recommended.
- Continuous assessment of methane and flow in the inlet gas is recommended.
- Continuous assessment for NOx and CO in the emission is recommended.

5.4.2 Landfill gas engines commissioned after 31 December 2005

All engines shall be designed, operated and maintained to comply with emission standards in Table 5.3b.

In addition to the numerical emission standards given in Table 5.3b, the following apply:

- Discharges must be vertically upwards and unimpeded by cowls or any other fixture on top of the exhaust (see Section 4.2 and HMIP, 1993).
- Sampling sockets (see Section 4.2.2) must be fitted to all new installations.
- Crankcase emissions must be managed to minimise their release to the environment (see below).
- Continuous assessment of methane and flow in the inlet gas must be undertaken.
- Continuous assessment for NOx and CO in the emission is recommended.

Emissions from the crankcase breather have been quantified (Biogas Association, 2002). These emissions can be significant in terms of total unburnt hydrocarbons and SOx at up to 30 per cent of the exhaust mass emission rates. However, CO and NOx emission rates were <1 per cent of those from the engine exhaust. A variety of best practice options to reduce these emissions exist such as recirculating leakage from engine container back for further combustion (Environment Agency, 2004b).

Table 5.3b Emission standards for spark ignition landfill gas engines (commissioned after 31 December 2005)

Parameter	Emission standard *
Nitrogen oxides	500 mg/m^3
Carbon monoxide	1,400 mg/m^3
Total volatile organic compounds	1,000 mg/m^3
Total non-methane volatile organic compounds	75 mg/m^3

* These standards are based on normal operating conditions and load. Site-specific risk assessments may require a stricter emission standard to be applied.

Temperature: 0°C (273K); pressure: 101.3 kPa; and oxygen: 5 per cent (dry gas). For more information, see Section 5.5.

5.5 Data standardisation

Monitored data should be reported according to the set of standard reference conditions given in Table 5.4. Appendix A contains an example of a standard report format that will allow easy interpretation and comparison of results. Where possible, an electronic version should be sent to the regulator. Alternative reporting formats should be agreed with regulator before they are submitted.

To convert the measured emissions concentrations to the reference conditions, a series of correction factors should be applied to the data. These correction factors are given in more detail in Technical Guidance Note M2 (Environment Agency, 2002d).

Table 5.4 Standard reference conditions for reporting landfill gas engine emission monitoring data

Parameter	Standard reference value
Temperature	0°C (273K)
Pressure	101.3 kPa
Oxygen	5 per cent (dry gas)

5.5.1 Concentration calculation

The concentration of a pollutant is calculated by dividing the mass of the pollutant collected by the volume of the sample of gas.

$$C_m = \frac{M_s}{V_s}$$

where:

C_m = concentration of emission as measured
M_s = mass of substance
V_s = volume of sample.

5.5.2 Temperature correction

The following temperature correction should be applied to the monitored data:

$$C_r = \frac{C_m * T_m}{T_r}$$

where:

C_r = concentration of emission at reference conditions
C_m = concentration of emission as measured
T_r = temperature at reference conditions (in K i.e. 273)
T_m = temperature as measured (in K i.e. 273 + °C).

5.5.3 Pressure correction

The following pressure correction should be applied to the monitored data:

$$C_r = \frac{C_m * P_r}{P_m}$$

where:

C_r = concentration of emission at reference conditions
C_m = concentration of emission as measured
P_r = pressure at reference conditions
P_m = pressure as measured.

5.5.4 Oxygen correction

The following oxygen correction should be applied to the monitored data:

$$C_r = \frac{C_m * (20.9 - (O_2)_r)}{(20.9 - (O_2)_m)}$$

where:

C_r = concentration of emission at reference conditions
C_m = concentration of emission as measured
$(O_2)_r$ = oxygen content at reference conditions
$(O_2)_m$ = oxygen content as measured.

5.5.5 *Moisture correction*

The moisture correction for application to monitored data obtained from extractive sampling based on particulate methods is given below:

$$C_r = C_m \times \frac{100}{(100 - (H_2O)_m)}$$

where:

C_r = concentration of emission at reference conditions

C_m = concentration of emission as measured

$(H_2O)_m$ = moisture content as measured (per cent).

5.5.6 *Mass emission calculation*

The following calculation is used if it is necessary to convert from mg/m^3 to g/second:

mg/m^3 to g/second	Multiply the concentration of the emission by the flow rate of the exhaust gases (i.e. $m^3/s \times mg/m^3/1000 = g/second$)

The conversion from concentration in g/s to kg/year is obtained using the following calculation:

To convert from:

g/second to kg/second	Divide by 1000
kg/second to kg/hour	Multiply by 3,600
kg/hour to kg/year	Multiply by 8,000 (as assuming the engines operate for 8,000 hours/year)

5.5.7 *Conversion of gaseous values*

In measuring gaseous emissions, it is common to find them expressed as parts per million (ppm). Conversion to the standard units of mg/m^3, at a base temperature of 273K and 101.3 kPa can be obtained using the following calculation:

$$mg/m^3 = ppm \times \frac{\text{molecular weight (g)}}{22.4}$$

5.5.8 *Calculation methods*

The calculations for emissions concentrations should be carried out in accordance with the relevant standards as set out in Tables 5.1 and 5.2. The calculations for emissions monitoring data must be carried out in accordance with the requirements described in Manual stack emission monitoring: performance standards for organisations (Environment Agency, 2002e).

5.6 Compliance assessment

The four recognised types of monitoring used to measure emissions are:

- continuous – a complete series of measurements covering all operating conditions;
- periodic – intermittent measurements covering different conditions of normal operation;
- group – a number of measurements made under the same operating conditions;
- individual – lone measurements, which are not part of a group.

The emissions standards presented in this guidance are derived from a group of measurements collected at a range of landfills and from a number of different spark ignition designs operating under normal conditions.

The guidance on monitoring requires periodic measurement to determine the emissions profile of the generating set. Inevitably, this monitoring covers only a small period in the emissions from the engine and, consequently, it is necessary to assume that the periodic measurement is representative of operation outside the monitoring period.

Increased confidence in this assumption can be provided by the development of an emissions profile for the engine. This profile may be built up over time, e.g. by making targeted measurements under the range of conditions encountered during normal operation. Surrogate determinants and operational information (e.g. methane and flow) can also be used to confirm the consistent operation of the engine.

If the operational information during the monitoring period differs substantially from that recorded for the preceding months, sampling will be unrepresentative of the earlier operation. It will only be representative of future operations if the operating profile does not change. The quality and consistency of the representative samples is best assured by using the standard techniques outlined in this guidance.

When assessing compliance against engine emissions standards, it is necessary to take into account the representative nature and reliability of the measured values. These uncertainties are considered below.

5.6.1 *Measurement uncertainty*

A number of different uncertainties (e.g. uncertainty from sampling position, sampling equipment, analytical equipment and chemical/physical uncertainty) have to be combined to assess the overall uncertainty of measurement.

The overall measurement uncertainty is calculated by:

- defining the steps of a measurement
- identifying the sources of uncertainty associated with these steps
- quantifying the respective uncertainties
- combining these uncertainties.

The component uncertainties are combined using the following formula, which involves taking the square root of the sum of the squares of the individual uncertainties, i.e.

$$U_{combined} = \sqrt{(u_1^2 + u_2^2 + u_3^2 + ...u_n^2)}$$

Each measurement and associated uncertainty must be determined within a known confidence limit, i.e. there is confidence that the interval chosen does contain the real value. For emission measurements associated with landfill gas engines, the chosen confidence level is 95 per cent.

Wherever possible, the specific uncertainty in a set of monitoring measurements should be reported and used in the assessment. A method for calculating uncertainty is given in *Guide to the expression of uncertainty in measurement* (ISO, 1995). However, where uncertainties cannot be reasonably estimated, the guidance below can be used to derive typical acceptable values. **Errors and uncertainty greater than those given below generally indicate unsatisfactory monitoring.**

Where methods are in accordance with a recognised measurement standard, the measurement uncertainty will be better understood. Table 5.5 gives the quoted uncertainty for the methods referenced in this guidance.

The uncertainties quoted in Table 5.5 apply only when the measurement complies fully with the standard method. However, the design and operation of landfill gas engines means it is not always possible to perform fully compliant emission tests. For example, the measurement standard requires five hydraulic diameters of straight exhaust before the sampling plane and five hydraulic diameters from the exhaust exit (should a consistent flow profile not be achieved, see Section 4.2.2). This is often not possible to achieve and, consequently, the measurements will have a different uncertainty from those quoted in the measurement standards. An overall measurement uncertainty would thus have to be calculated.

The Large Combustion Plant and Waste Incineration Directives (Council of the European Union, 2000 and 2001) cover the monitoring of several relevant combustion products. They quote measurement uncertainties at a daily emission limit value level. The Directives state that the values of the 95 per cent confidence intervals of a single measured result must not exceed the percentages of the emission limit values quoted in Table 5.6.

Table 5.7 shows the uncertainty to be expected in measurements by the recommended methods. These values are based on:

- the degree of the uncertainty identified in the standard methods
- guidance from relevant directives
- Environment Agency research data on monitoring engines.

Table 5.5 Quoted uncertainty for reference methods

Determinand	Reference (Environment Agency, 2002d)	Quoted uncertainty
Nitrogen oxides	ISO 10849 (ISO, 1996)	<10 per cent of full scale deflection
Carbon monoxide	ISO 12039 (ISO, 2001)	<10 per cent of full scale deflection
Total volatile organic compounds	BS EN 12619 (BSI, 1999) BS EN 13526 ((BSI, 2002b)	0.28–0.42 mg/m^3 for a concentration range of <1 to 15 mg/m^3
Non-methane volatile organic compounds	BS EN 13649 (BSI, 2002c)	1.6–5.7 mg/m^3 for a concentration range of 13–134 mg/m^3 *

* Depends on the component and method used.

Table 5.6 Measurement uncertainty quoted for selected determinants in the Large Combustion Plant and Waste Incineration directives

Component	Measurement uncertainty (per cent)
Hydrogen chloride	40
Sulphur dioxide	20
Nitrogen oxides	20
Carbon monoxide	10

Table 5.7 Measurement uncertainty for methods used in monitoring emissions from landfill gas engines

Determinant	Method description	Typical uncertainty (per cent)
Nitrogen oxides	Extractive NDIR and chemiluminescence (ISO 10849) (ISO, 1996)	20
Carbon monoxide	Extractive NDIR (ISO 12039) (ISO, 2001)	12
Total volatile organic compounds	Flame ionisation detection (BS EN 12619) (BSI, 1999)	25
Non-methane volatile organic compounds	Adsorption – thermal desorption (BS EN 13649) (BSI, 2002c)	25
Hydrogen chloride	Ion chromatography (BS EN 1911) (BSI, 1998)	40
Sulphur dioxide	Ultraviolet (ISO 11632) (ISO, 1998)	20

5.6.2 Monitoring instrument interferences

It is also important to be aware of the potential for interference on particular types of monitoring instruments used to measure exhaust emission concentrations.

The potential for ‘cross-sensitivity’ exists and some species, other than those of interest, can affect the measurement, with either a positive or negative interference. For example, two analysers (A and B) from different manufacturers, both using non-dispersive infra-red (NDIR) to measure sulphur dioxide, show different interferences with methane. Table 5.8 gives these interferences as stated by the manufacturers. It is clear that, for a site emitting 1,000 ppm of methane, analyser B will significantly over-estimate the reading for SO_2 compared with the result from analyser A.

Due to the complexity of the fuel source, landfill gas engines have the potential to emit a wide range of substances. This can give rise to a number of species with the potential for interference with the monitoring instruments. The instrument manufacturer, experienced testing teams and instrument technicians should all be aware of potential interferences that may affect the monitoring instruments and should be able to advise on the suitability of using particular analysers (before any sampling is carried out).

Table 5.8 Typical Interferences with methane

Analyser	Methane content in gas to be measured	Interference with reading of SO_2
A	1%	14 ppm
B	0.1%	78 ppm

5.7 Assessing compliance

Assessing compliance of the measured values against the emissions standards can be divided into four stages:

- confirmation of evidence
- determination of compliance with emission standard
- reporting
- consideration of response.

The operator is normally responsible for the first three stages, while the regulator assesses the report and considers the response.

5.7.1 Confirmation of evidence

The quality and representative nature of the measurements have to be considered in order to ensure that the data are within the scope covered by the limit value. Questions that need to be addressed include:

- Is the data of adequate quality?
- Have the correct monitoring methods been used?
- Have the monitoring methods been used correctly?
- Have there been any deviations from the recommended monitoring methods? If so, are these justified and what effect have they had on the quality of measurement?
- Does the emission profile indicate that the periodic sample was representative?

If any of these points cannot be answered satisfactorily, then the data may be inadequate for a full compliance assessment and further action may be required to achieve representative monitoring.

The reported uncertainty in measurements will not take into account the variability of the emissions between the periodic monitoring. The uncertainty arising from unrepresentative sampling periods will be site-specific and is likely to change during the operational period at the site. Where this uncertainty can be deduced from the emission profile, this should be stated and the additional uncertainty added to the measurement uncertainty. Where this cannot be deduced, the regulator will assume that the total uncertainty, including that related to the representative nature of the measurements, will not exceed the values given in Table 5.9. If the calculated total uncertainty exceeds these values, it will generally indicate unsatisfactory monitoring or erratic performance of the generating set.

5.7.2 Determination of compliance with the emission standard

All monitoring data are subject to error and uncertainty, and a determination of compliance must take account of this. The fundamental principle is that the emission standard itself is fixed and any allowance for uncertainty is associated with the monitoring data. Compliance assessment of the emissions from landfill gas engines is subject to the general principles applied to the regulation of other emissions.

- **Compliance**. All measurements giving outcomes that are within the standard, irrespective of uncertainty, will be regarded as compliant.
- **Approach to limit**. All measurements giving outcomes that are above the standard, but by an amount that does not exceed the uncertainty, will be regarded as approaching the limit. These will be deemed compliant.
- **Non-compliance**. All measurements giving outcomes that are above the standard after subtracting the uncertainty, will be regarded as non-compliant.

These situations are illustrated in Figure 5.2.

Table 5.9 Maximum values for measurement uncertainty to be applied when assessing compliance of emissions from landfill gas engines

Determinant	Method description	Typical uncertainty (per cent)
Nitrogen oxides	Extractive NDIR and chemiluminescence (ISO 10849) (ISO, 1996)	30
Carbon monoxide	Extractive NDIR (ISO 12039) (ISO, 2001)	20
Total volatile organic compounds	Flame ionisation detection (BS EN 12619) (ISO, 1999)	40
Non-methane volatile organic compounds	Adsorption – thermal desorption (BS EN 13649) (ISO, 2002c)	40

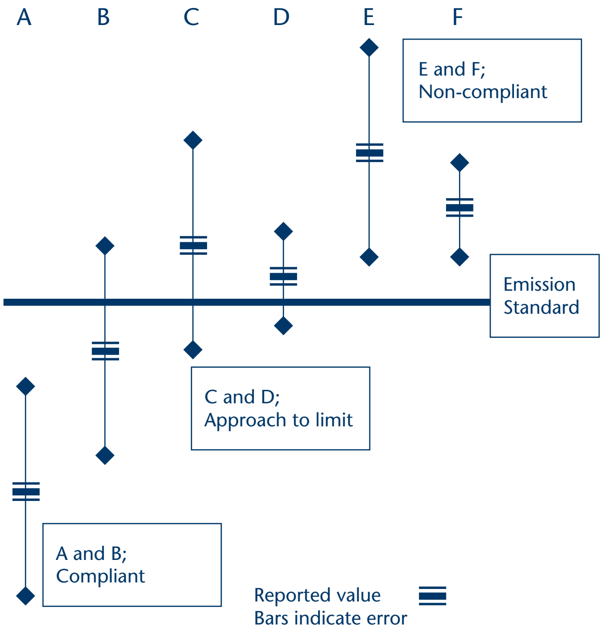


Figure 5.2 Schematic representation of the compliance classification used in assessing emissions from landfill gas engines.

5.7.3 Reporting

The test report must include details of:

- the test methods
- any variations from standard methods
- tabulated data summary
- ambient conditions during sampling

The results must be reported in the form:

$$\text{Result} = X \pm U \text{ (units)}$$

where:

X = calculated value

U = measurement uncertainty.

The measurement uncertainty should be estimated for the actual monitoring undertaken and, where this is not possible, the guidance above followed.

5.7.4 Consideration of response

If the data are assessed as compliant, then they can be routinely reported in accordance with the licence or permit requirements.

If the data are assessed as approaching the limit, they should be reported in accordance with the licence or permit requirements, but the operator should provide information on how the uncertainty on subsequent monitoring will be reduced.

If the data are assessed as non-compliant, this must be investigated and reported to the regulator immediately. The urgency of this investigation by the operator will be determined by the degree of non-compliance and the risk associated with the emission. For example, a marginally non-compliant case (i.e. up to 25 per cent over the standard after allowing for uncertainty) that is not close to a sensitive receptor would normally require a report within seven days. Alternatively, a grossly non-compliant case close to a sensitive receptor requires immediate investigation and a report within 24 hours. The action to be taken by the regulator will be consistent with its enforcement and prosecution policy.

Emission specific methods

6.1 Sampling equipment, methodology and sample analysis

The following section defines emission specific methods for each emission parameter and describes the sampling equipment, methodology and analysis to be used. Lists of regulator-accepted and alternative sampling methodologies are given in Tables 5.1 and 5.2. These methodologies are discussed in more detail below.

6.2 Emissions

Emissions from any combustion process will include both gaseous and particulate emissions. The sampling procedures for gaseous emissions and particulate emissions are entirely different; gaseous emissions are regarded as a homogeneous mixture in the gas stream, whereas particulates are not.

Due to the requirement to obtain representative, repeatable and accurate measurements, the techniques for monitoring vary. There are also significant differences between continuous and non-continuous monitoring techniques (see Section 6.3.2).

6.2.1 Gaseous emissions

When sampling gaseous exhaust emissions, it is generally relatively straightforward to obtain a representative sample due to the homogeneous nature of the emissions. Difficulties can occur when transporting the sample from the stack to the sampling apparatus or analyser as the integrity of the sample must be maintained.

For any extractive gas analysis, a suitably conditioned sample must be presented to the analyser. This will usually involve filtering the sample gases, the use of heated sample lines and moisture removal before the concentration is determined in the collector or analyser.

In some cases, the emission may react with a specific material in the sample probe and sample lines. For example, sulphur dioxide reacts with stainless steel. It is therefore essential that inert materials (e.g. PTFE lines) are used in all lines before the collector or analyser.

As well as manual methods, a wide range of direct measurement analysers is available for gaseous emissions. In these analysers, a sample of gas passes through a suitable absorption medium (often a liquid) for later analysis in a laboratory. Direct measurement analysers have advantages for site use, as they avoid the problems associated with handling adsorption media and the associated glassware on-site, which can lead to contamination of the sample.

6.2.2 Particulate emissions

Particulate emissions generated in a combustion system may have a wide range of sizes. This will result in a complex distribution of the particles in the gas stream.

The procedures to collect a representative sample of this suspension of matter are far more complex than those required for gaseous emissions. Section 1.3 of Technical Guidance Note M1 (Environment Agency, 2002b) should be consulted regarding the importance of representative sampling.

The wide range of particle sizes present in the gas stream means it is important to perform isokinetic sampling in order to obtain a representative sample. Sampling outside isokinetic conditions will lead to reduced accuracy and an incorrect size distribution of particulates. To ensure that isokinetic conditions are maintained across the duct during sampling, appropriately sized nozzles must be selected. A detailed and accurate flow profile is also required – particularly at the sampling points.

When the sampling velocity differs from that of the gas stream, some particles are deflected from their original path and the quantity entering the nozzle will differ from that obtained with isokinetic conditions. Fine particles, such as fume, follow the deflected gas path closely; the amount entering the nozzle is therefore proportional to the sampling velocity. For example, if the sampling velocity is less than the gas stream, then some fine particles will escape around the nozzle and the weight collected will be too low. On the other hand, if the sampling velocity is higher, then the quantity entering the nozzle will be too high.

In the case of very coarse particles, the quantity entering the nozzle is independent of the sampling velocity. Where the flue gas contains particles of various sizes, sampling other than isokinetically affects not only the weight of particles in the sample, but also their size. Figure 6.1 illustrates the principle of isokinetic sampling.

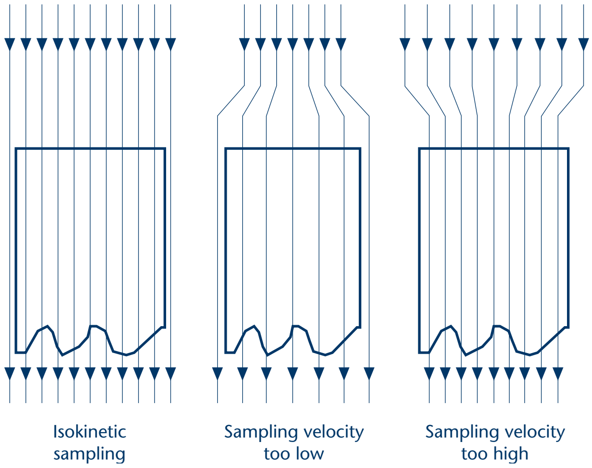


Figure 6.1 Illustration of the principle of isokinetic sampling

6.3 Sampling methods and instrumentation

6.3.1 Portability of monitoring equipment

The instruments used during emissions monitoring may be either semi-portable or fully portable. Semi-portable instruments are made up of a number of separate modules (each of which are hand transportable) and tend to be mains driven and/or use compressed gases (or chemical reagents). Fully portable equipment, however, tends to be a single item, which is hand transportable and battery driven.

6.3.2 Sampling methods

Two different methods can be employed when testing the emissions from landfill gas engines:

- **Extractive manual techniques**. These involve drawing an extracted sample of the flue gas through glass collection vessels containing absorbent solutions. These solutions absorb the target species, which are then quantified using one of the following:
  - ion chromatography
  - titration
  - a volume change
  - ion sensitive electrode
  - colorimetric method.

  Extractive manual methods require skilled operators and analysts to achieve acceptable accuracy and repeatability. It is also important to consider the potential hazards involved in the use of chemicals and glassware in a stack environment. However, the main benefits of using an extractive manual sampling system are that it can be intrinsically safe and the samples collected can be sub-divided to enable an archive sample to be collected and analysed later in case of dispute.
- **Automated instrumented techniques**. These are used to measure emissions continuously, with instruments (either extractive or cross stack) being permanently installed to provide continuous emission monitoring systems (CEMS). There is a high cost associated with maintaining a continuous monitoring system. The equipment used also needs to be calibrated regularly to ensure the integrity of the results recorded.

6.4 Combustion gases

The measurement of gaseous emissions [nitric oxide (NO), nitrogen dioxide (NO_2), SO_2, CO, CO_2, CH_4 and VOCs] is performed using a sample extraction system and individual gas analysers. Apart from the analyser unit, the most important part of an extractive system is the gas handling system. This is where the integrity of the gas must be maintained for the analyser to give meaningful results.

The flue gases are extracted through a ceramic filter, heated sampling line and gas conditioning unit before being presented to the analysers. The lines must be made of such material to avoid any of the gas components reacting or being adsorbed/absorbed along their length. To avoid further reactions occurring and altering the composition of the gas before it enters the analyser cell, it is important to take into account the operating temperature and the residence time of the gases within the sampling lines.

A typical extractive system is shown schematically in Figure 6.2.

This typical arrangement is suitable for all combustion gas measurements (e.g. NO, NO_2, SO_2, CO, CO_2 and VOCs). To avoid problems caused by adsorption/absorption and the affect of ambient conditions on the instruments, the system must be calibrated. The results should be logged every 30–60

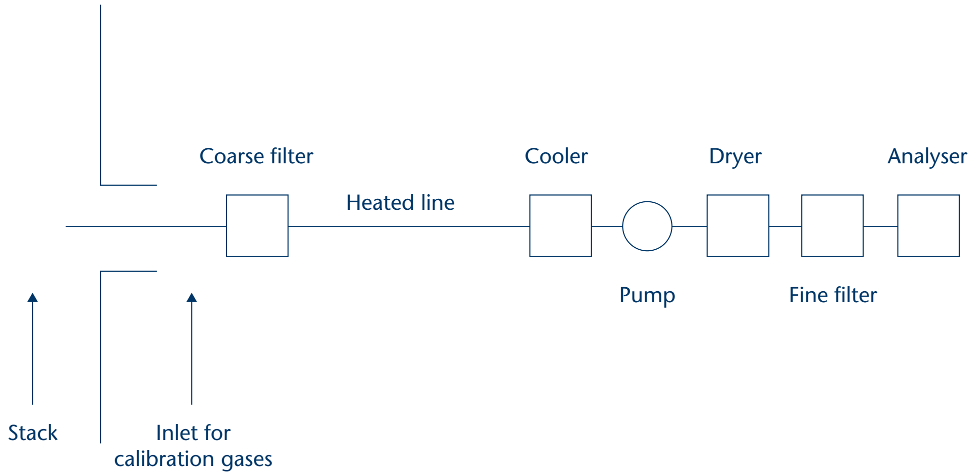


Figure 6.2 Typical extractive system

seconds over an extended monitoring period, normally in the range of two to four hours of continuous sampling.

6.4.1 Analyser suitability

Table 6.1 gives the different types of analysers used to measure combustion gases, along with their suitability. The Agency has established a monitoring certification scheme, MCERTS, to provide a framework within which quality environmental measurements can be made (Environment Agency, 2000). MCERTS provides for the product certification of portable monitoring systems, a number of which relate to Table 6.1.

6.4.2 Nitrogen oxides

The preferred method for analysing for nitrogen oxides (NOx) is by chemiluminescence. Chemiluminescence is the emission of light energy resulting from a chemical reaction. Ozone is generated in a quartz tube by the ultraviolet irradiation of oxygen, and is provided in excess in the reaction chamber to ensure a complete reaction takes place. The reaction between nitric oxide (NO) and ozone (O_3) produces infra-red radiation and nitrogen dioxide (NO_2). As NO_2 does not undergo this reaction with O_3, it must be reduced to NO before it can be measured by this method. Most commercial analysers contain a catalytic converter chamber to reduce NO_2 to NO, with the chamber being made of stainless steel or molybdenum to effect the catalytic decomposition. The NO produced is then reacted with the O_3, and the chemiluminescence is measured to give a total NOx reading ($NO + NO_2$).

Figure 6.3 shows a schematic layout of a chemiluminescence analyser for the measurement of NOx.

Table 6.1 Analyser suitability

	NOx	SO_2	CO	VOCs
Chemiluminescence	R			
Infra-red (IR)	X	X	R	
Ultraviolet (UV)	X	R		
Electrochemical	X	X	X	
Flame ionisation detector (FID)				R

R = Technical Guidance Note M2 reference technique (Environment Agency, 2002d)
X = suitable analyser

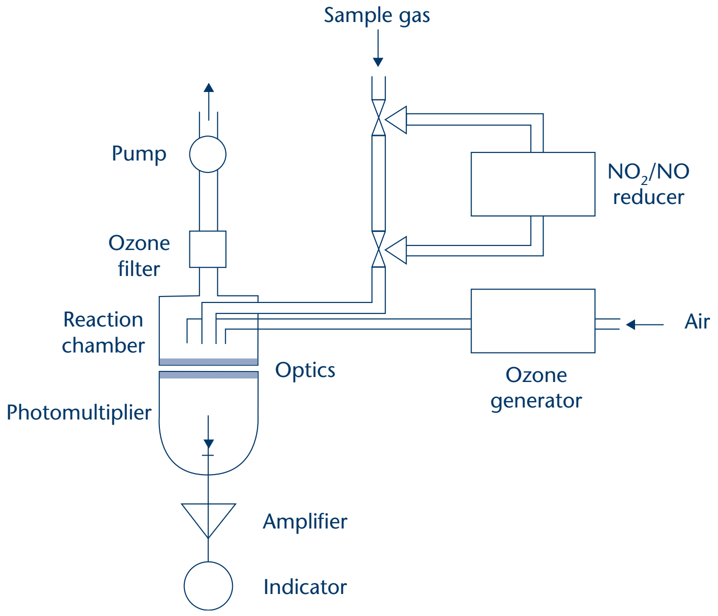


Figure 6.3 Typical layout of a chemiluminescence analyser for the measurement of NOx

Interferences
Known interferences to be aware of when using chemiluminescence are:

- carbon dioxide
- nitric acid
- water
- ammonia.

A comprehensive description of the preferred methodology for nitrogen oxides is given found in ISO 10849 (ISO, 1996). Technical Guidance Note M2 (Environment Agency, 2002d) discusses available methodologies for analysing for nitrogen oxides in more detail.

6.4.3 Carbon monoxide

The preferred method for measuring carbon monoxide (CO) is non-dispersive infra-red (NDIR) analysis. Because an NDIR analyser does not disperse the light emitted from an infra-red source, the emitted radiation is not broken up into its component wavelengths with a prism or diffraction grating. There are two types of analyser – single beam and twin beam. Schematics for each type are shown in Figures 6.4 and 6.5, respectively.

With a single beam analyser, the filter selects that part of the spectral range most characteristic of the substance to be measured. This type of instrument requires regular calibration and zeroing to overcome any zero and range drift. Some of these problems can be overcome by using twin beam instruments.

In a twin beam analyser, infra-red light is passed through two gas cells – a reference cell and a sample cell. The reference cell contains a gas such as dry nitrogen gas, which will not absorb light at the wavelength used in the instrument. As light passes through the sample cell, the emission molecules will absorb some of the infra-red light. When the light subsequently emerges from the end of the sample cell, it will have less energy than when it entered. This energy difference is sensed by a detector such as a thermocouple or thermistor.

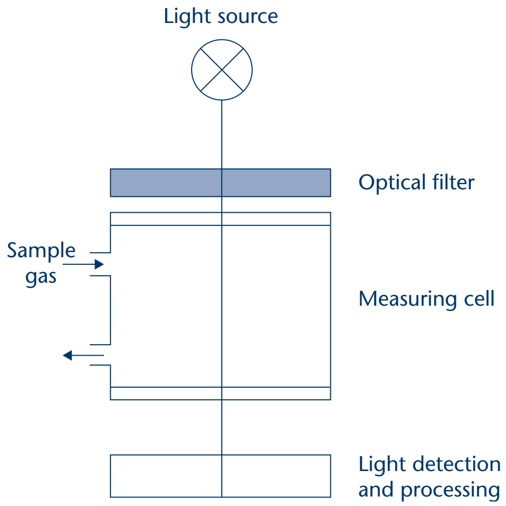


Figure 6.4 Single beam analyser

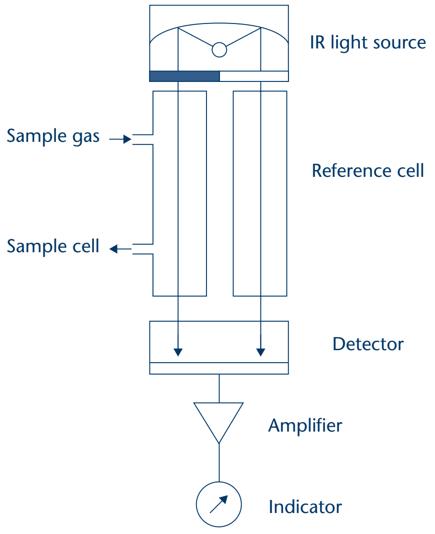


Figure 6.5 Twin beam NDIR monitor

Interferences
Known interferences to be aware of when using NDIR analysis are:

- water
- particulates.

A more detailed description of the preferred methodology for carbon monoxide is given in ISO 12039 (ISO, 2001). Technical Guidance Note M2 (Environment Agency, 2002d) discusses available methodologies for analysing carbon monoxide in more detail.

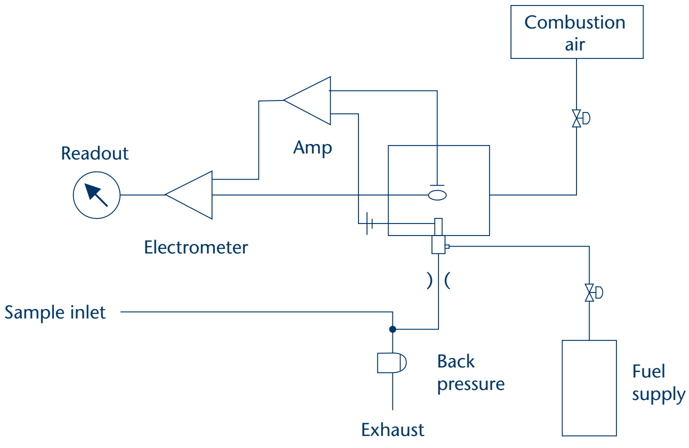


Figure 6.6 Typical flame ionisation detector

6.4.4 Total VOCs

The preferred method for measuring total VOCs is flame ionisation detection. The measurement principle is the determination of an ionisation current resulting from the combustion of organic compounds in a hydrogen flame. The flame readily ionises covalent organic carbon molecules and, when an electric field is applied across this ionised gas cloud, a current will flow. This current is approximately proportional to the mass flow rate of the carbon atoms and will vary slightly depending upon the type of compound and the carbon number.

Figure 6.6 provides a diagram of the FID measuring principle. The main advantage of a FID is that it responds strongly to organic carbon-containing components and less to inorganic flue gas components such as CO, CO_2, NO and water. However, FID monitors are very sensitive to changes in pressure, particulates in the sample gas and condensation in their internal lines.

Interferences
A known interference to be aware of when using flame ionisation detection is:

- non linear response to some hydrocarbons.

A more detailed description of the preferred methodology for total VOCs is given in BS EN 12619 (BSI, 1999) and BS EN 13526 (BSI, 2002b). Technical Guidance Note M2 (Environment Agency, 2002d) discusses available methodologies for analysing for total VOCs in more detail.

6.4.5 Non-methane VOCs

The measurement of Total VOCs will include methane, the predominant organic compound in landfill gas. In order to determine the other organic species excluding this methane, the preferred method is to speciate the VOCs and sum the individual components. Speciated VOCs are measured using a sampling line connected to two Tenax tubes in series, which trap the volatiles by means of adsorption. Emissions are extracted using low flow sampling pumps. An iced water trap is employed before the tubes to reduce the water content of the extracted gas stream and to remove condensable organic compounds. It also ensures that only the non-water soluble VOCs are analysed by this method. All the adsorption tubes used in sampling are thermally desorbed and analysed by scanning gas chromatography/mass spectrometry (GC/MS) to characterise and quantify the individual VOCs present.

The GC/MS analytical method is a modification of a United Kingdom Accreditation Service (UKAS) accredited sampling methodology. It provides a quantitative assessment for target compounds and a semi-quantitative assessment for non-target compounds. All the samples, blanks and standards are spiked with a solution of the selected standards in methanol. Two separate multi-point calibrations are set up by spiking tubes with solutions of the target VOCs and target aldehydes in methanol.

Any compounds that are not in the target compound lists should be reported as tentative identifications, with estimated concentrations of these compounds calculated using one of the internal standards. A minimum search fit of 75 per cent is used for the purpose of peak identification.

A more detailed description of the preferred methodology for speciated VOCs is given in BS EN 13649 (BSI, 2002c). Technical Guidance Note M2 (Environment Agency, 2002d) discusses available methodologies of analysing for speciated VOCs in more detail.

6.4.6 Sulphur dioxide

The preferred method for measuring sulphur dioxide (SO_2) is the use of ultraviolet spectrometry or ultraviolet fluorescence. Alternatively, an extractive method utilising ion chromatography set out in ISO 11632 (ISO, 1998) is acceptable.

Ultraviolet fluorescence

Fluorescence is a photoluminescent process in which light energy of a given wavelength is absorbed and light energy of a different wavelength is emitted. The principle behind the fluorescence technique is to irradiate the molecule with light at a given wavelength (usually in the near ultraviolet) and to measure the emitted light at a longer wavelength.

Figure 6.7 shows a schematic diagram of a UV fluorescence analyser. Ultraviolet radiation is passed from a xenon lamp through a 210 nm band pass filter before it reaches the measurement cell. In this cell, the SO_2 molecule becomes excited and fluoresces at 350 nm on returning to the ground state. The UV radiation leaving the measurement cell passes through a 350 nm band filter, before being measured by a photomultiplier. The photomultiplier signal is then translated into concentration terms.

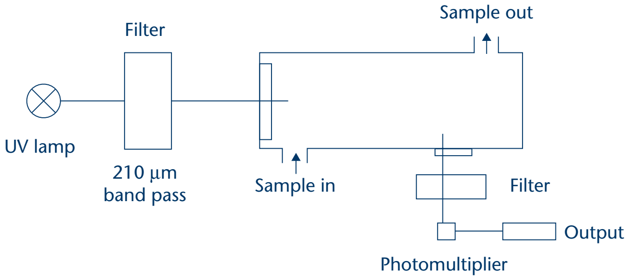


Figure 6.7 Schematic of a UV fluorescence analyser for sulphur dioxide

Interferences

A known interference to be aware of when using ultraviolet fluorescence is:

- nitrogen dioxide.

Ultraviolet spectrometry

Ultraviolet spectrometry involves the absorption of ultraviolet light by a molecule, causing the promotion of an electron from a ground electronic state to an excited electronic state. In an atom, the electron forms a single spectral line whereas, in a molecule, many spectral lines crowd together in bands. The spectra of vapours and gases at low pressures show broad bands at low resolutions, but a fine structure at high resolutions. The bands are related to the structure of the molecule, and thus the position, intensity and frequency of the bands can be used in identification.

Interferences

Known interferences to be aware of when using ultraviolet spectrometry are:

- carbon dioxide
- carbon monoxide
- nitrogen dioxide
- nitrogen oxide
- sulphur trioxide
- hydrocarbons
- particulates.

A more detailed description of the preferred methodology for sulphur dioxide is given in ISO 11632 (ISO, 1998). Technical Guidance Note M2 (Environment Agency, 2002d) discusses available methodologies for analysing for sulphur dioxide in more detail.

6.5 Particulate and heavy metal emissions

6.5.1 Particulates and heavy metals

Sampling for particulate matter is carried out isokinetically in accordance with BS EN 13284-1 (BSI, 2002a). A sample of the exhaust gas is removed from the emission gas stream and passed through a heated glass probe into a heated glass/fibre filter contained in an oven compartment. The filtered gas stream then passes through an impinger train containing five impingers. The first two impingers contain dilute nitric acid (HNO_3), the third impinger is empty, the fourth contains acidified potassium permanganate (KM_nO_4) solution (to absorb mercury and cadmium) and the fifth impinger contains silica gel to absorb residual moisture in the flue gas. All impingers are weighed before and after the sampling run to determine the mass of trapped water. This is then used to determine the moisture content of the gas stream.

Metals in particulate form are collected on the filter and any volatile metals (e.g. arsenic, cadmium and mercury) are absorbed in the HNO_3 solutions. The filter is weighed before and after sampling to determine particulate mass. The probe and filter housing are rinsed with acetone and nitric acid and the washings collected, with a secondary particulate mass determined from the acetone washings. The combined particulate mass, determined from the filter weight and acetone washings, provides the mass of particulate matter in the sample.

Figure 6.8 gives a schematic of the sampling set up for measuring particulates. It is based on USEPA Method 5 (USEPA, 1996b), which complies fully with BS EN 13284-1 (BSI, 2002a).

A more detailed description of the preferred methodology for particulates is given in BS EN 13284-1 (BSI, 2002a). Technical Guidance Note M2 (Environment Agency, 2002d) discusses available methodologies for analysing for particulates in more detail.

6.5.2 Dioxins

Isokinetic stack sampling equipment that satisfies the requirements of BS EN 1948-1 (BSI, 1997) is used to determine the concentration of PCDDs and PCDFs in emissions. The equipment is modified via the incorporation of a condenser and an XAD-2 resin trap. A sample of the emission gas is removed and passed, via a glass-lined probe and nozzle, through a heated quartz filter contained in an oven compartment. The filtered hot gas stream is passed through the condenser and resin trap into an impinger train, which is placed in an iced water bath to cool the gas stream and condense out less volatile gases and water vapour. The resin trap should be maintained at a temperature below 20°C to ensure efficient capture of VOCs.

The first two impingers encountered by the gas stream contain distilled water, the third impinger is left empty to condense out any excess moisture in the gas stream, and the fourth impinger contains anhydrous silica gel to dry the gas stream before it passes through a dry gas meter, which measures the volume of gas sampled. The gas is then exhausted to atmosphere. All the impingers must be weighed before and after the sampling run in order to determine the mass of water trapped by the impinger train. These data are used to calculate the moisture content of the gas stream in the exhaust.

At the end of sampling, the filter must be removed to a sealed container and the impingers re-weighed. The resin trap ends must be sealed with PTFE tape and stored in a cool box before being transferred to a refrigerator. The probe and all glassware must be rinsed with acetone, dichloromethane and toluene, with all the washings collected.

The solvent washings, liquid/liquid extraction of aqueous impinger solution and Soxhlet extraction of solid components are extracted to dryness under vacuum. The extracts are then processed through a number of clean-up stages before being resuspended in nonane for GC/MS analysis. The GC/MS analysis is then performed at 10,000 resolution by selected ion recording. Monitoring two ion species per component allows the identity to be confirmed by checking the isotope ratios.

Figure 6.9 shows a schematic of the sampling set-up for dioxins. It is based on USEPA Method 23 (USEPA, 1995), which complies fully with BS EN 1948-1 (BSI, 1997).

A more detailed description of the preferred methodology for dioxins is given in BS EN 1948: Parts 1, 2 and 3 (BSI, 1997). Technical Guidance Note M2 (Environment Agency, 2002d) discusses available methodologies for analysing for dioxins in more detail.

6.6 Polycyclic aromatic hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons are sampled using USEPA Method 5 sampling equipment modified by the inclusion of a XAD-2 resin trap. The equipment is similar to the layout of Method 23 equipment shown in Figure 6.10. A representative sample is extracted onto a filter from the gas stream under isokinetic conditions. The filter, resin trap and the probe washing are collected after sampling, labelled and returned to the laboratory. The laboratory sample is removed from the sampling filter, XAD-2 resin, by Soxhlet extraction. Analysis is undertaken using GC/MS.

6.7 Fluoride, chloride and bromide

Halides are sampled using the main procedural requirements of BS EN 1911 (BSI, 1998). A sample of exhaust gas is extracted, via a probe, through a quartz filter into an impinger train, which consists of dilute caustic solution (0.1M NaOH) in two impingers. A third impinger is left empty, while a fourth impinger contains silica gel to remove residual moisture. Upon completion, the probe is washed and the washings are combined with the impinger solutions. These impinger solutions are then used to determine gaseous fluoride (F), chloride (Cl) and bromide (Br) concentrations, using an ion specific electrode (ISE) or ion chromatography. The filters are digested and analysed for the solid phase fluoride, chloride and bromide, along with the acetone washing of the probe and front of the filter housing. This method will only report inorganic halides for the organic chlorine, fluorine and bromine fraction. Speciation of the VOC is required for organic chlorine, fluorine and bromine compounds.

6.8 Hydrogen sulphide

Sampling for hydrogen sulphide is carried out in accordance with USEPA Method 15 (USEPA, 1996a). Hydrogen sulphide is sampled by taking a representative sample extracted from the gas stream under non-isokinetic conditions. A quartz filter traps the particulate matter and the vapour phase hydrogen sulphide is captured in the relevant absorbing solutions. The total sulphide determination is measured using gas chromatography/flame photometric detection spectophotometry. The principle forming the basis of this spectrometry is the excitation of a molecule by the absorption of energy.

Alternatively, a gold film monitor may be used, which operates on the principle that H_2S adsorbs on to a gold electrode whose electrical conductivity changes in proportion to the amount of H_2S present. The instrument is able to measure concentrations from 50 ppm down to 1 ppb. However, instruments such as these are affected by other sulphides and particularly organosulphur compounds, which are found in raw landfill gas. In the majority of landfill gas samples, the levels of hydrogen sulphide are at a concentration many times higher than potential interferents and the effect will be minimal.

A more detailed description of the preferred methodology for hydrogen sulphide is given in USEPA Method 15 (USEPA, 1996a). Technical Guidance Note M2 (Environment Agency, 2002d) discusses available methodologies for analysing for hydrogen sulphide in more detail.

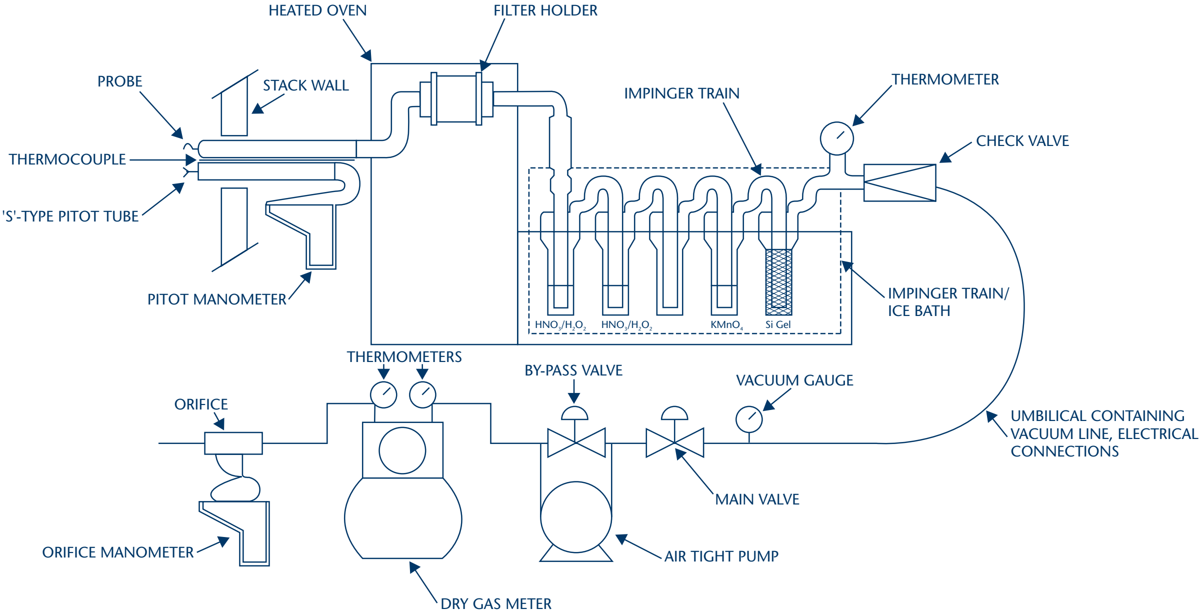


Figure 6.8 Sampling set up for measuring particulates (USEPA Method 5)

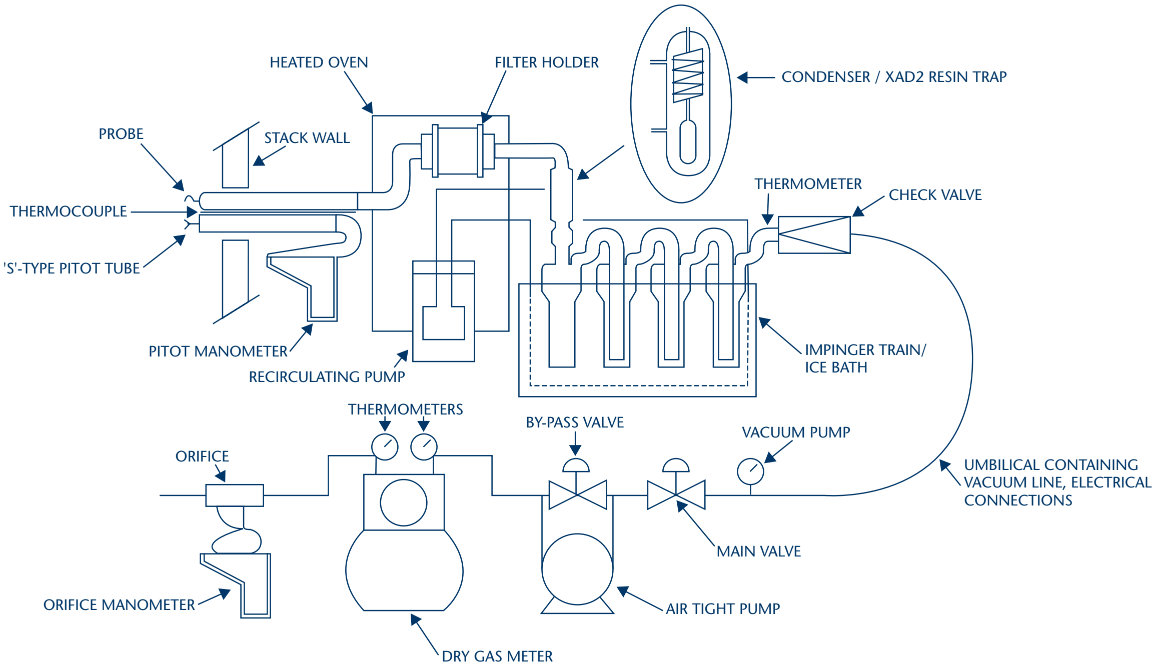


Figure 6.9 Sampling set up for measuring particulates (USEPA Method 23)

6.9 Auxiliary measurements

6.9.1 *Velocity*

A velocity profile is required for any emissions measurement. This will allow:

- a decision on the suitability of the sampling position
- the concentrations to be converted to mass emission rates.

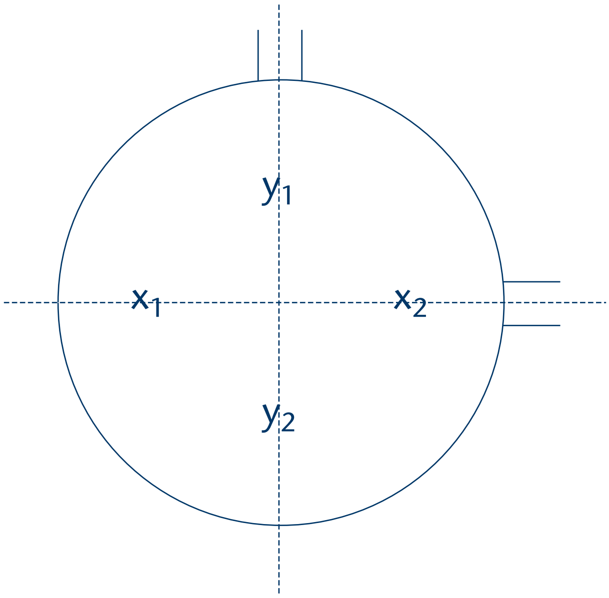
A Pitot tube, pressure lines, a Pitot balance valve and a manometer are required to measure velocity. Various types of Pitot tube are available. The two commonest are the NPL Pitot static tube and the 'S' type tube. Both measure pressure differential, but the 'S' type requires an additional coefficient to be included in the calculation. A manometer is used to measure the pressure differential and electronic versions are available. A liquid fill inclined manometer can be used, although this requires significant experience to achieve good results.

Once the Pitot apparatus is set up, the Pitot tube is marked with the positions for the measurements and the sampling positions for the emission test. The positions for a circular duct are shown in Figure 6.10. For rectangular ducts, refer to BS 6069 (BSI, 1993).

The reading should be recorded at each measurement position. If the flow is varying, the median of the deviations should be taken. At points 2 and 9, a swirl test should be carried out to determine the level of turbulence in the duct. If the angle of swirl is too much, a new test position should be sought. Pitot measurements should be taken and recorded, both when inserting and when removing the tube. The calculated average gives the actual velocity of the gas in the exhaust.

The procedure should be repeated for the other sampling plane. The temperature profile can be combined with the flow profile, if a thermocouple is attached to the Pitot tube.

The minimum flow that can be accurately measured is approximately 3 metres/second and the maximum is about 60 metres/second. Landfill gas engines typically operate well within this velocity range.



Transverse point	1	2	3	4	5	6	7	8	9	10
Position	0.05D	0.15D	0.25D	0.35D	0.45D	0.55D	0.65D	0.75D	0.85D	0.95D
Sample point (<0.09 m duct area)					0.5D					
Sample point (0.09–0.38 m duct area)		0.15D							0.85D	
Sample point (0.38–0.79 m duct area)	0.065D		0.25D					0.75D		0.935D

Figure 6.10 Velocity measurement and sampling positions for circular ducts

6.9.2 Temperature

Temperature is measured using thermocouples built into sampling probes. When a temperature gradient is present in an electrical conductor, a flow of electrons is created, which gives rise to an electromotive force (emf).

Thermocouples are constructed of two different metals with well-known temperature/emf characteristics (e.g. chromel/alumel) in contact at one end. The emf depends upon the magnitude and direction of the temperature gradient. Typical ‘k’ type thermocouples will monitor temperatures up to 1,000°C.

6.10 Quality control and quality assurance

For quality purposes and integrity of the analytical results, all sampling and analysis should be carried out by a laboratory with appropriate UKAS accreditation schedules for the selected suite of analysis.

6.10.1 Quality control

Quality control (QC) procedures exist to reduce uncertainties to a minimum. There are two different types of uncertainties:

- **Random** uncertainties usually result from small changes in a procedure. They are generally overcome by ensuring that the procedures are followed exactly.
- **Systematic** uncertainties introduce a bias into the measurements taken and, regardless of the number of measurements taken, the mean result will not represent the true value of the parameter being measured. Systematic uncertainties can be overcome by ensuring:
    - the systems are correctly assembled
    - any equipment meets the correct specification
    - equipment is maintained and calibrated correctly.

For each sampling method used, a checklist should be used that sets out:

- the sampling method to be used
- the equipment to be used
- clear instructions on the assembly of the equipment
- details of any leakage tests to be undertaken
- details of calibration procedures
- details of the analytical method to be used
- details of the reporting procedures
- details of maintenance procedures for equipment.

Quality control is concerned with a number of factors highlighted below.

Calibration
Calibration is an important aspect of QC because it determines the relationship between the actual concentration of the parameter being tested and the readout on the instrument.

There are two different types of calibration.

- **Routine zeroing** is a guide to the changes in an instrument since it was last fully validated and can be carried out by the person who is using the instrument.
- A **full-scale validation** exercise should be carried out at least annually (depending upon manufacturer’s recommendations) and can require the instrument to be sent away.

Maintenance procedures
Instrument operators must have received adequate training in the use of recommended maintenance procedures.

Sample storage and transport
To ensure that the integrity of the sample is maintained, samples must be clearly identifiable throughout the whole sampling process. This is easily undertaken by marking each sample with a unique reference number.

Sample analysis
The sample should be analysed to the relevant standard at a UKAS accredited laboratory.

Data handling
The data must be presented in a clear manner and must satisfy the needs of the regulator.

6.10.2 Quality assurance

Quality assurance (QA) is described as quality control of the quality control. It is important to set up a QA programme to ensure that all measurements are carried out to the same standard, such that comparable results can be achieved.

The main elements of a QA programme are:

- preparation of sampling methods
- instruction in the correct use of the methods (to anyone involved in the sampling)
- ensuring that good QC procedures exist for whoever is undertaking the sampling
- ensuring uniformity by inspecting the work of different measuring organisations
- provisions to be made for a suitable reporting procedure
- documentation of the QA procedures to be circulated to everybody involved in taking the samples.

A QA procedure should ensure that:

- any measurements are made in accordance with an agreed protocol
- the correct quality control procedures are in place
- quality control procedures are being adhered to
- sample identification and chain of custody are well documented
- the correct reporting procedures are used.

6.10.3 Sampling methods

Sampling methods are important as they ensure that the sampling procedure is carried out correctly and that the results obtained characterise the engine emissions.

The main elements of a sampling method include:

- a reference method for measurements, usually relate to specific standards (e.g. ISO);
- a standard methodology for each process, which details:
    - the frequency and duration of sampling
    - the emissions to be measured
    - the analytical methods to be used
    - the health and safety considerations to be adopted
    - the procedures to be used if meaningful measurements can not be achieved using standard procedures.
- QC and QA (see Sections 6.10.1 and 6.10.2).
- reporting procedures.

Appendix A:

Example sample report format

Report period: .... to ....
Permit number ....
Operator name ....
Name of monitoring organisation(s).....................................
Name of analytical organisation(s).......................................
Date issued by operator (dd/mm/yy)....................................

Installation address ....
....
....

Emission point						
Substance						
Summary						
Permit limit (value, units)						
Concentration (value, uncertainty, units)						
Mass emission (value, uncertainty, units)						
Measurement details						
Sampling method (e.g. CEN, ISO, national standard)						
Accreditation of sampling method (e.g. UKAS Ref. No.)						
Analytical method (state technique e.g. gravimetric)						
Accreditation of analytical method (e.g. UKAS Ref. No.)						
State if sampling compliant with method						
State if analysis compliant with method						
Date of sampling (dd/mm/yy)						
Time sampling started						
Time sampling finished						
Date of analysis (dd/mm/yy)						
Limit of detection (LOD) of overall method (value, units)*						
Span gas concentration (if applicable) (value, units)						
Process conditions						
Process status**						
Supporting information						
Emission point grid reference						
Interval between sampling						
Date of previous sampling (dd/mm/yy)						
Percentage of base load						
Ref conditions used (273K abd 101.3kPa) wet/dry, oxygen						

* Ideally LOD should be <10 per cent of the permit limit

** Process conditions: N = normal, A = abnormal (e.g. failure of abatement control), T = transitional (e.g. start-up), O = other

Glossary and acronyms

Absorption
A process in which a gas is taken up by a liquid or a solid.

Adsorption
A process in which a layer of atoms or molecules of one substance forms on the surface of a solid or liquid.

AFNOR
Association Française de Normalisation

ASTM
American Society for Testing Materials

Base load power generation
Continuous operation at maximum output.

Biodegradable waste
Any waste (e.g. food, garden waste and paper) capable of undergoing decomposition by micro-organisms under anaerobic or aerobic conditions.

Biogas
A methane-based fuel that is produced through the bio-digestion of organic material.

BSI
British Standards Institution

CEMS
Continuous emission monitoring system

CEN
Comité Europeén de Normalisation

Chemiluminescence
The emission of light during a chemical reaction.

Continuous Monitoring
The use of automated inline analysers that provide frequent, though not uninterrupted, data.

Covalent
A covalent bond is a chemical bond formed between atoms by the sharing of electrons.

Diesel engine
Any compression-ignited internal combustion engine.

DIN
Deutsches Institute für Normung

DTI
Department of Trade and Industry

Dual-fuel engine
Any internal combustion engine that is designed to burn a liquid and a gaseous fuel mixture during a single operating cycle.

Duct
An enclosed structure through which gases travel

Electromotive force
Electromotive force (also known as voltage) is a quantitative expression of the potential difference in charge between two points in an electrical field. The greater the voltage, the greater the flow of electrical current (i.e. the quantity of charge carriers that pass a fixed point per unit of time) through a conducting or semi-conducting medium for a given resistance to the flow.

ELV
Emission limit value

FID
Flame ionisation detector

Flue
See duct

FPD
Flame photometric detection. Detection unit in a gas chromatograph that specifically measures compounds containing phosphorus and sulphur.

FTIR
Fourier transform infra-red spectrometry

GC
Gas chromatography. The process to enable the components of a sample gas to be separated by passing the gas through a column with a high surface to volume ratio. The separated components are measured using an appropriate detector.

GC/MS
Gas chromatography/mass spectrometry

Homogeneous
A homogeneous mixture is uniformly and complete mixed.

IC
Internal combustion

ICCR
Industrial Combustion Co-ordinated Rulemaking Federal Advisory Committee of the USEPA

Internal combustion (IC) engine, stationary
Any reciprocating, piston driven IC engine that is operated or intended to be operated at one specific location for more than 12 months or that is attached to a foundation at the location.

Ionise
To convert wholly or partly into ions.

IR
Infra-red

ISE
Ion-selective electrode

ISO
International Organisation for Standardization

Isokinetic sampling
Isokinetic sampling is achieved when the gas enters the sampling nozzle at exactly the same velocity and direction as the gas travelling in the exhaust.

Landfill gas
All gases generated from the landfilled waste.

Lean-burn engine
Any spark ignited internal combustion engine that is operated with an exhaust stream oxygen concentration of ≥4 per cent by volume prior to any exhaust stream control device.

MCERTS
Monitoring Certification Scheme

MS
Mass spectrometry

NDIR
Non-dispersive infra-red spectrometry

NFFO
Non-Fossil Fuel Obligation

NMVOCs
Non-methane volatile organic compounds

PAHs
Polycyclic aromatic hydrocarbons

PCDD
Polychlorinated dibenzo-p-dioxin

PCDF
Polychlorinated dibenzo furan

QA
Quality assurance

QC
Quality control

REC
Regional electricity company

Rich-burn engine
Any spark ignited internal combustion engine that is operated with an exhaust stream oxygen concentration of £4 per cent by volume prior to any exhaust stream control device.

ROC
Renewables Obligation Certificate

RPI
Retail Price Index

Sampling location
A suitable position on the site where representative samples can be obtained.

Sampling plane
A plane normal to the centreline of the duct at the sampling position.

Sampling point
The point(s) on the sample plane where the sample is collected.

Sampling ports
Points in the wall of the stack, duct or flue through which access to the emission gas can be gained.

Sampling position
See Sampling location.

Sampling section
See Sampling plane.

Spectral line
A particular wavelength of light emitted or absorbed by an atom, ion or molecule.

STA
Source Testing Association

Stack
A structure (i.e. chimney) through which emissions are released to atmosphere.

Stoichiometric
The exact proportions in which substances react. For combustion, a theoretical minimum amount of air or oxygen required to consume the fuel completely.

UKAS
United Kingdom Accreditation Service

Ultraviolet (UV)
A form of electromagnetic radiation, shorter in wavelength than visible light.

USEPA
United States Environmental Protection Agency

VDI
Verein Deutscher Ingenieure (Dutch national standards body)

VOC
Volatile organic compound

XAD
Trade name for polystyrene adsorbent resin beads

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Index

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