LFTGN 05

Lfd **Landfill** directive

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Guidance for monitoring enclosed landfill gas flares

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Statement of Use

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

This document is intended to help officers in the regulation of emissions from enclosed landfill gas flares. This guidance is concerned only with emissions from enclosed flares and does not consider emissions from other forms of landfill gas combustion. A separate guidance document is available that discusses the operation and emission from landfill gas engines.

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

Table A summarises the emissions testing requirements for enclosed landfill gas flares. For each determinand, the reference method and recommended analytical techniques used are identified, along with the required testing frequency and emission standards based on best practice.

Table A Summary of emissions testing requirements for enclosed landfill gas flares

Determinand	Reference method[a]	Sampling and analytical technique	Minimum testing frequency	Emission standard (mg/m^3)[b]	
				Flare commissioned before 31 Dec 2003	Flare commissioned after 31 Dec 2003
NO_x[c]	ISO 10849	Chemiluminescence	Annually	150	150
CO	ISO 12039	Non-dispersive infra-red analysis	Annually	100	50
Total VOCs	BS EN 12619[d] BS EN 13526[e]	Extractive sampling and flame ionisation detector analysis	Annually	10	10
NMVOCs	BS EN 13649	Extractive sampling onto sorbent, desorption with carbon disulphide, analysis by gas chromatography.	Annually	5	5

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

[b] These limits are based on normal operating conditions and load. Temperature: 0°C (273K); pressure: 101.3 kPa; and oxygen: 3 per cent (dry gas). For more information, see Section 9.3.

[c] NO_x expressed as NO_2

[d] At sites with low VOC concentrations.

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

These emission standards are for a minimum suite of determinands; emission limits may be modified and additional determinands identified by site-specific risk assessment. Alternatives to the reference methods stipulated in Table A can be used, provided they are shown to be fit-for-purpose and a suitable justification is presented before sampling is undertaken.

In addition to the numerical emissions limits, the following provisions must also be met:

- Sample ports must be fitted in accordance within the requirements of Technical Guidance Document M1 (Environment Agency, 2002a) or, alternatively, in situ probes.
- Sampling must be undertaken downstream of the flame. Flare designs must include sufficient shroud to fully enclose the flame at all times.

- Emissions must not be impeded by cowls or any other fixture on top of the flare during operation.
- Operational control must be so as to achieve a minimum output of 1,000°C and 0.3 seconds retention time at this temperature (or an equivalent validated set of conditions to give complete combustion). The operating temperature must be monitored.
- The flow and composition of the input gas must be monitored at the flare to demonstrate consistency with operational requirements and the design specification of the flare.

Flares that do not meet the operational standards or have not been maintained may not be monitored in a representative or safe manner. They are unlikely to meet the emission standard and should be regarded as non-compliant. Emissions testing should not be undertaken on these flares until these operational faults have been rectified.

This guidance applies to new enclosed landfill gas flares. Existing flares (i.e. those commissioned before 31 December 2003) must be upgraded to new flare standards as the sites go forward under the Pollution Prevention and Control regime. The application of this guidance to enclosed flares at sites that remain subject to the waste management licensing regime will be determined by an Emissions Review and subsequent improvement programme. This will be undertaken on a risk basis for completion as soon as is reasonably practicable. The improvements identified in an Emissions Review must be completed at all Agency-regulated landfills by 16 July 2009.

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Introduction

1.1 Purpose of the guidance

This document sets out guidance on the procedures to be followed when determining emissions from enclosed landfill gas flares. Enclosed (ground) flares are those where the landfill gas is combusted in a vertical enclosure. This document does not provide guidance for sampling emissions from open flares. It is impossible to sample emissions from these devices either accurately or safely.

The purpose of this document is to provide a best practice approach to the sampling and analysis of emissions from enclosed landfill gas flares. The guidance aims to:

- ensure a consistent and transparent approach to measuring emissions from enclosed flares
- ensure that the most appropriate sampling and analytical standards are followed.

Section 9.1 sets out the emission standards to be met by enclosed landfill gas flares.

1.2 Document structure

The document is divided into nine sections:

- Section 1 – a summary of the purpose of the guidance
- Section 2 – a description of the processes of landfill gas generation and combustion
- Section 3 – a discussion on the design of landfill flares, their operation and maintenance, the emissions released and applicable abatement technologies
- Section 4 – a review of emissions limits
- Section 5 – a review of the relevant safety legislation and details of specific health and safety issues relating to the measurement of emissions from landfill flares
- Section 6 – an emission monitoring protocol describing the general approach to monitoring flare emissions
- Section 7 – descriptions of various emission monitoring methods that may be used to monitor flares
- Section 8 – quality control and quality assurance information specific to flare emission measurements
- Section 9 – data assessment and reporting (including emission standards).

1.3 Relationship with other guidance

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.

Information is also drawn from the following documents:

- *Sampling requirements for monitoring stack emissions to air from industrial installations.* Technical Guidance Document (Monitoring) M1 (Environment Agency, 2002a)
- *Monitoring of stack emissions to air.* Technical Guidance Note (Monitoring) M2 (Environment Agency, 2002b).

This guidance has developed from general Agency guidance on landfill gas flaring published in 2002 (Environment Agency, 2002c) and the documents listed above. The monitoring procedures and emission standards in this document supersede those recommended in previous guidance.

In the medium term, it may be possible to augment emissions-based regulation with a system of type approval/operational monitoring. Under this system, specific landfill gas flare and engine models would be demonstrated to be capable of achieving the emissions standards set by the regulator and would be shown to do so reliably when operational. The UK waste industry is keen to develop this method for the future management of emissions from landfill gas combustion systems. The regulator supports such research as it might lead to more cost effective monitoring of landfill gas combustion equipment, content in the knowledge that the emissions standards were being met.

Setting the scene

2.1 Landfill gas: the issues

Landfill gas is an inevitable product of the decomposition of biodegradable wastes in landfill sites. One of the major components of landfill gas is methane, which is the second most significant greenhouse gas after carbon dioxide. Landfill sites are one of the most important contributors to the UK's total annual emissions of methane; they accounted for over 27 per cent of total man-made emissions in 1999 as reported to United Nations Economic Commission for Europe (UNECE) (Goodwin *et al.*, 2002). Methane is also flammable and thus its uncontrolled migration and release poses a hazard to the environment, human health and amenity. In addition, a number of the trace constituents of landfill gas are odorous and/or potentially harmful to health.

Collection of landfill gas is typically undertaken using gas wells within the landfill. At all sites, some landfill gas does escape to atmosphere through the surface and lining. The amount of fugitive gas escaping will depend on the efficiency of the gas collection system, the design of the lining, the capping of the site and the volume of gas generated.

The Landfill (England and Wales) Regulations 2002 (as amended) define landfill gas as: 'all the gases generated from the landfilled waste'. Schedule 2 of these Regulations require the control of emissions of this gas in a safe and environmentally acceptable manner. In particular:

- appropriate measures must be taken 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.

Flares are used solely or in-conjunction with landfill gas engines as a means of controlling the release of landfill gas to the environment.

2.2 Landfill gas composition

The composition of the landfill gas is a major factor in determining the emissions following its combustion. This will affect the flare operation and thus influence the nature of the emissions. The properties of the deposited wastes affect the composition of the landfill gas. These properties include:

- site characteristics
- waste type (hazardous, non-hazardous, inert)
- age of waste
- density
- moisture content
- pH
- temperature
- ingress of air and hence oxygen
- gas management regime
- atmospheric conditions.

The variability of landfill gas composition from one site to another and even between cells on the same site means that measurements of enclosed flare stack emissions should always be reported in the context of the inlet gas composition. In addition, it is necessary to record and report details of:

- the age of the landfill
- the atmospheric conditions prevailing at the time of sampling
- the composition and construction of the landfill.

A detailed discussion on these factors can be found in *Guidance on the management of landfill gas* (Environment Agency, 2004a).

Landfill gas is a mixture of gases that can be categorised into:

- bulk components
- trace components.

The main bulk components are methane, carbon dioxide, hydrogen, nitrogen and oxygen. Each represents a substantial proportion of the overall gas.

The trace components are a wide range of volatile and semi-volatile organic and inorganic components,

Table 2.1 Indicative bulk constituents of landfill gas

Component	Typical value (% volume)	Observed maximum (% volume)
Methane (CH_4)	64	88
Carbon dioxide (CO_2)	34	89
Oxygen (O_2)	0.2	20.9*
Nitrogen (N_2)	2.4	87
Hydrogen (H_2)	0.05	21

Source: Environment Agency (2004a)

* Includes data at atmospheric levels.

which are present in very small quantities and together represent less than 1 per cent by weight (or about 0.1–0.35 per cent by volume) in a typical landfill gas (Environment Agency, 2002d).

Table 2.1 provides an indication of the typical composition of the bulk fraction present in landfill gas. The values are based on reported measurement data.

Over 500 trace compounds have been identified in landfill gas (Environment Agency, 2002d). The majority of these are volatile organic compounds (VOCs). However, inorganic compounds (including ammonia, arsenic, mercury, cadmium, chromium, etc. in both elemental and compound form) and volatile metallic compounds may also be present. Trace quantities of a number of compounds with potential health impacts may also be found in landfill gas such as vinyl chloride, polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). Indicative concentrations of organic compounds in landfill gas are given in Table 2.2.

In a landfill site, decaying wastes deplete the oxygen entrained within the waste mass, creating anaerobic conditions. There are several phases of landfill gas generation. Under anaerobic conditions, the waste continues to degrade to produce landfill gas, which contains roughly 50 per cent methane and 50 per cent carbon dioxide.

In sites with no gas control, the gas migrates to the surface or through the side walls of the landfill and is released. In sites with gas control, a low permeability cover and a system of wells and pumps restrict gas release to facilitate extraction of the gas for either flaring or combustion for energy recovery.

Detailed descriptions of the evolution and management of landfill gas are given in *Guidance on the management of landfill gas* (Environment Agency, 2004a).

2.3 Landfill gas combustion

Combustion may be defined as being a chemical reaction between fuel and oxygen, resulting in the liberation of heat and light. Once the fuel is ignited, it must supply sufficient heat to raise the temperature in order to establish continuous combustion.

Flares use landfill gas as the fuel and air is 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 given by

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

This stoichiometric mixture represents the precise amount of air needed to completely burn one molecule 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 becomes too rich and reducing, and carbon monoxide and saturated/unsaturated hydrocarbons (non-methane volatile organic compounds – NMVOCs) form during the combustion process. Excess air is added to provide a lean mixture to aid complete combustion within the flare.

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 present in the air used in combustion.

A number of studies have assessed emissions from landfill gas flares. The measurement methods used in these studies have been diverse, as has been the choice of sample positions and paucity of reported supporting data. It is therefore difficult to compare results from one study with another – especially as emissions will also vary with landfill gas composition, the type of flare system employed, and how well it is operated and maintained. Appendix A contains a summary of the results from a number of these studies and identifying key emissions from enclosed landfill flares.

To aid development of this guidance and to supplement these data, the Environment Agency commissioned a series of measurement exercises at ten landfill sites in England and Wales. A summary of the data derived from these measurements is given in Tables 2.3a and 2.3b. At a number of the sites, the data identified operational problems with the flares monitored.

Table 2.2 Example concentrations of organic compounds in landfill gas

Compound	Concentration (mg/m^3)					
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Hydrocarbons						
Alkanes	920	370	510	670	470	360
Alkenes	420	180	240	0.5	9	10
Alkynes	ND	ND	<2.0	ND	–	–
Cycloalkanes	29	10	5	ND	80	170
Cycloalkenes	530	120	79	170	190	470
Aromatic	1,600	310	350	140	940	430
Oxygenated compounds						
Alcohols	180	2	7	32	2	49
Esters	290	0.2	ND	4.7	–	–
Ethers	1.8	0.4	0.2	ND	–	–
Ketones	120	2.9	1	16	–	–
Carboxylic acids	ND	ND	ND	ND	–	–
Other	ND	0.5	0.7	1.2	75	68
Other compounds						
Halogenated	330	27	39	41	510	50
Sulphonated	18	1.5	3.9	5.6	0.5	0.9
Amines	ND	ND	ND	ND	–	–

Source: Baldwin *et al.* (1993a,b); Environment Agency (2002d)
ND = not detected (limit of detection not specified)
– = not measured

Table 2.3a Enclosed flare monitoring data at test sites

Determinand	**Measured value**									
Site	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
Inlet gas										
Methane (%)[a]	55	56	45	44	33	54	36	39	36	46
Carbon dioxide (%)[a]	39	41	31	32	30	43	30	34	23	37
Oxygen (%)[a]	0.4	<0.1	0.2	4.4	7.0	0.9	6.2	0.6	7.0	1.8
Nitrogen (%)[a]	5.0	3.2	24	20	30	1.9	28	21	34	15
Hydrogen sulphide (ppm)[a]	<5	587	23	30	85	1416	33	89	5	18
Carbon monoxide (ppm)[a]	<2	11	24	45	786[c]	40	530[c]	56	36	194
Emissions										
Temperature (°C)[a]	513	956	588	986	1208	1162	992	849	738	862
Oxygen (%)[a]	17.3	12.6	15.3	11.0	5.1	6.4	11.5	12.4	14.3	11.5
Carbon dioxide (%)[a]	2.6	5.7	4.1	8.6	14.7	12.4	8.3	5.8	5.3	8.3
Moisture (%)[a]	3.1	5.6	3.6	15.0	13.0	16.3	8.4	15.3	7.2	12.2
Carbon monoxide (mg/m^3)[b]	1042	617	2178	27	32	34	253	34	99	<2
Oxides of nitrogen (as NO$_2$) (mg/m^3)[b]	75	111	43	92	99	149	82	59	63	14
Total VOCs (as C) (mg/m^3)[b]	21	3	2	<2	2	<2	10	6	17	<2
Hydrogen chloride (mg/m^3)[b]	36	9.5	4.6	7.4	11	4.2	36	7.4	4.9	16.2
Hydrogen fluoride (mg/m^3)[b]	21	2.5	0.4	2.5	0.7	1.6	7.8	2.5	0.5	0.5
Sulphur dioxide (mg/m^3)[b]	482	239	63	30	43	359	181	61	58	83

[a] On-site measurement.

[b] Averaged emission by laboratory analysis at reference conditions of standard temperature and pressure (STP), i.e. 3 per cent oxygen, 273K, 101.3 kPa, dry.

[c] Result may be affected by possible interference due to the presence of hydrogen.

Table 2.3b Enclosed flare monitoring data at test sites – NMVOCs, PCDDs and PCDFs

Determinand	**Concentration****			
Site	**D**	**E**	**F**	**J**
NMVOCs * (mg/m^3)	0.083[#]	2.54[#]	3.89[#]	0.073[#]*
PCDDs and PCDFs (ng/m^3)	–	0.040	–	0.068[#]

* Environment Agency (2002d)

** At reference conditions of standard temperature and pressure (STP), i.e. 3 per cent oxygen, 273K, 101.3 kPa, dry.

[#] Average of two tests

– = not measured

3

Landfill gas flares

3.1 Operational design of flares

A flare consists of a burner or burners located at the base of a shroud. Enclosed flares provide for better combustion conditions than those found in open flares. Combustion control is usually provided with air control and the enclosure is insulated in order to maintain consistently high combustion temperatures.

Enclosed flares can be sub-divided according to the way in which they combust the landfill gas into:

- ‘diffusion flame’ flares – primary air and landfill gas are mixed before the burner
- ‘pre-aerated flame’ flares – air diffuses into the landfill gas leaving the burner.

If there is sufficient air mixed with the landfill gas to ensure complete combustion, then the flame produced will be relatively short, bluish in colour, and relatively hot. If there is insufficient air or it is poorly mixed with the landfill gas, the flame will tend to be reducing, characteristically long, luminous and possibly sooty.

The flare height is usually over three times its diameter. The height of the flare has a key effect on the combustion process (particularly for diffusion burners), as it affects the air supply to support the combustion process. Air is drawn into the shroud by the natural draught caused by the height of the flare and the buoyancy of the hot combustion gases.

The burners are typically placed in a rectangular box at the base of the cylindrical shroud. Materials such as ceramic fibre or a refractory lining insulate the shroud. This ensures that the temperature is maintained within the combustion chamber. Figure 3.1 shows a basic flare arrangement and Figure 3.2 a typical enclosed flare.

Although there are a number of flare systems and types, all have the following basic components:

- a landfill gas collection and distribution system (the network of wells, pipework and manifolds that collect the landfill gas and transport it to the gas conditioning stage);

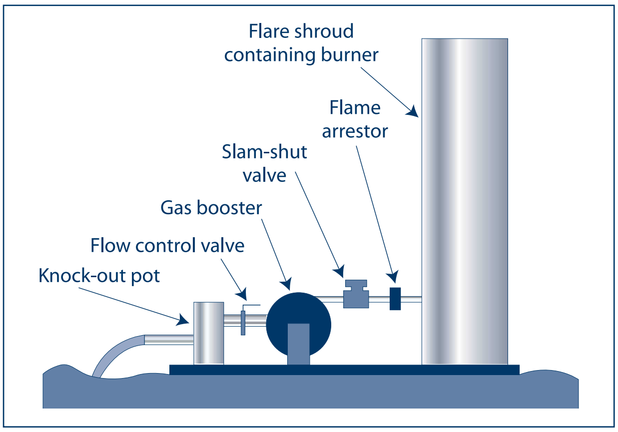


Figure 3.1 Basic flare arrangement

Figure 3.2 An example enclosed flare

- a landfill gas conditioning system to remove moisture and particulate matter from the landfill gas to ensure burners do not become blocked;
- a pressurising system to ensure that the pressure of the landfill gas is adequate for correct operation of the burner (a blower or other gas compressor is used to increase the landfill gas pressure to about 3–15 kPa);
- a flame arrestor device to avoid flashback of a flame to the fuel feed pipe;

- burner(s) to provide controlled mixing of the fuel and air, and to ensure controlled combustion over a range of landfill gas flow rates (burner design can vary considerably and there may be one or several burners installed within a flare);
- an ignition system to provide safe, controlled ignition of the landfill gas;
- flame detection to determine that ignition has occurred and that the burner is operational (this is normally a temperature sensor or ultra-violet based detector which is used to determine the presence of a flame and to initiate controlled shutdown and/or re-ignition);
- a combustion air system to provide air for combustion support, depending on burner load. There are two methods of providing primary air to support combustion. The first involves mixing of air with the fuel prior to the burner (premix). The second involves the air being drawn into the combustion chamber (diffusion). In both cases, additional air is drawn into the chamber by natural draught via control louvres or open vents. The louvres are usually controlled on the temperature within the shroud (see Figure 3.3).

3.2 Flare operating profile

The operating profile of a flare depends on the application in which the flare is deployed. A flare used as a primary means of landfill gas combustion should operate at or close to its design capacity. A flare should not be operated beyond its design capacity because the flame is unlikely to remain completely enclosed and the emission standard will not be met.

The specification of the flare(s) for use with a landfill gas engine must take account of the significant variation in gas flow depending on whether the gas engines are operational or not. When the engines are not operational, the flare(s) will need to be capable of burning all the collected landfill gas. However, when the landfill gas engines are operating, the flow of landfill gas to the flare(s) will be reduced or absent altogether. This introduces potential problems with combustion control, as the pressure of the landfill gas may not be sufficient to produce complete combustion. In addition, the air control may be such that too much air may be provided for the quantities of landfill gas available, resulting in quenching and incomplete combustion. One option is to install a number of flares of varying capacities to allow greater flexibility of operation.

Figure 3.3 Air control louvres employed on an enclosed flare

3.3 Standby flares

Standby flares operate in conjunction with landfill gas utilisation units such as engines. Enclosed flares that provide a standby role for utilisation plant do not need to be monitored for emissions as long as:

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

3.4 Maintenance

Enclosed flares have a fairly simple design. Each design has its own maintenance schedule specified by the manufacturer, which should be adhered to.

Such schedules typically consist of routine checks of:

- fan and motor
- mechanical systems (e.g. joints and valves)
- safety systems (e.g. flame arrestors)
- electrical systems
- instrumentation (including calibration of the oxygen and methane gas inlet analysers)
- gas conditioning vessels.

3.5 Emissions from landfill gas flares

3.5.1 Overview

The emissions from the combustion of landfill gas within an enclosed flare are determined by many factors. These include:

- the components present in the landfill gas;
- the type and design of flare being used;
- operation and maintenance of the flare;

Table 3.1 Key emission components

Component	Reason for presence in emission
Carbon dioxide	Combustion product of methane and other carbon compounds (e.g. hydrocarbons). Fuel component.
Carbon monoxide	Product of incomplete combustion
Nitrogen oxides	Combustion product, nitrogen in fuel or secondary formation in flame
Sulphur dioxide	Combustion product of inorganic and organic sulphur compounds in fuel gas
Hydrogen chloride	Combustion product of chlorinated organic compounds in fuel gas
Hydrogen fluoride	Combustion product of fluorinated organic compounds in fuel gas
Methane	From unburnt fuel gas (indicating incomplete combustion)

- combustion conditions, temperatures, residence time, excess air, etc.;
- balancing of the gas field (including condensate management).

The mechanism of combustion in a landfill gas flare differs from that of other combustion plant such as spark ignition engines. These differences influence the proportions of combustion products. In an engine, a short-lived explosive reaction occurs under pressure whereas the combustion process in a flare occurs over a comparatively long period.

A wide range of emissions can be produced from the combustion of landfill gas in an enclosed flare. Consequently, a pragmatic approach to the measurement of emissions and the setting of emission standards has been adopted. The typical emission components listed in Table 3.1 have been chosen on the basis of:

- previous studies
- the measurement exercise carried out by the Agency in support of this guidance
- emission standards set elsewhere in the European Union.

3.5.2 Carbon dioxide

Carbon dioxide is present in the emission from the landfill gas flare as the final oxidation product of carbon in the fuel gas. However, up to half the carbon dioxide present in the emission maybe derived from the carbon dioxide present in the raw landfill gas. Carbon dioxide is present at concentrations in the order of percentages by volume.

The formation of CO_2 is due to the following basic reaction:

$$CH_4+2O_2 \rightarrow CO_2+2H_2O$$

3.5.3 Carbon monoxide

Carbon monoxide (CO) is primarily the product of incomplete combustion of carbon. Some of the factors contributing to its production include:

- inadequate supply of oxygen
- poor turbulence
- incomplete mixing
- short residence time.

Carbon monoxide concentrations are a good indication of the combustion efficiency of the process. If the combustion efficiency of the process is high, then carbon monoxide is found in low concentrations relative to concentrations of carbon dioxide.

3.5.4 Nitrogen oxides

For the purposes of this guidance, nitrogen oxides (NO_x) are defined as the sum of nitric oxide (NO) and nitrogen dioxide (NO_2). Both species are derived from the oxidation of nitrogen. There are three mechanisms for the formation of NO_x:

- oxidation of the nitrogen present in the air used during combustion (formation increases significantly at temperatures above 1,200°C);
- reaction between nitrogen and fuel-derived radicals and their subsequent oxidation;
- oxidation of nitrogen-containing species present in the fuel.

Thus, the quantity of each component of NO_x produced during the combustion process in an enclosed flare depends on:

- the amount of oxygen present
- the flame temperature
- the source of the nitrogen
- the residence time.

3.5.5 Sulphur dioxide

Sulphur dioxide (SO_2) is formed by the oxidation of sulphur-containing compounds during combustion of the landfill gas. To a lesser extent, sulphur trioxide (SO_3) may also be formed. A primary source of sulphur in landfill gas is hydrogen sulphide (H_2S), but other sulphur-containing species such as mercaptans may also be present.

3.5.6 Hydrogen chloride and hydrogen fluoride

These highly reactive acidic gases result from the combustion of chlorinated and fluorinated organic compounds present as trace components in the landfill gas. The halide radicals resulting from combustion, then react with water or moisture to produce hydrogen chloride (HCl) and hydrogen fluoride (HF).

3.5.7 Methane

Methane is one of the primary constituents of landfill gas and provides a high proportion of the fuel's calorific value. Complete combustion of methane results in the formation of carbon dioxide and water with a release of energy. Incomplete combustion of methane results in the production of carbon monoxide. The presence of methane at elevated concentrations in the emission is an indicator of poor combustion.

3.6 Factors influencing landfill gas combustion and flare emissions

3.6.1 Design temperature and retention time

The three most important factors affecting combustion and emission control are time, temperature and turbulence (see Figure 3.4). These related performance factors together contribute to the maintenance of acceptable performance and help prevent deterioration in emissions quality.

To maintain performance, the three 'T's relationship for a non-specific burner must be as follows:

- at constant temperature – as the time decreases, the turbulence must increase;
- at constant time – as the temperature decreases, the turbulence must increase;
- at constant turbulence – as the temperature decreases, the time must increase.

In a typical landfill gas flare, the combustion air supply should be controlled so as to achieve a minimum of 1,000°C and 0.3 seconds retention time at this temperature regardless of the landfill gas composition and operational throughput. This is an indicative performance standard to demonstrate that the emission standard is being achieved. Alternative performance standards may be acceptable if compliance with the emission standard can be demonstrated, i.e. by a lower temperature and increased residence time or more efficient mixing.

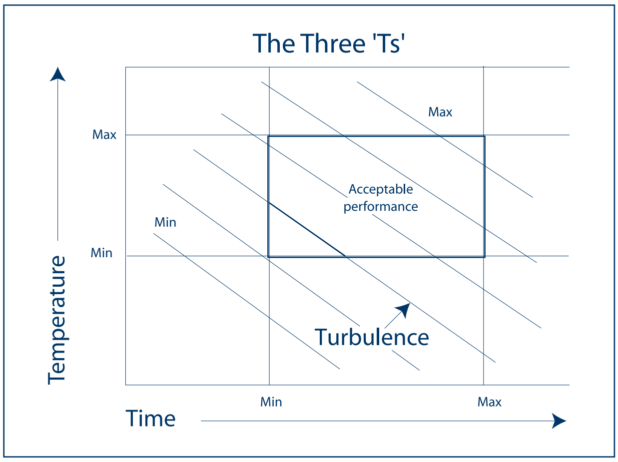


Figure 3.4 The three 'Ts': time, temperature and turbulence

The operating temperature of the flare must be monitored on a continuous basis i.e. automated instrumentation providing frequent, though not uninterrupted, data.

3.6.2 Landfill gas volume and fuel pressure

The operation of a flare depends on the volume and pressure of fuel gas available at the burner. If the pressure at the burner falls, then the combustion characteristics at the burner are likely to be altered. This will result in a reduction in combustion efficiency and an increase in the emission of products of incomplete combustion.

If the volume of landfill gas is below the minimum design capacity of the flare (i.e. minimum turndown ratio), then the flame temperature may be insufficient to achieve complete combustion. Conversely, if the volume of landfill gas is above the maximum design capacity of the flare (i.e. maximum turndown ratio), then combustion may be incomplete at the monitoring point within the flare.

The flow rate and composition of the gas entering the flare must be monitored at the flare on a continuous basis i.e. automated inline oxygen and methane analysers providing frequent, though not uninterrupted, data.

3.6.3 *Influence of burner and burner design*

Both the burner type and its arrangement will affect the combustion and hence the emissions from a flare. Properly designed (and operated) burners will give acceptable combustion efficiencies within their rated capacities. However, a premixed burner is likely to have a higher NO_x emission than a diffusion burner of a similar capacity.

The fuel gas composition will affect combustion efficiency at the burner. To allow combustion to take place, the burner has to allow the mixing of oxygen in the correct proportion relative to the combustible materials present in the fuel. The burner design must be able to cope with changes in landfill gas composition or incomplete combustion may result. This gives rise to reduced temperature and destruction efficiencies, and increased quantities of emissions such as CO, hydrocarbons and trace organic compounds.

3.6.4 *Influence of combustion chamber design*

The combustion chamber design affects the amount of turbulence and hence the mixing of the flame and air supply. This will affect the combustion efficiency of the flare and hence the emissions.

3.6.5 *Influence of weather*

Local atmospheric conditions can affect the combustion of some designs of flare. Air for combustion is provided by the natural draught caused by the difference in pressure between the air vents and the top of the flare. In addition, the direction and force of the wind can change the position of the flame within the shroud. Combustion may also be adversely affected by extreme weather conditions such as high winds.

3.7 Emission abatement technologies for enclosed flares

3.7.1 *Post-combustion measures*

The nature and design of flares provides limited opportunities for the use of post-combustion abatement technologies.

3.7.2 *Landfill gas clean-up*

The regulator has produced technical guidance on gas treatment technologies for landfill gas engines (Environment Agency, 2004b). Although the technologies discussed relate specifically to spark ignition engines, a number are also relevant to landfill gas flares.

3.7.3 *Emissions recirculation*

Emissions can be recirculated to reduce NO_x emissions and provide additional opportunity to achieve complete combustion of VOCs. This technology is well established on other combustion processes for reducing NO_x emissions.

3.7.4 *Combustion control*

Combustion control systems provide a means of managing the mixing of air and fuel gas supply to achieve complete combustion.

4

Review of emission standards and legislation

4.1 International emission standards

European standards for emissions from landfill gas flares are summarised in Table 4.1. In addition to these standards, the Dutch regulators and United States Environmental Protection Agency (USEPA) specify minimum residence times and furnace temperatures for the flares. The USEPA also defines destruction and removal efficiencies for organic compounds.

In Germany, a ‘type’ approval system for landfill gas flare designs is operated whereby the regulatory authority determines whether a design is suitable for use with landfill gas.

4.2 UK legislation on landfill gas emissions

The principal legislation covering the operation of landfills within Europe is the Landfill Directive (Council of the European Union, 1999), which provides for measures and procedures to prevent or reduce as far as possible negative environmental effects from the landfilling of waste.

Landfills are currently regulated in the UK through either waste management licensing under the Environmental Protection Act 1990 or the Pollution Prevention and Control (PPC) Regulations 2000. The technical requirements of the Landfill Directive have

Table 4.1 Emission standards for landfill gas flare emissions in European countries

Determinand	**Emission standards (mg/m^3)** [a]					
Country	**Germany 1996 (proposed)**	**Germany 2001**	**Switzerland**	**Belgium**	**England, Wales and Scotland (existing)**	**England and Wales (new plant)**
Particulate matter	10	–	10	5	–	–
Sulphur dioxide	–	–	50	35	–	–
Oxides of nitrogen	200	200	80	150	150	150
Carbon monoxide	50	100	50	100	100	50
Hydrogen chloride	10	–	20	–	–	–
Hydrogen fluoride	1	–	2	–	–	–
Hydrogen sulphide	–	–	–	–	–	–
Ammonia	–	–	5	–	–	–
Organo sulphur compounds	–	–	–	–	–	–
Cadmium	0.05	–	0.1	–	–	–
Mercury	0.05	–	–	–	–	–
Total metals	0.5	–	1	–	–	–
Total VOCs (as C)	10	–	20	–	10	10
NMVOCs	–	–	–	–	5	5
PCDDs/PCDFs (I-TEQ ng/m^3) [b]	0.18	–	–	–	–	–

[a] mg. m^{-3} at 3 per cent oxygen, dry and 0ºC, 101.3 kPa

[b] International Toxicity Equivalent – a normalised expression of concentration for PCDDs and PCDFs

been implemented in England and Wales via the Landfill (England and Wales) Regulations 2002 and in Scotland by the Landfill (Scotland) Regulations 2003. These supplement and amend the PPC Regulations. In this way, landfills and their operation will eventually be regulated under a single regime that complies with both the Landfill Directive and the Integrated Pollution Prevention and Control (IPPC) Directive.

4.3 Air quality standards

Landfill gas flares can contribute to local air quality and landfill operators should consider the impact of flare and other emissions on local air quality. Dispersion models can be used to derive ground level concentrations from emission, process, meteorological and other data (see Appendix B).

Air quality standards for the UK are published in the Air Quality Strategy for England, Wales, Scotland and Northern Ireland (Defra, 2000). A summary of these standards, which are based largely based on EC directives on air quality, is given in Table 4.2. Further guidance on these standards and their application to landfill sites is given in *Guidance on the management of landfill gas* (Environment Agency, 2004a).

In the absence of air quality standards (e.g. hydrogen chloride and hydrogen fluoride do not have air quality standards), the modelled concentrations may be assessed against environmental benchmarks such as Environmental Assessment Levels (EALs). These are published by the Environment Agency and are typically based on occupational exposure standards (Environment Agency, 2002e).

Table 4.2 UK ambient air quality guidelines and standards

Pollutant	Air quality standard and guideline	Criteria based on	Value	
			ppb	mg/m^3
Nitrogen dioxide	Objective for 31 December 2005	1-hour mean Not to be exceeded more than 18 times per calendar year.	105	200
	Objective for 31 December 2005	Annual mean	21	40
	Objective for 31 December 2000	Annual mean NO_x vegetation guideline	16	30
Sulphur dioxide	Objective for 31 December 2005	15-minute mean Not to be exceeded more than 35 times per calendar year.	100	266
	Objective for 31 December 2004	1 hour mean Not to be exceeded more than 24 times per calendar year.	132	350
	Objective for 31 December 2004	24 hours (daily mean) Not to be exceeded more than 3 times per calendar year.	47	125
	Objective for 31 December 2000	Calendar year annual mean vegetation guideline	8	20
	Objective for 31 December 2000	Winter mean vegetation guideline	8	20
Carbon monoxide	Objective for 31 December 2003	Running 8-hour mean	10	11.6
Benzene	Objective for 31 December 2003	Running annual mean	5	16.25
	Target for 31 December 2005	Running annual mean	1	3.25
PM_{10}	Objective for 31 December 2004	24 hours (daily mean) (Gravimetric data) Not to be exceeded more than 35 times per calendar year.	–	50
	Objective for 31 December 2004	Calendar year annual mean (Gravimetric data)	–	40

Source: Defra (2000)

5

Safety of monitoring flares

5.1 Health and safety guidance and regulations

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).

The Health and Safety at Work Regulations 1974, etc. place 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 MCERTS (Environment Agency, 2002f) standards also requires a risk assessment to be produced. Technical Guidance Note M1 (Environment Agency, 2002a) contains detailed guidance on the assessment of safety requirements at a test site.

The fundamental stages of the risk assessment process are summarised in Figure 5.1.

It is important 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 (STA) also provides guidelines (e.g. STA, 2001a) that describe the general hazards and potential risks associated with emissions testing; these are updated annually. It has also produced *Example risk assessments for stack sampling operations* (STA, 2000).

Although not aimed specifically at landfill gas, a number of other regulations are relevant to the safe control and handling of landfill gas. These include:

- Health and Safety at Work Act 1974
- Control of Substances Hazardous to Health Regulations 2002 (COSHH)
- Management of Health and Safety at Work Regulations 1999
- Personal Protective Equipment at Work Regulations 1992
- Notification of Installations Handling Hazardous Substances Regulations 1982
- Provision and Use of Work Equipment Regulations 1998
- Construction (Health, Safety and Welfare) Regulations 1996
- Construction (Design and Management) Regulations 1994.

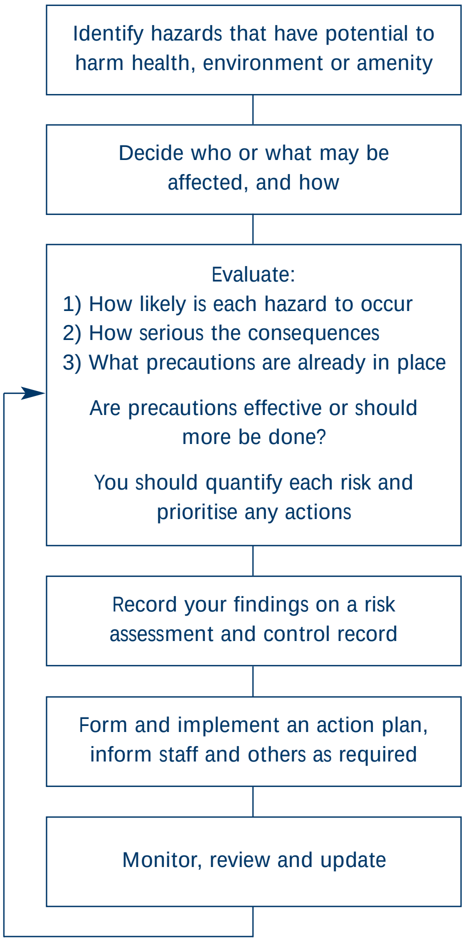


Figure 5.1 Fundamental stages of the health and safety risk assessment process

A Code of Practice approved by the Health and Safety Commission gives practical guidance with respect to the Construction Regulations and how to comply with the law (HSE, 2001). Other HSE guidance notes of relevance to landfill gas are:

- Guidance Note EH 40: occupational exposure limits (HSE, 2002), which provides toxicological information on the gases to which monitoring personnel may be exposed;
- Guidance Note CS1: industrial use of flammable gas detectors (HSE, 1987), which provides information on the safe operation of equipment that may be used in stack monitoring;
- Construction Information Sheet No. 49 General access scaffolds and ladders (HSE, 2003).

For electrical safety, there are a number of regulations and sources of information:

- BS 7671 Requirements for electrical installations (BSI, 2001)
- Institution of Electrical Engineers' Code of practice for in-service inspection and testing of electrical equipment (IEE, 2001);
- HSE Guidance Note No. 25 Memorandum of guidance on the Electricity at Work Regulations 1989 (HSE, 1998);
- HSE Guidance Note No. 85 Electricity at work, safe working practices (HSE, 2003);
- HSE Guidance Note No. 107 Maintaining portable and transportable electrical equipment (HSE, 1994);
- HSE Guidance Note No. 141 Electrical safety on construction sites (HSE, 1995).

5.2 Typical safety issues relating to emissions testing

Figure 5.2 sets out the typical hazards that need to be considered during any emissions testing programme. These hazards are indicative of influencing factors that may be included in a normal risk assessment, but the list shown is not exhaustive. For each site test, an individual risk assessment should be completed, as there will be site-specific issues to be considered.

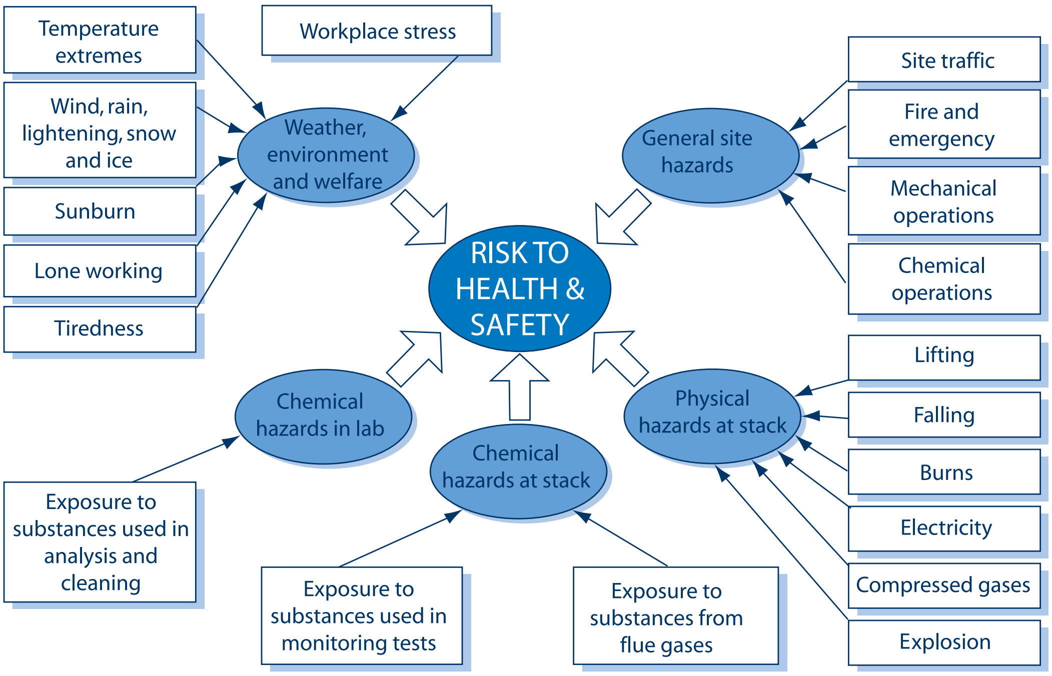


Figure 5.2 Prominent hazards associated with stack monitoring

Source: Environment Agency (2002a)

Table 5.1 Likely hazards and potential control measures when monitoring landfill gas flares

Hazard	Example Control Measures
Fugitive emissions of flammable gases from the landfill	● Carefully locate sampling equipment remotely from identified sources of fugitive emissions (e.g. passive vents). ● Use intrinsically safe equipment where practicable. ● Use personal and or ambient monitors equipped with alarms to monitor background levels of methane.
Fugitive emissions of potentially toxic gases from the landfill	● Use of personal and or ambient monitors equipped with alarms to monitor background levels of specific components. ● Avoid areas where odour is severe or substantial gas emission is apparent.
Heat – both radiative and from direct contact with hot ducting, equipment or 'lick back' of flames	● Use appropriate hot work gloves when handling sample point access ports/flanges and hot sampling equipment. ● Use full-face visors when removing access covers.
Working at heights	● Use safety harnesses. ● Use sampling platforms that are approved before use and which are provided with adequate hand rails and kick boards.

5.3 Landfill gas emissions testing

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

Table 5.1 gives examples of some of the most likely hazards to be encountered together with potential control measures.

5.4 Personal protective equipment

In any sampling strategy, the emphasis should be on avoiding exposure to hazards and the use of personal protective equipment (PPE) should be a last resort.

For instance, monitoring should not be undertaken if the flame is not fully enclosed. It is recommended that the working area should be at least 3 metres below the stack exit to reduce the risk of downwash.

Nonetheless, it is recommended that the sampling team wear flameproof overalls, a flameproof balaclava and a face shield along with normal PPE.

5.5 Safe working platform and means of access to the sampling position

Facilities for the sampling of emissions to air should, as a minimum, meet the standards stipulated in Technical Guidance Note M1 (Environment Agency, 2002a). Additional guidance is given in the STA's booklet Hazards, risks and risk control in stack test operations' (STA, 2001a).

Risk assessment for the installation works should include, the risk of working at height, the risk of gas leaks, risks of gas accumulation in poorly ventilated spaces during the work, and the potential exposure to any other flare emissions in the area of the work. **Access to the flare tip and working platforms when the flare is operational should not be permitted**. It is the presumption that operatives conducting monitoring work on operational flares will be at ground level, and in a safe place away from the flare stack. The following guidance on access relates to positioning and installation of monitoring equipment only. The illustrations show how appropriate sampling arrays may be installed. **The flare must be isolated before the installation work is started.**

All platforms, whether temporary or permanent, must meet the minimum weight criteria required for sampling. This is defined in BS EN 13284 as a 400 kg point load (BSI, 2002a). Sampling from ladders and small mobile access platforms such as cherry pickers is not acceptable.

The platform and access must:

- meet all current legislative requirements regarding dimensions and construction
- be maintained to a safe standard
- undergo regular inspection by a competent person (e.g. the scaffolding company). Inspections should include:
  - daily pre-use checks of guard rails, walking surfaces and toe boards;
  - inspections after severe weather;
  - any incident reports.

Records of inspections should be available for review before any work commences. All ladders must be secured at the top with a purpose-built gap in the hand rails to allow access to the platform. Ideally, this should be blocked when not in use.

One approach that is utilised on scaffolds to provide documentary evidence that the scaffolding has been inspected and approved is the Scaff-tag system. This must be properly completed and dated.

If a permanent platform has been installed, this must also be regularly inspected and records of these inspections kept. The platform must be provided with handrails and kick-boards, which meet the requirements of the Construction (Health, Safety and Welfare) Regulations 1996 or subsequent regulations.

The responsible person on site should not accept inadequate scaffolds or platforms. The platform should not be used if it is not constructed as described (e.g. in a proposal drawing).

The size of the working platform should be sufficient to enable a test team to operate safely using awkward and heavy sampling equipment (see Figure 5.3). A general scaffolding layout is shown in Figure 5.4; standard platform layouts are provided in Technical Guidance Note M1 (Environment Agency, 2002a). Access needs to be around the entire circumference of the flare.

Emissions from some flares in use can currently be accessed only via the flare exit. An extended two-storey sampling platform is therefore required to manoeuvre the sampling equipment over the top of the flare. In addition, there needs to be free access around the entire flare to allow work on the windward side at all times.

The future provision of access ports in the shroud of the flare should reduce the need for extended sampling platforms. It is recommended that platforms are provided which extend around the entire circumference of the flare and that the sampling platform is about 3 metres below the top of the flare. In addition, the future use of permanent in situ probes combined with heated lines may reduce the reliance on sampling platforms.

Figure 5.5 shows an actual sampling platform used to monitor the emissions from a landfill gas flare.

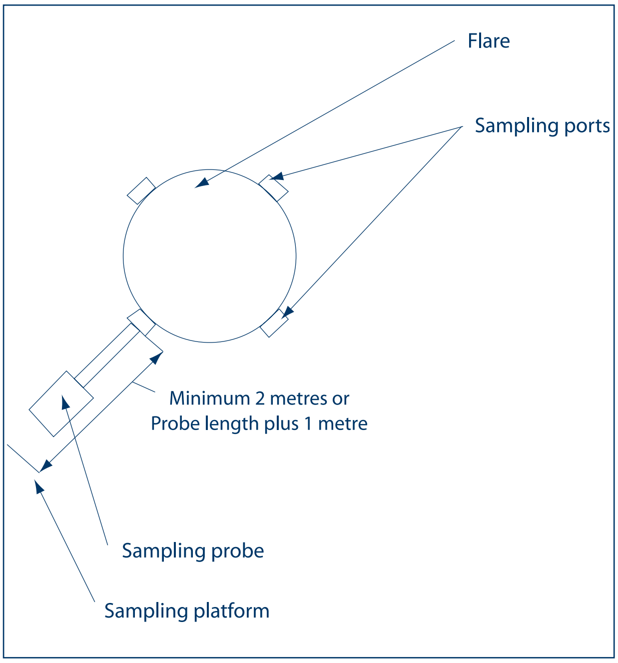
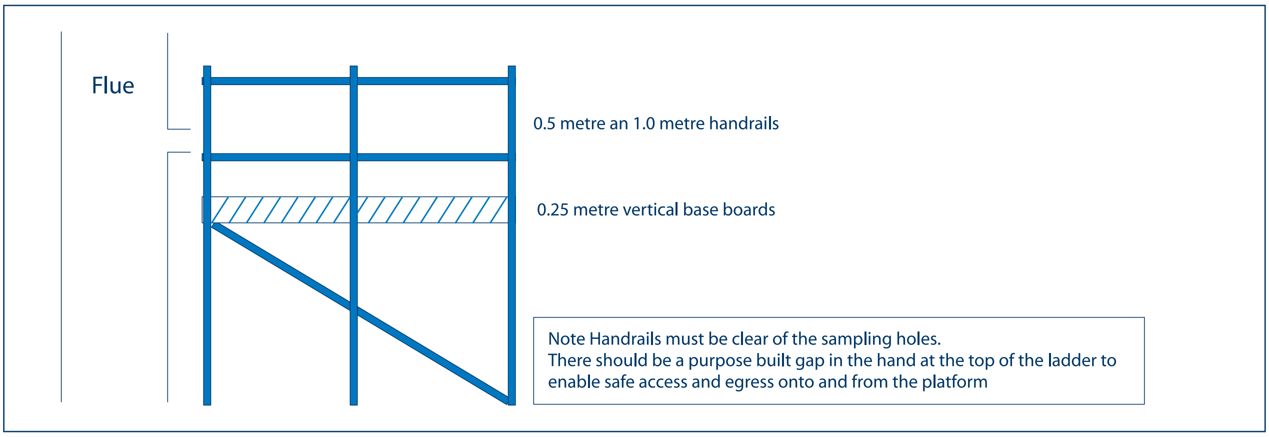


Figure 5.3 Plan view of platform working area and orientation recommendations for enclosed flares



Note Handrails must be clear of the sampling holes.
There should be a purpose built gap in the hand at the top of the ladder to enable safe access and egress onto and from the platform

Figure 5.4 General scaffolding layout

Figure 5.5 Two-stage sampling platform for monitoring emissions from a landfill gas flare

Figure 5.6 Top of flare shroud with sampling port with access platform in place

Technical Guidance Note M1 (Environment Agency, 2002a) specifies the use of a sampling access port of 125 mm diameter (see Figure 5.7). This diameter of sampling port is not necessarily required for gaseous monitoring – although it is for particulate monitoring. However, the high temperatures associated with a flare may result in the seizure of sampling socket caps of a smaller diameter. In this case, flanged ports may be used provided their internal diameter is not less than 125 mm (to enable use of suitable monitoring systems).

If sampling ports are not available or it is not practicable to fit the ports to an exhaust, end-of-pipe sampling may be undertaken. However, this should only be an interim measure and more suitable arrangements should be constructed (e.g. sampling sockets, in situ probes).

5.6 Power supplies

Flares tend to be remote from other operations and a power supply may not always be available. Portable power supplies such as generators provide a convenient means of providing power in these circumstances. Ideally, up to 10 kVA at 110V is required – preferably split between several supplies to minimise power fluctuations arising from use of sampling pumps, heated lines, coolers and other devices.

5.7 Avoiding emissions testing on sub-standard flares

Emissions testing must not be undertaken on a flare that is clearly not operating within its design parameters and operational standards or has not been properly maintained. A visual inspection of the installation, its controls and associated pipework should be undertaken before commitment to emissions testing. For instance a flare with mechanical faults, inoperable instruments or a flame that is not enclosed at all times must be judged non-compliant without the need for emissions testing.

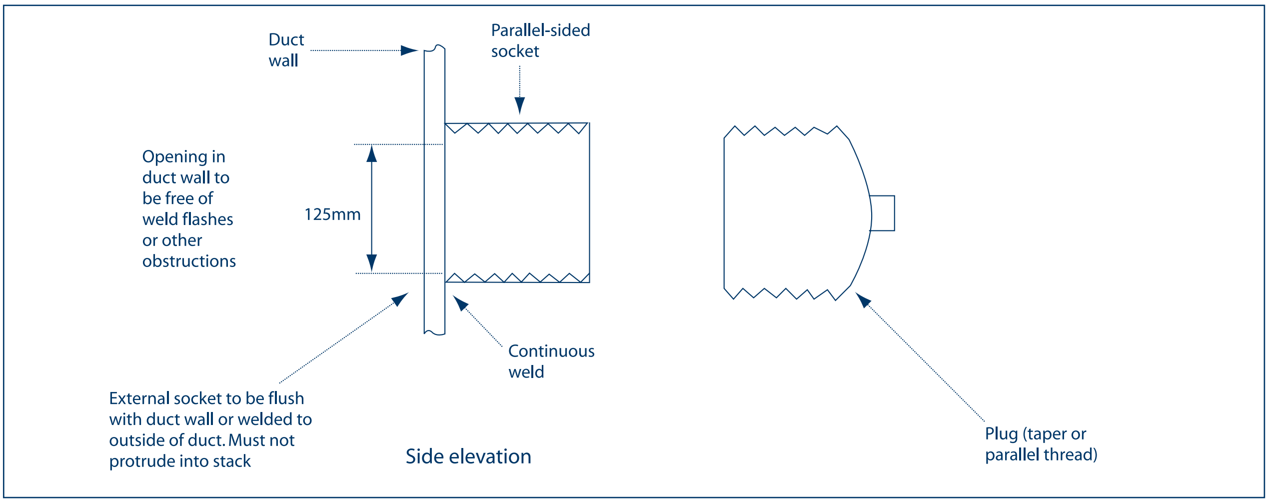


Figure 5.7 Standard 125 mm sampling socket

Emission monitoring protocol

6.1 General monitoring considerations

Combustion of landfill gas in the flare can be variable resulting in fluctuations of the emissions at points within the flare. The variability of combustion will often result in a changing emission profile. Typically, it is not possible to select one point as being representative of the total emission. Multiple sample points are therefore required.

6.2 Sample plane

The selection of the sampling plane is crucial to enable representative sampling of the flare emission.

6.2.1 *Primary parameters (CO, NO_x, VOCs, NMVOCs)*

A preliminary survey of the sampling plane should be undertaken for primary parameters (i.e. CO, NO_x). If the variation across the plane is less than ±15 per cent, then this plane is acceptable. If the variation is greater than this, an alternative measurement position is required. Alternatively, modifications to the operation of the flare should be investigated in order to achieve the required distribution. These could include control of the fuel flow, increased turbulence and control of combustion air.

It is recommended that, as a minimum, the sample plane be at least 1 metre from the flare exit and meet the above acceptance criteria. Additionally, the flare should be operated in such a way as to ensure that there is no flame evident at the sample port position within the shroud. Sampling should be undertaken at a position beyond the flame front to avoid the uncertainties caused by flame chemistry and thus facilitate the most representative sample of the emission to be taken.

Although the temperature may still be over 500°C at the sample position, the emission measurements will be representative of those leaving the flare stack. Chemical reactions involving the primary parameters will be near completion and representative of those emitted to the environment. At these temperatures, the ratio of NO to NO_2 may not have stabilised but, by measuring total oxides of nitrogen, any change in this ratio will not affect the measurement.

6.2.2 *Secondary parameters (particulates, dioxins)*

The variability of combustion will often result in a changing emission profile for particulates and dioxins. BS EN 13284 for particulates (BSI, 2002a) ideally requires five hydraulic diameters between a bend and the sample plane and a further five hydraulic diameters from the top of the flare. Hydraulic diameter can be calculated using the following formula:

$$\textit{Hydraulic diameter} = \frac{4 * A_{sp}}{P_{sp}}$$

where:

A_{sp} = area of the sampling plane

P_{sp} = perimeter of the sampling plane.

This ideal is typically currently unattainable within a flare. However, the standard also gives acceptance criteria for the sampling standard. These are:

- angle of flow less than 15° with regard to duct axis
- no local negative flow
- the minimum duct velocity if measured using Pitot differential pressure must be greater than an equivalent pressure of 5 Pa
- ratio of the highest to lowest local velocities less than 3:1.

This is the recommended approach; this is, if the sample plane is shown to meet these criteria, then it is deemed acceptable for secondary parameters.

6.3 Sample points

The variability of the combustion in flares can result in wide variations in the emission concentrations at any one point within the flare. To achieve the most representative sample, a number of sample points should be selected.

The sample points should be arranged across two perpendicular planes as indicated in Figure 6.1.

The minimum number of sampling points should be determined as in ISO 9096 (ISO, 2003); Table 6.1 outlines its requirements.

6.4 Sample period

It is recommended that a sample point should be sampled for at least three times the analytical system response time.

6.5 Access into the flare

The sampling equipment requires defined sampling ports arranged in a configuration to enable the required sample points to be reached. End-of-pipe sampling can be used with a multiple probe system that extends down into the flare by at least 1 metre to avoid effects at the top of the flare (see Figure 6.2).

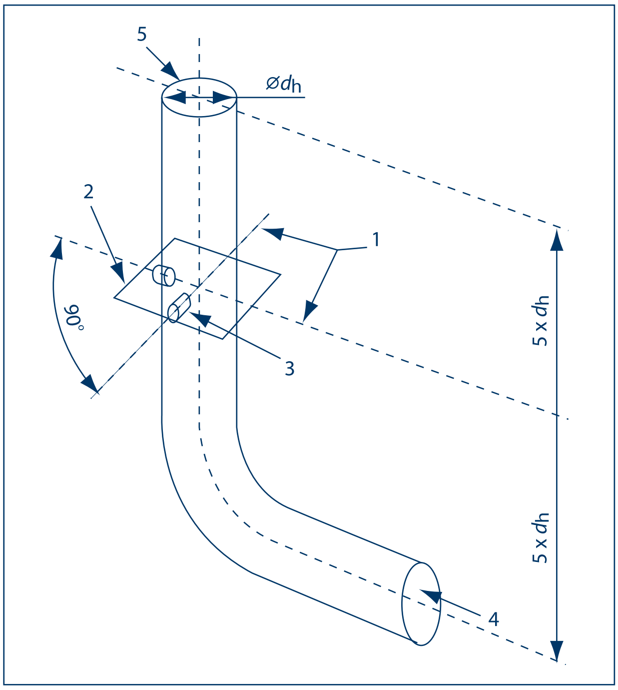


Figure 6.1 Diagram showing sampling points and planes [dh is the hydraulic diameter of the emission source]

It is the presumption that operatives conducting monitoring work on operational flares will be at ground level, and in a safe place away from the flare stack. Thus the operator should make arrangements for suitable remote monitoring equipment to be installed, such that either this is automatic and does not require manual interventions during a sampling run, or is remote from the area of risk. Given the level of risk and severity of the potential consequences from downwash, falls, heat exposure, etc only exceptionally should alternative measures be considered, and in all cases those measures taken should provide an equivalent degree of safety to remote monitoring, which is the presumed standard for safety purposes.

The arrangement of any end-of-pipe sampling system should be such that the sample is extracted and transported to a safe place well below the shroud exit, and normally at ground level. This means that the sampling team is not at the top of the shroud and thus reduces the possibility of exposure to emissions via down-wash. When installing any such system, the flare must be shut down and isolated so that there is no possibility of

Table 6.1 Minimum number of sampling points for circular ducts

Range of sampling plane areas (m^2)	Range of ducts diameters (approx.) (m)	Minimum number of sampling lines (diameters)	Minimum number of sampling points per line		Minimum number of sampling points per plane	
			Include centre point	Exclude centre point	Include centre point	Exclude centre point
<0.1	<0.35	–	1[a]	0	1[a]	
0.1 to 0.4	0.35 to 0.7	2	3	2	5	4
0.4 to 0.8	0.7 to 1.0	2	5	4	9	8
0.8 to 3.14	> 1.0 to 2.0	2	7	6	13	12
>3.14	>2.0	2	9	8	17	15

[a] Using only one sampling point may give rise to errors greater than those specified in ISO 9096: 2003.

Figure 6.2 Multiple-probe system for end-of-pipe sampling

ignition while sampling personnel are above the working platform.

Where there are sampling sockets in the side of the flare, a sampling probe can be fitted through these ports. However, for safety reasons it is not normally feasible to move the probe between several sampling positions while the flare is in operation. Multiple sampling points on the same probe allow the unit to be pre-installed and take an average sample from across the chosen sampling plane. The spacing and sizing of each sample orifice need to be carefully selected so that the combined sample is representative. Averaging Pitot tubes are commercially available to measure the average flow. The evaluation of an appropriate multi-hole sample probe to extract an averaged gas sample is described in Technical Monograph EMTIC GD-031 (USEPA, 1995). The length of a multi-point averaging probe and the spacing of the holes must be selected to fit the particular diameter of the flare.

The use of in situ probe systems combined with heated transport lines permanently installed into the flare is an acceptable alternative, as these could be arranged to allow samples of the primary parameters to be taken at ground level. This would remove a number of the health and safety issues associated with normal emission measurements.

The health and safety of anyone working on the sampling platform or in close proximity to the flare is of the utmost importance. Every action should be taken to ensure their safety.

Monitoring of a flare should not be undertaken if there is visible flame above the shroud. This situation should be assessed throughout the measurement programme as conditions can change, resulting in a visible flame. If this is the case, the sampling team should vacate positions close to the flare until the situation is resolved.

6.6 Flare gas temperature

Standard emission sampling equipment is constructed of materials designed to cope with temperatures up to about 400°C. The use of high temperature steels should be avoided above 600°C, as there is a possibility that the carbon present in the steel will oxidise resulting in the production of CO. However, much higher temperatures are encountered during flare monitoring. Hence, it is necessary to employ other materials with a specification up to 1,200°C (e.g. Incolloy).

6.7 Preliminary site visit

Before undertaking any emission measurements, the hazards and risks associated with this activity (see Section 5) should be assessed as part of a preliminary site survey. The purpose of the preliminary survey is to identify safety issues and practical considerations for sampling.

Before planning any emissions test a visual inspection of the installation and its controls must be undertaken. If this illustrates that the flare does not meet the operational standards or has not been maintained it may not be monitored in a representative or safe manner. It is unlikely to meet the emission standard and any planned emissions test should be cancelled until these operational faults have been rectified. Until the emissions can be monitored in a representative and safe manner the flare should be regarded as non-compliant.

The preliminary visit should be formally recorded and should include, but not be restricted to:

- site description, location, etc.;
- age of site, composition of waste;
- details of flare type, manufacturer, age;
- details of sample plane location;
- details of flare sampling ports;
- details of access and egress for the site and sampling platform;
- details of previous monitoring (if available);
- identification of site hazards;
- details of flare operation (e.g. continuous or whether operation has to be scheduled);
- details of applicable site rules.

An example of a suitable pro-forma for recording the preliminary site visit is provided in Appendix C.

Portable test equipment (e.g. electrochemical cell analysers) can be used during such a reconnaissance visit to provide indicative values for NO_x, CO and oxygen. These indicative values will assist:

- the selection of sampling and analytical equipment
- the range of calibration gases required for the main sampling tests.

Typically, emission analysers are linearised across 10–90 per cent of a measuring range and are calibrated above 60 per cent of the measuring range. To ensure quality measurements, it is therefore recommended that an appropriate measuring range for the expected concentration values is provided.

6.8 List of required test parameters

Tables 6.2 and 6.3 set out the standard methods to be used when determining the emissions from enclosed landfill gas flares. These are also listed in Technical Guidance Note M2 (Environment Agency, 2002b) and Technical Guidance Note M4 (HMIP, 1995). A number of emissions monitoring standards exist internationally. The order of priority of the use of these standards is:

- International Standards Organisation (ISO)
- Comité Européen de Normalisation (CEN)
- British Standards Institution (BSI).

If a substance cannot be measured using one of the above methods, then other national standards should be used, e.g. United States Environmental Protection Agency (USEPA) and Verein Deutstcher Ingenieure (VDI).

6.9 Fugitive emissions

As well as emissions from the flare, a number of other emission sources that may be present adjacent to the landfill gas flare need to be considered. These sources will include:

- landfill gas engines (e.g. crankcase emissions) (Environment Agency, 2004c);
- pipelines and well heads on the gas field;
- leakages from fans and pipe work prior to the flare;
- diffuse surface emissions from the landfill site (Environment Agency, 2004d).

These emissions will principally consist of raw landfill gas and potentially have both health and environmental implications.

Table 6.2 Monitoring methods for primary monitoring determinands – landfill gas flares

Parameter	Method referenced in M2	Alternative
Nitrogen oxides x (as total of NO + NO_2)	ISO 10849 (ISO, 1996)	USEPA Method 7 Parts D and E USEPA online 1 and 2)
Carbon monoxide	ISO 12039 (ISO, 2001)	USEPA Method 10 (USEPA, online 3)
Total volatile organic compounds	<20 mgC/m^3: BS EN 12619 (BSI, 1999) >20 mgC/m^3: BS EN 13526 (BSI, 2002b)	USEPA Method 25A (USEPA, online 8)
Non-methane volatile organic compounds	BS EN 13649 (BSI, 2002c)	USEPA Method 18 (USEPA online 5)

Table 6.3 Potential additional monitoring determinands – landfill gas flares

Parameter	Method referenced in M2	Alternative
PCDDs and PCDFs	BS EN 1948 (BSI, 1997)	USEPA Method 23 (USEPA online 7)
Hydrogen chloride	BS EN 1911 (BSI, 1998)	USEPA Method 26A (USEPA, online 9) VDI 3480 Part 1 (VDI, 1984)
Halides	USEPA Method 26A (USEPA online 9)	–
Oxygen	ISO 12039 (ISO, 2001)	–
Particulates	BS EN 13284-1 (BSI, 2002a)	–
Sulphur dioxide	ISO 11632 (ISO,1998)	ISO 7934 (ISO, 1989)
Flow	BS EN 13284-1 (BSI, 2002a)	ISO 9096 (ISO, 2003) ISO 10780 (ISO, 1994) USEPA Method 19 (USEPA online 6)
Temperature	BS EN 13284-1 (BSI, 2002a)	ISO 9096 (ISO, 2003) ISO 10780 (ISO, 1994)

Emission specific protocols

This section provides supporting information on various monitoring methods applicable to landfill gas flares. Tables 6.2 and 6.3 in the previous section give the recommended methods to be used when determining the emissions from enclosed landfill gas flares.

7.1 Types of emission

7.1.1 Gaseous

Although an exhaust gas can normally be regarded as being a homogeneous mixture, the operating characteristics of a flare can give rise to significant stratification and variation in the composition of the emission. The flare must therefore be traversed during monitoring to ensure a representative measurement.

7.1.2 Particulate

Although the primary emissions from enclosed flares are in the gaseous phase, several secondary emissions can be associated with the particulate phase.

In contrast to gaseous emissions, particulate material is rarely a homogeneous suspension in the gas stream and additional procedures are required to collect a representative sample. Particles with widely differing characteristics behave differently unless the sampling conditions are carefully controlled. Particles are strongly affected by inertia; therefore, the choice of sampling location is important and multi-point sampling is required.

The wide range of particle sizes present in the emission means that it is necessary to sample isokinetically to ensure a representative sample of the particulate emission is obtained. Further information is given in *Guidance for monitoring landfill gas engines* (Environment Agency, 2004c).

7.2 Integrated and continuous measurement

An integrated measurement is characterised by the extraction of a sample of emission, which is collected in or on a sampling medium (e.g. a filter, sample bag, absorbent solution, sorbent tube) over a period (typically one hour). Analysis of the sampling medium is undertaken some time after sampling and often at a different location. BS EN 13284-1 (BSI, 2002a) for particulate measurement is an example of an integrated measurement technique in which particulate material is collected on a filter and the mass of material collected is determined gravimetrically.

Measurements using a continuous emission monitoring system (CEMS) allow real-time or near real-time analysis for an emission component. ISO 10849 (ISO, 1996) describes a method for continuous measurement of NO_x using an automated analysis system.

7.3 Continuous measurement methods

7.3.1 Extractive sampling system design

Many gaseous emissions can be monitored continuously within the flare. The detection system uses physical/chemical characteristics, which can be related to the gas concentration (e.g. via spectrophotometry of the absorption of electromagnetic radiation). Recognised detection principles are described in Appendix F.

When sampling any gas, care is necessary to ensure that the integrity of the sample is preserved between the sampling point and the collector or analyser. For extractive gas sampling, the sample is withdrawn from the duct through a probe and any particulate matter should be removed using a suitable filter.

For most gases, it is important to transport the gases through a heated line. This is necessary to prevent condensation of water and subsequent loss of water-soluble gases and VOCs.

An alternative to extraction using heated lines is a dilution probe system. This technique involves the addition of an inert, stable and dry gas (such as nitrogen or synthetic air) at the probe to reduce the dew point of the sample gases and thus eliminate the problem of condensation.

Sampling lines and other surfaces exposed to the sampled gases should be constructed of inert materials to avoid losses of reactive components. For example, sulphur dioxide, hydrogen chloride and oxides of nitrogen undergo reactions with stainless steel. Hydrogen fluoride reacts with most sampling materials and only PTFE (which must be used below its temperature of decomposition) has been shown to be an adequate material for most sampling line purposes.

A typical instrumental extractive system (see Figure 7.1) consists of the following components:

- **Probe/filter.** The analysers will only give reliable results if the sample withdrawn from the system is representative of the gas stream.
- **Heated transport system.** The sample integrity must be maintained while it is being carried from the stack/duct and pumped to the conditioning system and analyser.
- **Conditioning system.** Any conditioning (drying, cooling and filtration) undertaken to make the gas compatible with the analyser detection principle should not remove the component being monitored.
- **Analyser.** This is necessary to undertake the analysis of the sample and should be specific for the determinand of interest.
- **Data recording system.** This provides a record of analysis results at an appropriate recording interval.
- **Calibration.** Certified reference gas mixtures to set the response of the analysis system and provide traceability to recognised standards.

7.3.2 Nitrogen oxides

Several techniques are available for the continuous measurement of NO_x and are compared in Table 7.1. Chemiluminescence and non-dispersive infra-red (NDIR) spectrometry are the most common techniques chosen for emission measurements using ISO 10849 (ISO, 1996). Use of electrochemical cell analysers is common, but is not usually associated with ISO 10849.

Chemiluminescence is the recommended method for measuring oxides of nitrogen in flare emissions.

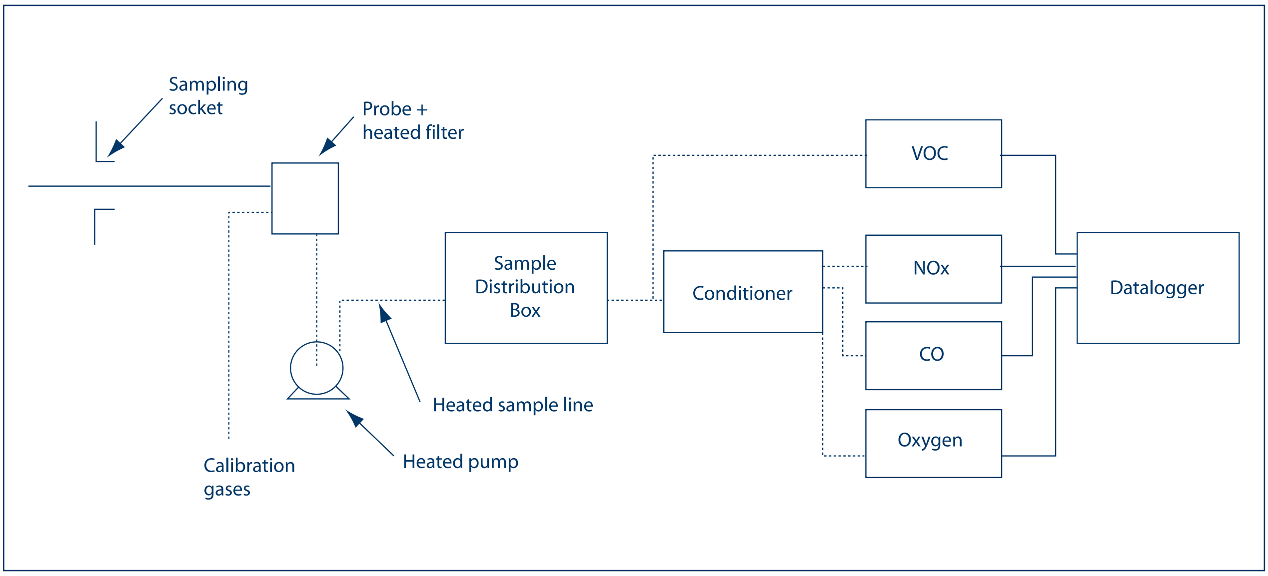


Figure 7.1 Typical instrumental extractive system

7.3.3 *Volatile organic compounds*

The techniques available for the measurement of hydrocarbons are listed in Table 7.2. BS EN standards for total gaseous organic compounds require the use of flame ionisation detectors.

Extractive sampling combined with an FID detector is the recommended method for measuring Total VOCs in flare emissions. For NMVOCs (ie total VOCs excluding methane), extractive sampling onto a sorbent followed by desorption using carbon disulphide and separation of components by gas chromatography is recommended for flare emissions.

FID monitors are very sensitive to pressure changes, condensation forming on the internal lines and particulate in the sample gas. Efficient filtration and the minimisation of the possibility of condensation are therefore essential. Some FID monitors have

Table 7.1 On- line analytical techniques for oxides of nitrogen

Detection principle	Interferences	Comments
Extractive NDIR (for NO, NO_x)	Water vapour and particulates	Established technique. Interferences can be reduced by conditioning and selection of appropriate wavelength.
In situ (cross stack) NDIR	Water vapour and particulates	Interferences can be reduced by conditioning and selection of appropriate wavelength. Primarily used by installed process CEMS. Not generally appropriate for short-term monitoring.
Electrochemical	H_2S, ammonia (NH_3) and SO_3	Use of cross-sensitivity between sensors in a multi-sensor unit and microprocessor interpretation has improved accuracy and sensitivity. The system requires gas conditioning and temperature reduction. Commonly used in portable analysis systems. Can measure both NO and NO_2 directly.
Chemiluminescence for NO and NO_x	CO_2, water vapour and NH_3	Established technique. Analysers have the capability to measure both NO and NO_x and can operate at temperatures well above the dew point of most gases.

Table 7.2 On-line analysis of hydrocarbons

Detection principle	Interferences	Comments
Extractive NDIR (CH_4 only)	Other IR absorbing compounds, water vapour and particulate matter	Generally suitable only for high concentrations
Extractive flame ionisation detector (FID)	Other hydrocarbons; oxygenated hydrocarbons produce a lower response Reduced response is seen with nitrogen, chlorine and oxygen-containing hydrocarbons	These analysers operate at temperatures of 180–190ºC, so can handle source gases if required. Particulates have to be removed. Can be coupled with gas chromatography (GC) to provide some speciation of VOC.
In situ infra-red (IR) visible (fibre optics)	Absorption by other IR components Losses within the fibre optic transmission cable	A relatively new technique
Gas chromatography/FID	Components that damage the column during separation, e.g. acid gases	Use of GC enables the separation of the hydrocarbons present
Catalytic oxidation	CO	Pre-filter required to remove CO to avoid errors in the measurement

internally heated gas lines. Alternatively, the sample gas is diluted using a compressor which provides hydrocarbon-free, dry air, or a permeation tube dryer is used. Dilution reduces FID sensitivity.

To comply with BS EN emission monitoring standards, FIDs are calibrated using propane. The results are therefore expressed 'as propane'. In order to convert to a mass emission of total carbon, the displayed concentration is multiplied by a factor of three. If reference gases other than propane are used, then other factors are applied to provide total carbon emission. This method works well if the sample is made up of mainly alkanes and alkenes, but underestimates concentrations of oxygenated organic compounds.

7.3.4 Carbon monoxide

The techniques available for the continuous measurement of carbon monoxide are listed in Table 7.3. ISO 12039 (ISO, 2001) does not specify the analytical technique, although NDIR is the established technique. Electrochemical cell analysers are convenient and commonly used, but are not often deployed due to interferences.

7.3.5 Oxygen

The techniques available for the instrumental measurement of oxygen are listed in Table 7.4. Paramagnetism is often used for measurements to ISO 12039 (ISO, 2001), although electrochemical analysers for oxygen are commonly deployed.

7.3.6 Carbon dioxide

The most widely used instrumental techniques for CO_2 employ infra-red technology and are listed in Table 7.5. The main differences are the type of IR detection system applied.

Table 7.3 On-line analysis of carbon monoxide

Detection principle	Interferences	Comments
Extractive NDIR	Water vapour and particulate	Interferences are easily removed by conditioning as the solubility of the gas is very low.
In situ IR (fibre optics)	Other IR absorbing components, water vapour and particulate	Losses within fibre optic Only monitors to percentage range due to interferences and losses of IR in the fibre optic.
Extractive mass spectrometry (MS)	Nitrogen	CO is derived by calculation as CO has the same charge/mass ratio as N_2. Method only used for percentage levels.
Electrochemical	Unsaturated hydrocarbons, hydrogen and ammonia	Interferences are easily removed by conditioning as the gas solubility is very low.

NDIR is the recommended method for measuring carbon monoxide in flare emissions.

Table 7.4 On-line analysis of oxygen

Detection principle	Interferences	Comments
Electrochemical	SO_2, NOx and acid gases	Extractive
Electrocatalytic	Hydrocarbons and CO	
Paramagnetic	NO, NO_2, water vapour and particulate matter	Extractive Interference effects minimal with conditioning
Polarographic	Particulate matter and water vapour	Gases preferably need to be at ambient temperature Cells used after a period of operation.

Table 7.5 On-line analysis of carbon dioxide

Detection principle	Interferences	Comments
Infra-red (in situ or extractive)	Water vapour and particulates Other species with similar infrared absorbance characteristics	Water vapour and particulates should be removed. Corrosive gases etch the optics.

Table 7.6 Instrumental techniques for sulphur dioxide

Detection principle	Interferences	Comments
NDIR	Water vapour, CO_2, NO, NO_2, CO, SO_3 and particulates	Sample conditioning and use of filtering techniques allows rejection of most interferents.
Non-dispersive ultra-violet (NDUV)	CO_2, NO, NO_2, CO, SO_3, hydrocarbons and particulates	Sample conditioning allows removal of key . interferents
UV fluorescence	None expected for landfill gas	Sample conditioning and use of filtering techniques required before analysis.
Flame photometry	Water vapour and sulphur compounds	Not specific to SO_2. Will determine total sulphur in emission.
Electrochemical cell	Water vapour, H_2S and NH_3.	Sample conditioning essential to remove water and prevent formation of salts.

7.3.7 *Sulphur dioxide*

The instrumental techniques for SO_2 are listed in Table 7.6. However, at the low emission concentrations generally expected at enclosed landfill gas flares, an integrated sampling technique such as ISO 11632 (ISO, 1998) is the most appropriate measurement approach as it is likely to provide a better limit of detection.

7.3.8 *Hydrogen chloride*

Instrumental techniques for HCl are based on NDIR or a continuous chemical absorption system with detection by ion selective electrode. While these systems provide much better reproducibility than the integrated BS EN 1911 method (BSI, 1998), they are generally intended for permanent operation on process plant rather than short-term emission monitoring.

7.4 Integrated sampling methods

7.4.1 *Carbon monoxide and total VOCs*

Although no integrated method has been specified for CO and total organic compounds, an integrated sampling approach is possible using sample bags. However, this approach is outside the scope of the reference test methods.

7.4.2 *Speciated VOCs*

Speciated VOCs can be determined using BS EN 13649 (BSI, 2002c) by sampling into sample bags or onto sorbent tubes for subsequent recovery and analysis – usually by gas chromatography. The media used include Tenax, a type of activated carbon.

The samples are taken using a sample line attached to two tubes in series by means of a low flow pump. An iced moisture trap is positioned prior to the tubes to reduce the moisture content and to remove condensable organic compounds. After sampling, the tubes are thermally desorbed and analysed by scanning GC-MS to identify and quantify target compounds individually. Further details on method BS EN 13469 are given in Technical Guidance Note M2 (Environment Agency, 2002b).

7.4.3 *Nitrogen oxides*

USEPA Method 7D (USEPA, online 1) offers a methodology based on absorption of NO_x into alkaline potassium permanganate coupled with ion chromatography analysis.

7.4.4 *Sulphur dioxide*

The integrated method set out in ISO 11632 (ISO, 1998) is an acceptable and widely used method for determining SO_2 emissions. A measured volume of flue gas is drawn through an impinger train containing an aqueous solution of hydrogen peroxide. The impinger contents are recovered and analysed for sulphate ion content by ion chromatography.

7.4.5 Hydrogen chloride

BS EN 1911 Parts 1, 2 and 3 (BSI, 1998) provide a methodology for determining HCl emissions and covers both gaseous and multiphase sampling. Isokinetic sampling is required when chloride-containing particulate or aerosol material are anticipated. The sample is collected in demineralised water and analysed by defined techniques including ion chromatography.

The alternative procedure for HCl is USEPA Method 26A (USEPA, online 9) for isokinetic sampling and is intended to allow sampling of halogens (e.g. chlorine) and hydrogen halides. Hence, this method uses more complex sampling media than BS EN 1911.

7.4.6 PCDDs and PCDFs

BS EN 1948 Parts 1, 2 and 3 (BSI, 1997) provide methodologies for sampling and analysing for PCDD and PCDF congeners. Isokinetic sampling is required to ensure representative sampling of particulate phase material. Most UK test houses employ the filter condenser method and the sampling equipment is generally similar to the sampling system used for USEPA Method 23 (USEPA, online 7). The analytical requirements of BS EN 1948 are demanding and very few analytical laboratories currently offer United Kingdom Accreditation Service (UKAS) accreditation to this standard.

The high temperatures in enclosed flares require special consideration for the design of the PCDDs sampling system to avoid possible reformation or ‘de novo’ formation of PCDDs within the sampling system.

7.4.7 Hydrogen sulphide

USEPA Method 11 (USEPA, online 4) can be used for the quantitative determination of hydrogen sulphide in fuel gases at refineries. However, the methodology should be applicable to emissions with low SO_2 concentrations. The method has a limit of detection for emission measurements of about 8 mg/m^3, but this limit can be improved by increasing the sampled volume.

The sample is extracted through a series of four chilled micro impingers. The first impinger contains hydrogen peroxide to remove any sulphur dioxide, which would interfere with the analysis. The last three impingers contain cadmium sulphate solution at pH 3. Cadmium sulphate reacts with hydrogen sulphide to form cadmium sulphide. The cadmium sulphide is then titrated against standard sodium thiosulphate solution using a starch indicator. This titration determines the mass of cadmium sulphide produced and hence the mass of hydrogen sulphide in the sample.

7.5 Methods for auxiliary measurements

7.5.1 Velocity

A velocity profile is necessary in order to establish sampling rates and the emission rate from the flare. The usual approach is to use a Pitot tube and a differential pressure measuring device to determine the velocity at a number of specified points across two perpendicular diameters. This is described in ISO 10780 (ISO, 1994) and in Technical Guidance Note M2 (Environment Agency, 2002b).

However, at some flares where the temperature exceeded 600°C, steel Pitot tubes start to degrade resulting in a change of calibration factor. If an Incolloy Pitot tube is available and calibrated within a recognised quality system, then a standard flow traverse can be undertaken. The velocities within a flare can be as low as 3 metres/second, which is the lowest velocity measurable by this system.

An alternative approach is offered by USEPA Method 19 (USEPA, online 6). This primarily determines emission rates, but also offers an approach to calculating flows using parameters such as fuel feed rate, fuel parameters, air flows and temperatures.

7.5.2 Temperature

Temperature is measured using thermocouples. When subjected to heat, a flow of electrons is generated which produces an electromotive force (emf). The standard K type (chromel/alumel) thermocouples will monitor temperatures up to 1,200°C.

7.5.3 Moisture

Measurement of the moisture content of landfill gas flare emissions is necessary in order to enable component concentrations to be corrected to reference conditions (i.e. dry).

Most of the sampling methods used for the determination of components in landfill gas flares give a concentration relative to dry conditions directly, as moisture is removed during the sampling and measurement process. However, some methods for the measurement of some species such as VOCs (e.g. BS EN 12619 (BSI, 1999) use measurement systems that do not remove moisture. Such methods give a ‘wet’ result, which must be corrected to dry conditions.

The measurement techniques applied to determine moisture or water content of emissions from landfill gas flares fall into two categories. These are described below.

Manual methods

The moisture content of landfill gas flare emissions can be measured using a technique where a sample of the flue gas is extracted over a period of time – typically at a flow rate of 1.5 dm^3/minute – through a probe and filter to remove particulate material (where present). The sampling system must be designed to avoid any condensation prior to the absorption medium.

The sample gas is then passed through a cooled dropout bottle, followed by two impingers containing anhydrous calcium chloride (or another hygroscopic material such as silica gel) to collect the water. A gas meter is used to measure the total volume of the (dried) flue gas sampled.

It is good practice to monitor the actual sample flow rate throughout the process using a rotameter. The moisture or water content is then determined gravimetrically from the total weight of water collected and the volume of the dried flue gas sampled. This gives a single value for the average water or moisture content of the flue gas over the period the sample was collected.

Continuous methods

Moisture can also be measured using on-line methods; for example, using NDIR techniques which utilise the IR absorption characteristics of water.

There are also analysers available that can provide on-line measurements by direct measurement of the oxygen present in the water molecule. In this application, one unit typically measures the oxygen in the flue gas ‘wet’ and a second unit makes a dry measurement. The difference gives a measure of the moisture present in the sample.

8

Quality control and quality assurance

This section introduces the principles of quality assurance and quality control specific to measuring emissions from landfill gas flares. Types of uncertainties (sometimes known as errors), calibration and maintenance programmes are described, together with an outline of the important elements of protocols.

8.1 Quality control

Quality control describes the procedures set up to reduce uncertainties and errors when carrying out a measurement campaign. In measurement, there are two types of uncertainty – random and systematic.

8.1.1 Random and systematic uncertainties

Random uncertainties can be related to statistical probability functions (e.g. normal, log normal). They give rise to variations about a mean (average) and, in general, the mean will be a good estimate of the true value being measured. The more measurements made, the greater the confidence that the mean is close to the true result.

Random uncertainties are introduced as a result of small variations in procedure and can be controlled by ensuring that all procedures are described correctly and are straightforward to follow. Training is important in minimising departures from specified procedures. Authorised deviations from standard methods may introduce random uncertainties and must be reported together with the results, so that the effect on this introduced uncertainty can be addressed.

Systematic uncertainties are not related to any recognised probability function and introduce a consistent bias (departure from true value) in one direction. No matter how many measurements are made, the mean result will not represent the true value although there may be a fixed relationship.

Systematic uncertainties are reduced by ensuring that all items of equipment meet their specification such that all systems are assembled correctly and are leak-free. It is also important to ensure that all primary standards are properly certified and that all secondary standards (e.g. gas meters) are correctly calibrated.

Maintenance and calibration schedules serve to minimise systematic uncertainties. Monitoring of quality control factors is a useful way of identifying systematic uncertainties, e.g. recording the result of a reference equipment item on a quality control chart during every calibration batch.

For each manual method of sampling and analysis, a checklist should be prepared that sets out:

- description of the sampling and analytical method
- type and specification of equipment required
- instructions for assembling the equipment
- leak testing to be carried out
- calibration procedures
- maintenance procedures
- details of the reporting procedure.

All details of methods and reporting procedures should be carefully documented. Laboratories accredited to ISO 17025 (ISO, 1999) (e.g. UKAS) should already have these procedures documented. To ensure the integrity of the analytical results, all extractive samples should be analysed where possible by a laboratory accredited to ISO 17025.

8.1.2 Calibration

All instrumentation is susceptible to drift, which may result in either an overestimate or underestimate of the true concentration. These effects can be minimised – although not eliminated – by strict application of documented calibration and maintenance procedures. Calibration determines the relationship between an instrument's reading and the actual concentration of the chemical species of interest. Calibration is therefore essential; it provides the link between the measurements carried out and recognised standards.

Calibration procedures fall into two categories – full and routine validation.

Full validation
A full validation of an instrument relates the response of the instrument to a range of standards, which are certified standards or can themselves be related to certified standards. A full validation of a method relates the method to a recognised standard method, which can itself be related to certified standards. Full validation exercises are costly and time-consuming. A typical exercise should be based on parallel measurements at a minimum of three points ranging from low, medium and high, and be repeated at least three times.

Routine validation
For routine validation, calibration is carried out at a single point frequently. Routine calibration serves as guide to the changes that an instrument has undergone since its last full validation.

Full validation demonstrates the instrument's response over its full working range and should be carried out when the instrument is first commissioned and whenever the instrument undergoes maintenance.

The calibration of equipment and analysis of calibration gases must be traceable to recognised standards and the uncertainty associated with the test equipment and gases used in the estimate of measurement uncertainty.

8.1.3 Maintenance procedures

Instruments require trained personnel to operate and maintain them. A number of suppliers provide annual servicing, support staff and courses for users of their equipment.

Specialised instrumentation rarely operates for long periods without trouble. This is not surprising given the extreme nature of enclosed flares, e.g. high temperature, fine particulate, water and acid gases.

Below are a number of points to bear in mind when operating on-line instruments:

- All maintenance should be carried out according to the manufacturer's guidelines.
- A thorough check of each stage of the sampling system should be carried out at least once a week.
- A record should be kept of all maintenance work.
- During any period when the instrument is shut down, condensation traps should be drained and all lines purged with an inert gas such as nitrogen.
- Temperature and humidity changes around the instrument should be avoided.

8.1.4 MCERTS

The Agency has established a Monitoring Certification Scheme (MCERTS), which aims to provide a framework within which quality environmental measurements are made. MCERTS provides for:

- the product certification of monitoring systems (e.g. instruments, meters, analysers and equipment);
- the competency certification of personnel;
- the accreditation of laboratories under the requirements of European and international standards.

An MCERTS register has been established. This includes details of monitoring systems, personnel and laboratories certified as meeting MCERTS standards on the basis of conformity testing and assessment procedures.

8.1.5 Inter-laboratory comparison exercises

If possible, organisations involved in sampling and analysis should participate in inter-laboratory proficiency schemes involving the determination of the species of interest in an appropriate matrix. Performance in such schemes can help to identify random and systematic uncertainties.

8.1.6 Data handling

Data handling systems can be as basic as a simple chart recorder or a file of data sheets. More sophisticated systems are available, which can present information in a variety of forms. Electronic systems can be linked to a monitoring centre via modems. This can enable easy access to information from a particular enclosed flare.

8.2 Quality assurance

8.2.1 Quality assurance system

The aim of quality assurance is to ensure that the procedures set up for quality control are working effectively. For example, where an organisation uses a number of different sampling teams to carry out the same type of measurement, it is important that a quality assurance system is set up to ensure that all measurements are carried out to a similar standard. This is particularly important if different sampling and analysis methods are employed.

Table 8.1 Existing and proposed MCERTS schemes

MCERTs scheme	Date	Level*	Additional information
Continuous emission monitors (CEMs)	April 1998	Implemented	
Continuous ambient monitors (CAMs)	April 2002	Implemented	
Manual stack emission monitoring	April 2002	Implemented	This scheme covers both the people and the organisation involved in emissions monitoring. Personnel are formally certified as being competent by assessment involving past experience, training and examinations. Organisations have to be accredited by UKAS to ISO 17025.
Data recording	May 2003	Consultation	
Continuous water monitoring	Feb 2003	Implemented	
Site arrangements	July 2003	Consultation	
Self monitoring of effluent flow	April 2003	Implemented	
Soil testing	Mar 2003	Implemented	
Portable manual monitors	Oct 2002	Consultation	

* As of the date of publication of this document.

The quality assurance system should contain the following elements:

- quality manual and procedures describing all aspects of quality assurance and quality control;
- instructions to measurement teams to ensure measurements are made in accordance with the correct procedures;
- procedures to ensure that measurement teams, contractors and operators use correct quality control procedures (calibration, maintenance, data handling, number and duration of samples, etc.);
- inspection regimes to ensure quality control procedures are being followed and that sample identification and routing procedures are well documented;
- provision for a suitable reporting procedure and its utilisation;
- circulation of documentation on the procedure to those concerned with the measurement;
- clear nomination of the person responsible for quality assurance;
- a system for handling non-conformances and quality improvements.

8.2.2 Protocols

The documented procedure by which reliable and comparable results are obtained from measurements at source is known as a protocol. Protocols ensure that the sampling procedures are carried out correctly and that the results obtained characterise the process accurately and that there is a clear audit trail.

The main components of a protocol are:

- a reference measurement method (standard methods may not always be available);
- a standard methodology setting out:
  - health and safety considerations
  - operating conditions required
  - emissions of interest
  - variability of emissions
  - sampling position
  - sampling characteristics (e.g. isokinetic)
  - sampling frequency
  - sampling duration
  - number of samples
  - required accuracy
  - analytical methods
  - analytical precision
  - procedures to be adopted if standard methods are unavailable.

8.2.3 Audit

The monitoring organisation should be subject to an independent audit to assure the standard and quality of data.

Data assessment and reporting

9.1 Emission standards

Table 9.1 sets out the emissions standards to be achieved by enclosed landfill gas flares.

The emission standards given in Table 9.1 will be introduced by the regulator as landfill sites are permitted or re-permitted in accordance with the PPC regulatory regime (or sooner if site-specific risk assessment determines that improvements should be completed earlier).

For closed sites where a waste management licence remains in force, the Agency will require the licence holder to carry out a landfill gas Emissions Review. An Emissions Review is based on the development of a risk screening/conceptual model of gas management for the site and will include the provision of flaring. Where the review identifies unacceptable site-specific risks from landfill gas, an emissions improvement programme will be required that incorporates the appropriate best practice contained within this guidance. An Emissions Review and improvement programme must be implemented according to site-specific risk and be completed as soon as reasonably practicable. The improvements identified in Emissions Reviews must be completed at all Agency regulated landfills by 16 July 2009.

For each flare, the emission standards given in Table 9.1 should be assessed on an individual basis. This may necessitate a stricter emission standard based on risk, either in terms of the primary generic emission standards or in terms of additional parameters. Guidance on carrying out generic environmental risk assessment (DETR et al., 2000) and specific information on landfill gas risk assessment are available (Environment Agency, 2004a).

The factors that should be considered include:

- topography
- receptor location
- composition of the landfill gas.

The primary emission determinands are based on research undertaken by the Agency and the UK waste industry. Analysis of the landfill gas can provide a good indication of the requirement for additional emission monitoring. Landfill gas analysis also provides valuable information on the likely combustion products. For example, the presence of sulphur and chlorine compounds in the landfill gas would suggest that SO_2, HCl and other chlorinated compounds will be found in the emissions.

Table 9.1 | Emission standards for enclosed landfill gas flares

Determinand	Emission standard*	
	Flare commissioned before 31 December 2003	Flare commissioned after 31 December 2003
Oxides of nitrogen as NO_2	150	150
Carbon monoxide	100	50
Total volatile organic compounds as carbon	10	10
Non-methane volatile organic compounds	5	5

* Concentration in mg/m^3 at STP, dry, 3 per cent oxygen

In addition to the numerical emission standards, the following provisions must also be met.

- Sample ports must be fitted in accordance within the requirements of Technical Guidance Note M1 (Environment Agency, 2002a) or, alternatively, in situ sample probes.
- Sampling must be undertaken after combustion is completed (i.e. downstream of the flame). Flare designs must include sufficient shroud to fully enclose the flame at all times.
- Emissions must not be impeded by cowls or any other fixture on top of the flare during operation.
- Operational control must be so as to achieve a minimum of 1,000°C and 0.3 seconds retention time at this temperature (or an equivalent validated set of conditions) (Environment Agency, 2002a).
- The flow and composition of the input gas must be monitored regularly to demonstrate consistency with operational requirements and the flare's design specification.

Monitoring of the flame temperature is undertaken to demonstrate the consistent performance output of the enclosed flare.

Monitoring of the inlet gas is undertaken to demonstrate that:

- the enclosed flare is operating within design limits for gas flow and gas composition;
- the performance of the flare at the time of the periodic emissions monitoring is representative of normal operation.

In order to monitor input gas, suitable sampling points for flow and gas composition should be installed in the pipework at a representative location close to the flare. The minimum monitoring requirement for inlet gas composition is methane and oxygen.

The frequency and degree of automation of the monitoring will depend on the operational circumstances. Where a flare is operating on a stable, consistent gas field, a small number of readings per day will be sufficient to demonstrate performance. Where a flare is handling gas from a large field with multiple manifolds, frequent readings to provide a signal trace may be required.

Monitoring data associated with the inlet gas (e.g. methane, oxygen and flow rate) and the output (i.e. temperature) of the enclosed flare should be logged.

It is recommended that monitoring data are transferred through a telemetry link to those responsible for operational control. The need for telemetry will depend on the site-specific risks that may result from short-term deviation from operational standards. Factors that will influence the need for telemetry include:

- the proximity to receptors
- size of the enclosed flare
- whether the flare is associated with an engine installation.

9.2 Testing frequency

The frequency of testing of emissions from a flare will be derived from an individual site environmental risk assessment. The minimum frequency is annual. Once a consistent emissions profile has been established, the frequency of monitoring may be reduced to the minimum (annual) frequency in agreement with the regulator.

On commissioning, test work to verify combustion temperature and residence time should be considered.

In addition to servicing, spot checks of combustion to demonstrate the unit is functioning as designed should be undertaken. Consideration should be given to the installation of permanent sample systems to enable this to be undertaken easily at ground level without the need to fit platforms. Basic instrumentation exists on most flares (e.g to indicate the combustion chamber temperature) and spot checks using hand-held systems allow combustion gases such as CO, CO_2 and O_2 to be monitored easily.

9.3 Data standardisation

9.3.1 Reference conditions

Emission concentrations determined at enclosed landfill gas flares should be standardised to reference conditions of:

- mass concentration;
- standard temperature and pressure (STP), i.e. 273K (0°C) and 101.3 kPa (1 atmosphere);
- 3 per cent v/v oxygen;
- dry gas.

Nitrogen oxides should be expressed as NO_2 and VOCs as carbon. Details of the calculations used to standardise emission data are given in Appendix D, but the key calculations are described below.

All landfill gas flare emissions should be reported as concentrations and mass emission rates, together with supporting information. To convert the measured emissions concentrations to the reference conditions, a series of correction factors should be applied to the data. Basic details about these correction factors are provided below and more detail is given in Technical Guidance Note M2 (Environment Agency, 2002b).

9.3.2 *Conversion from volume concentration to mass concentration*

Many emission measurements using instrumental techniques report emission data as volume concentrations such as parts per million (ppm). These can be converted to mg/m^3 at STP using the following formula:

$$mg / m^3 = ppm \times \frac{Mw}{22.4}$$

where:
Mw = molecular weight (e.g. NO_2=46 and CO=28).

9.3.3 *Oxygen correction*

Standardising emission concentrations to a fixed oxygen concentration removes dilution effects caused by different levels of excess air in the enclosed landfill gas flare. This allows a true comparison of emission concentrations.

The relationship between the measured oxygen and measured emission species concentration is not linear as oxygen from air is added or removed. The equation for the concentration at reference conditions can be written as:

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

where:
C_r = emission concentration at reference conditions
C_m = measured emission concentration
$(O_2)_r$ = reference oxygen concentration (percentage v/v dry)
$(O_2)_m$ = measured oxygen concentration (percentage v/v dry).

As the reference oxygen condition for landfill gas flares is 3 per cent, this equation becomes:

$$C_r = C_m \times \frac{17.9}{(20.9 - (O_2)_m)}$$

If oxygen enhancement is used, then a modified form of the equation can be applied (see Appendix D).

9.3.4 *Moisture correction*

Standardised concentrations are expressed in the dry condition and, although some emission concentrations are measured dry, other measurements are undertaken on ‘wet’ gas. The moisture content of such gas is usually expressed in volume/volume (v/v) terms. For example, the percentage volume of water vapour is the total wet gas volume.

Emission concentrations can be corrected to the standardised dry condition using the following formula:

$$C_{dry} = C_{wet} \times 100/(100 - \% H_2O)$$

where:
C_{dry} = concentration of emission at dry condition
C_{wet} = concentration of emission at wet condition
$\%H_2O$ = moisture content of exhaust gas (percentage v/v wet).

9.3.5 *Emission rate*

An emission rate is determined from the flue gas flow rate and emission concentration. It is essential that the emission concentration and flow rate are expressed at the same temperature, pressure, oxygen and moisture content.

Due to the high temperature and low velocities within an enclosed flare, direct flow measurements may not be practical at many sites. However, flow can be determined from combustion calculation and landfill gas analysis, e.g. using USEPA Method 19 (USEPA, online 6) (see Section 7.5.1).

9.4 Representative sampling

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 flare designs, which are representative of normal operations in the UK. The measurements were generated as an average over one-hour test periods.

The guidance on monitoring requires periodic measurement for the determination of the emissions profile of an enclosed landfill flare. The protocol involves sampling over an hour but, inevitably, this only covers a small period in the emissions from the flare. Consequently, it is necessary to assume that the periodic measurement is representative of operation outside the monitoring periods.

Increased confidence in this assumption can be provided by development of an emissions profile for the flare. This profile may be built up over time and by making targeted measurements under the range of different conditions in normal operation. In addition, surrogate determinands and operational information (e.g. maintenance logs, gas flow) can be used to confirm consistent operation of the flare.

If the operational information during the monitoring period differs substantially from that recorded for the preceding months, the 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 the guidance.

9.5 Errors and uncertainty

When assessing compliance against the emission standards for flares, it is necessary to take account of the representative nature and reliability of the measured values. The uncertainty arising from unrepresentative sampling and the errors from measurement uncertainty are considered below.

9.5.1 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. Section 8.1 identifies methods of keeping the measurement uncertainty as low as possible.

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 flares, 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 measurements (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**.

The Source Testing Association has assessed the uncertainty associated with particular analytical methods used in monitoring combustion (STA, 2001b). Based on a review of literature and enquiries made to stack sampling contractors, it was concluded that the uncertainty associated with most analytical methods for measuring NO_x and carbon monoxide was 12 per cent (at the 95 per cent level of confidence). However, the method of NO_x analysis using an electrochemical cell had an uncertainty of 20 per cent and methods of determining speciated VOCs using adsorption-thermal desorption had an uncertainty of 25 per cent. These uncertainties take account of:

Table 9.2 Quoted uncertainty for reference methods

Determinand	Reference	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*

Source: Environment Agency (2002a)

* Depends on the component and method used.

- limitations in the method, e.g. sampling, analysis, instruments, interferences;
- variations due to human factors between different, but competent, monitoring teams.

Where methods are in accordance with a recognised measurement standard, the measurement uncertainty is better understood. Table 9.2 gives the quoted uncertainty for the methods referenced in this guidance.

The uncertainties quoted in Table 9.2 only apply when measurement complies fully with the standard method. However, the design and operation of enclosed flares means it is not usually possible to undertake fully compliant tests. For example, the measurement of NO_x and CO using ISO 10849 and ISO 12039, respectively, requires a species variation across the sample plane of less than ±15 per cent to justify a single point sampling campaign; otherwise a multi-point sampling procedure must be adopted at the points described in ISO 9096 (ISO, 2003). Where this multi-point sampling has to be employed, there will be additional uncertainties relating to the multi-point procedure.

In addition, the measurement standard also requires five hydraulic diameters of straight shroud before the sampling plane and five hydraulic diameters from the shroud exit. This is often not possible to achieve; consequently, the measurements will have a different uncertainty from those quoted in the measurement standards. An overall measurement uncertainty would then have to be calculated.

Nevertheless, it is important that attempts to improve the uncertainty by taking samples further from the shroud exit do not undermine the primary need to sample above the flame. Measurement uncertainty will be unacceptable if the sampling plane is less than a metre below the shroud exit to avoid sampling within the flame. For this reason, flares must be installed with the maximum height of post-combustion shroud that is consistent with planning requirements.

The Large Combustion Plant and the Waste Incineration Directives (Council of the European Union, 2002 and 2001) cover the monitoring of several relevant combustion products. They quote measurement uncertainties at the 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 9.3.

Table 9.3 Measurement uncertainty quoted for selected determinands in 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 9.4 Typical measurement uncertainty for methods used in monitoring emissions from enclosed flares

Determinand	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, 2002c)	25
Non-methane volatile organic compounds	Adsorption – thermal desorption (BS EN 13649) (BSI, 2002c)	25

The values in Table 9.3 should be regarded as ‘target uncertainties’ for monitoring flare emissions.

Table 9.4 shows the uncertainty to be expected in measurements by the recommended methods. These values are based on:

- the degree of the uncertainty in the standard methods
- guidance from relevant directives and the extent of deviation needed when applying these to flares
- results obtained from Agency R&D on monitoring.

9.6 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.

9.6.1 *Confirmation of evidence*

The quality and representative nature of the measurements have to be addressed 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 at times between the periodic monitoring. The uncertainty arising from unrepresentative sampling periods will be site-specific and will change during the operational period at the site. Where this can be deduced from the flare profile, this should be stated and the additional uncertainty added to 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 9.5. If the calculated total uncertainty exceeds these values, it will generally indicate unsatisfactory monitoring or erratic performance of the flare.

9.6.2 *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 flares is subject to the general principles applied to the regulation of other emissions. These are covered by the Agency’s Compliance Common Breaches Classification Scheme.

Table 9.5 Maximum values for measurement uncertainty to be applied when assessing compliance of emissions from enclosed flares

Determinand	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 13640) (ISO, 2002c)	40
Hydrogen chloride	Integrated method with ion chromatography (BS EN 1911) (BSI, 1998)	60
Sulphur dioxide	Integrated method with ion chromatography (ISO 11632) (ISO, 1998)	30

- **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 9.1.

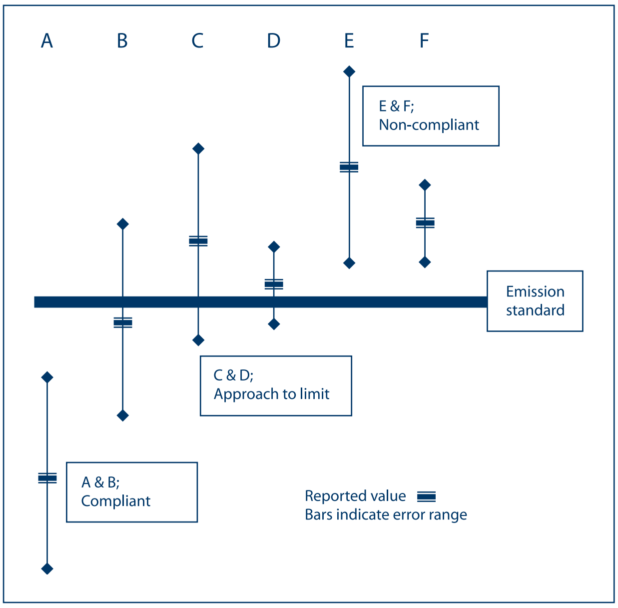


Figure 9.1 Schematic representation of the compliance classification used in assessing emissions from flares

9.6.3 *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 of:

Result = X ± U (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 should be followed.

The report should indicate whether the sampling period was representative of the normal operating period of the flare. It should give supporting evidence for this (e.g. from the flare profile) or make allowance for it in the data where it appeared not to be fully representative. The report should contain an assessment of the monitoring data from the flare for compliance against the relevant emission standard.

The appendix to the report should record subsidiary information including:

- landfill type and age
- meteorological conditions
- sample data sheets
- completed calculation pro-formas
- chart recorder printouts.

Appendix E provides an example of an emissions report sheet. The full report must be submitted to the regulator, where possible, in electronic format.

9.6.4 Consideration of response

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

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

If the data is assessed as non-compliant, this must be investigated and reported to the Agency immediately. The Agency response will be in accordance with its Compliance Common Classification Scheme. The urgency of the 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 Agency will be consistent with its enforcement and prosecution policy.

Appendix A:

Additional emission data

Table A1 Summary of reported landfill gas flare emissions (various sources)*

Parameter	Concentration	Notes	Reference
Methane	0.04–0.52%	Concentrations reported as measured basis	Baldwin *et al.* (1993a,b)
Carbon dioxide	3–4%		
Nitrogen	75–80%		
Oxygen	17–18%		
Carbon monoxide	Not detected		
Total organic carbon	2–9 mgC/Nm^3		
	All concentrations expressed at reference conditions of 3 per cent oxygen		
Carbon monoxide (mg/Nm^3)	8	Turbulent diffusion flame	Eden (1993)
	460–2,020	Non-optimum air	Engel (1991)
	8–122	Optimum air	Engel (1991)
	<5	Optimum air - modified burner	Engel (1991)
	3–10	High temperature flare	Graf (1990)
	3–44		Kreigl (1991)
Nitrogen oxides (as NO_2) (mg/Nm^3)	35–48		Eden (1993)
	<8–103	Optimum primary air	Engel (1991)
	67–117	Optimum primary air and modified burners	Engel (1991)
	<8–107	Non optimum primary air	Engel (1991)
	80–140	High temperature	Engel (1991)
	72–136		Graf (1990)
	65–100		Kreigl (1991)
	87–142		Kaimann *et al.* (1991)
Total hydrocarbons (mgC/Nm^3)	2–4		Graf (1990)
	2–7		Eden (1993)
	<3		EMPA (1989)
Hydrogen chloride (mg/m^3)	9		Eden (1993)
	60		EMPA (1989)
	4–41		Kaimann *et al.* (1991)
Sulphur dioxide (mg/Nm^3)	65		EMPA (1989)

* While these data provide a useful indication of the range of expected values for major landfill gas components, they should be regarded with caution as little information is provided on flare operation or data standardisation.

Table A2 Summary of reported landfill gas flare emissions (Biogas Association study)

Parameter	Summary of values [a,b]		
	Mean	Standard deviation	95 % confidence interval
SOx	304.8	467.6	695.7
NOx	62.3	24.9	79.2
CO	1,007.1	1,076.1	1,730.0
HCl	23.3	19.9	39.9
HF	4.7	6.9	10.4
PCDDs/PCDFs (ng/m^3) [c]	0.0053	0.0026	0.0117
Polycyclic aromatic hydrocarbons (PAHs)	0.00068	–	–
Particulate	5.47	5.7	56.7
CO_2 (%)	7.2	3.3	9.5
Total hydrocarbons (THC) (as C)	298.1	606.5	764.3
NMVOCs	0.56	–	–
O_2 (%)	12.1	3.7	14.8
Moisture (%)	8.6	4.4	11.7
Stack temperature (°C)	782	173	914
Flow (m^3/hour)	6,086	2,447	9,124

[a] Data as reported by Gillet *et al.* (2002).

[b] Unless otherwise stated, measured as mg/m^3 at 3 per cent O_2 dry and STP.

[c] Normal reporting for PCDDs/PCDFs incorporates toxic equivalency quotients based on internationally-accepted toxic equivalency factors (I-TEQ).

Appendix B:

Flare height and dispersion assessment

General

This appendix provides a short overview of the dispersion and impact of enclosed flare stack emissions management. It includes elements of the design of discharge stacks and dispersion modelling applied to assess impacts.

In theory, a flare stack elevates the plume so that initial dispersion of the plume is at a greater altitude. By the time the plume has dispersed to the ground, emission concentrations should have reduced to acceptable levels. A flare stack should generally be high enough to ensure that this occurs. 'Local' may mean anything from 10 metres to 1 kilometre. At large distances from a flare stack (100 stack heights), the effect of stack height on dispersion is no longer distinguishable (unless the plume has penetrated the boundary layer). In addition, the effects of single sources start to become indistinguishable at such distances from the background produced by other sources.

In carrying out its statutory duty, the local planning authority must consider other factors (e.g. visual impact and noise) and thus may impose a restriction on flare stack height and location.

Adjustment of flare height

The following impacts can be reduced by adjusting the height of the flare stack:

- odours
- effects of ambient concentrations
- deposition of emissions – mainly heavy metals, acidic materials or long-lived chemicals (e.g. PCDDs)
- noise
- nuisance dusts
- visibility/obscuration.

The importance of emission exposure times

Where emissions are associated with a range of exposure limits with different exposure times (as, for example, with SO_x and NO_x), it is usually the short-term exposure which is critical. This is mainly because short-term exposures are not repeated very often at the same point; so although short-term concentrations may be high, the effect on longer-term averages are usually low in relation to their respective limit concentrations. With longer-term averages, the background concentrations of common emissions become more important and may make a larger contribution to overall levels than that from a single local source.

Determining the appropriate height of the flare

The following information is required to calculate a potential flare stack height:

- details of the emission rate
- details of the site and its surroundings
- identification of the critical emissions including rates and typical background concentrations
- a dispersion model
- any controls or limitations imposed by guidance notes, etc.
- meteorological conditions

Typically, landfill gas flares have low emission velocity which can result in downwash being a common problem, regardless of the high temperature (hence thermal buoyancy). A standard method of determining stack heights for broader discharges is available (HMIP, 1993).

Emission exposure times for potential impacts are listed in Table B1.

Table B1 Emission exposure times for potential impacts from flares

Impact	Emission exposure time
Odours	Very short-term, i.e. a few seconds
Toxic effects	Short-term (a few minutes for exposure to acid gases)
Deposition	Mainly long-term, i.e. annual
Nuisance dusts and deposits	Can be short-term, but mainly daily or longer
Visibility/obscuration	Mainly short-term (a few minutes at most), but may repeat intermittently

Identification of the critical emissions and their emission rates

The critical determinand is the one that requires the greatest flare stack height. This can be found by calculating the Pollution Index (Pi) for each emitted determinand. This is defined as:

$$\mathrm{Pi} = \frac{D}{(G_d - B_c)}$$

where:
D = discharge rate of the determinand
G_d = guideline concentration of the determinand
B_c = background concentration of the emission.

Standard stack height calculation methods are used to determine these parameters, which can vary from simple formulae to complex computer-based methods.

Dispersion modelling

There are many dispersion models covering a whole spectrum of complexity and reliability. However, there are limitations in their use because:

- dispersion models are approximations to a very complex process;
- dispersion itself is a stochastic process, so that there is never a single, accurate, answer to a dispersion calculation.

For enclosed flare stack height calculations and hence dispersion calculations, the following need to be taken into account when modelling:

- basic plume dispersion data as a function of atmospheric conditions
- a method of determining plume rise
- deposition modelling (if deemed necessary)
- ideally, the effects of buildings and other structures (including trees) on plume downwash and dispersion rates.

Numerical models are most effective for straightforward dispersion calculations where the basic plume dispersion model can be applied. They account for large-scale meteorological effects, but are relatively poor at dealing with complex flows.

Alternatively, look-up tables that are specific for landfill gas combustion systems (Environment Agency, 2004a) provide a simple screening methodology. The calculations in these look-up tables assume typical exit velocities and emission temperatures for a range of stack heights, with off-site maxima dependent upon the distance from the stack to the landfill boundary.

Most numerical plume dispersion calculations are presently carried out using the Pasquill-Gifford type of Gaussian dispersion model in combination with a plume rise model. The ADMS 3 model (CERC, 2002) or AERMOD (USEPA, online 10) are state-of-the-art Gaussian plume dispersion models, which take into account the effects of topography, buildings and other structures. When deciding which model to use, it is important to ensure it is fit-for-purpose.

Appendix C:

Proforma for recording preliminary site visits

Item number	**Permit number**	**Operator name**	**Installation name**	**Installation address**
Section to be repeated for additional emission points				

Item	**Emission point**	**Emission point**	**Emission point**	**Emission point**
Emission point reference	A1	A2	A3	A4
Grid reference				
Emission point description				
Description of flare				
Reference conditions for reporting				
Description of sampling location				
Details of operator risk assessment				
Consultant risk assessment completed (Y/N)				
Personal protection equipment requirements				
Other special equipment required				
Confined space working requirements				
Requirements for intrinsically safe equipment				
Other heath and safety issues				
Provision for parking of vehicles at sampling location(s)				
Horizontal distance from vehicle parking location to sampling point (metres)				
Vertical height of sampling platform or location above adjacent ground level (metres)				
Sampling platform or sampling location dimensions (metres)				
Required safe working load for sampling at the platform or sampling location (point load and uniformly distributed load)				
Actual safe working load capacity of existing platform or sampling location (point load and uniformly distributed load)				
Access arrangements for personnel to sampling platform				
Access arrangements for equipment to sampling platform				
Required safe working load for lifting equipment (kg)				

Appendix D:

Further information on calculations

Data standardisation

All data handling and calculations should be undertaken as described in fully documented procedures that comply with standards or equivalent requirements. All calculation formulae used should conform with the appropriate sampling and analysis standard. Emission concentrations should be reported, as appropriate, be reported to reference conditions of:

- mass concentration;
- standard temperature and pressure (STP), i.e. 0°C (273K), 101.3 kPa;
- 3 per cent v/v oxygen;
- dry gas.

All flue gas emissions must be reported as concentrations and mass emissions, together with supporting information using the regulator's standard monitoring report forms.

Conversion from volume concentration to mass concentration

Emission concentrations are often measured in volume/volume (v/v) terms, e.g. parts per million (ppm) or percentages. This approach is most common for gaseous air emission species, especially when the measurement is carried out using an instrumental monitoring technique. For example, carbon monoxide monitors normally present measured data as ppm, while oxygen meter readouts are given as percentages. For ideal gases, concentrations measured in volume/volume terms are independent of temperature and pressure.

This approach has an important advantage for on-line monitoring applications, as there is no need to correct the readings on the monitors for analyser cell temperature and pressure conditions. This condition holds as long as the certificated concentration value of the calibration cylinder and monitor scale are both given in volume/volume units.

The emission standards for enclosed landfill gas flares are expressed in mass volume terms (mg/m^3). For reporting purposes and to assess compliance, measured data will often need to be converted from volume/volume terms to mass/volume units.

The conversion from ppm to mg/m^3 is straightforward. The relationship is derived from the ideal gas equations and relies on the fact that 1 mole of an ideal gas occupies a volume of 22.4 litres at STP.

As moles and volumes of ideal gases are interchangeable, all that is required to convert from a ppm concentration to mg/m^3 at STP is to multiply the ppm figure by the ratio of the molecular weight of the emission component to 22.4, i.e.

$$mg / m^3 = ppm \times \frac{Mw}{22.4}$$

where:
Mw = molecular weight, e.g.
for NO_x, Mw = 46 (NO_x is expressed as NO_2 for regulatory purposes);
for CO, Mw = 28.

Oxygen standardisation

If excess air is added to an enclosed landfill gas flare (e.g. to promote better combustion), measured flue gas emission concentrations of non-combustible species such as SO_2 will fall. However, emission concentrations only appear to be reducing while, in reality, emission mass rates have remained constant. Thus, it is necessary to compare concentrations at a standard oxygen concentration.

However, the relationship between the measured oxygen and measured emission species concentration is not linear as oxygen from air is added or removed. For example, halving the flue gas oxygen content does not result in a doubling of the emission concentration. The oxygen found in the flue gases is a measure of the excess air over that required for theoretical complete combustion (termed the stoichiometric air requirement).

Therefore, the measured oxygen level is a measure of the dilution of the flue gases from the stoichiometric condition. The percentage of oxygen in dry air is 20.9 per cent (v/v) and the proportion of excess air (X/V) can be calculated using the following formula:

$$\frac{X}{V} = \frac{(O_2)_m}{(20.9 - (O_2)_m)}$$

where:
X = volume of excess air (m^3)
V = stoichiometric volume of the flue gases (m^3)
$(O_2)_m$ = percentage of oxygen (v/v) in the flue gas (dry basis).

The proportion of excess air can be converted to the percentage excess air by multiplying X/V by 100.

The dilution factor (D) at oxygen concentration $(O_2)_m$ is given by:

$$D = 1 + \left(\frac{(O_2)_m}{(20.9 - (O_2)_m)}\right) = \left(\frac{20.9}{(20.9 - (O_2)_m)}\right)$$

The general equation for the conversion factor, which is the ratio of the dilution factors at the measured and reference conditions is obtained from the above equation. Thus the ratio D_m/D_r is given by:

$$\frac{D_m}{D_r} = \frac{[20.9 - (O_2)_r]}{[20.9 - (O_2)_m]}$$

where:
D_m = dilution factor at the measured $(O_2)_m$ concentration
D_r = dilution factor at the and reference $(O_2)_r$ oxygen concentration.

Table D1 gives conversion factors for the 3 per cent oxygen reference concentration used for enclosed landfill gas flares.

Table D1 Conversion factors for different oxygen percentage concentrations

Oxygen concentration (per cent)	Conversion factor to 3 per cent O_2
1	0.90
2	0.95
3	1.00
4	1.06
5	1.13
6	1.20
7	1.29
8	1.38
9	1.50
10	1.64
11	1.80
12	2.01
13	2.26
14	2.59
15	3.03

Since the emission concentration C is equal to the reciprocal of dilution D, the equation for the concentration at reference conditions can be written as:

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

Because the reference condition being used for enclosed landfill gas flare is 3 per cent, this equation becomes:

$$C_r = C_m \text{ x } \frac{17.9}{(20.9 - (O_2)_m)}$$

Enhanced oxygen

Under enhanced oxygen conditions (i.e. where oxygen is added to aid combustion and reduce gas volumes), the conversion to standard oxygen conditions is not so straightforward.

The percentage of oxygen by volume in dry air is 20.9 per cent. Under normal combustion conditions, the sum of the carbon dioxide and oxygen concentrations (measured on a wet basis), together with half the moisture content of the flue gas (from the combustion of hydrogen in the fuel – not the fuel moisture) is equivalent to 20.9 per cent of the volume of the flue gas. That is:

$$[(CO_2) + (O_2) + 0.5(H_2O)]_m = 20.9$$

Under enhanced oxygen conditions, the normal oxygen standardisation equation is not appropriate as the sum of these items is not 20.9 per cent, but some larger figure depending on the enhanced oxygen input. Unless the degree of enhancement is known or can be measured directly, it will be necessary to estimate it from other measurements such as the oxygen and carbon dioxide concentration in the flue gas.

If the hydrogen/carbon ratio is known, a modified equation that takes account of the water emitted as a result of the hydrogen in the fuel can be used. If the percentage of carbon in the fuel is C and that of hydrogen H, the equation is as follows:

$$C_r = \frac{C_m \left[(CO_2)_m \left(1+3\frac{H}{C} \right) + (O_2)_m - (O_2)_r \right]}{(CO_2)_m \left(1+3\frac{H}{C} \right)}$$

Moisture correction

Moisture content is usually expressed as in volume/volume terms; for example, as the percentage volume of water vapour in the total wet gas volume.

Water content is normally determined gravimetrically by passing extracted flue gases through a weighed drying train. The volume of dried sample gas is measured and the increase in mass of the drying train is recorded. The ratio of volumes of water vapour and of dry gas is the same as the ratio of the moles of water vapour and dry gas (treating them both as ideal gases at STP). The number of moles of water (MW) is found by dividing the increase in mass of the drying train in grams by the molecular mass of water (i.e. 18).

The number of moles of dry gas MD is found by dividing the metered volume of dry gas (in m^3 corrected to STP) by 0.0224 (the molar volume of any gas at STP). The percentage H_2O v/v can then be calculated as follows:

$$H_2O(\%) = 100 \text{ x } \frac{M_w}{M_w + M_D}$$

Thus, the emission concentration converts as follows:

$$C_r = C_m \text{ x } \frac{100}{(100 - H_2O(\%)}$$

where:

C_r = concentration of emission at reference condition (dry)

C_m = concentration of emission at measured condition.

The correction of a flow rate to dry condition is given by:

$$F_r = F_m \text{ x } \frac{(100 - H_2O(\%))}{(100)}$$

where:
F_r = flow rate at reference condition (dry)
F_w = flow rate at measured moisture content.

Temperature correction

Emission standards for enclosed landfill gas flares are quoted in terms of mass/unit volume, (mg/m^3). They contain a gas volume term (in this case m^3) and, since the volume of a gas may vary according to the temperature and pressure, the volume needs to be fixed to a reference temperature and pressure. Converting from the temperature and pressure under the actual measurement conditions to a standard temperature and pressure is based on the gas laws and is relatively straightforward. If each correction is considered in isolation, then the effect of a temperature change on the measured gas volume is:

$$V_r = V_m \text{ x } \frac{273}{T_m}$$

where:
V_r = gas volume at reference conditions (273K) (m^3)
V_m = measured volume (m^3)
T_m = measured temperature (K)

Thus, emission concentrations, which are mass over volume, convert as follows:

$$C_r = C_m \text{ x } \frac{T_m}{273}$$

where:
C = concentration (the subscripts ‘r’ and ‘m’ indicate reference and measured conditions, respectively)
T_m = measured temperature (K).

Pressure correction

Pressure correction is also based on the ideal gas laws. Thus:

$$V_r = V_m \text{ x } \frac{P_m}{101.3}$$

and:

$$C_r = C_m \text{ x } \frac{101.3}{P_m}$$

where:
P_m = measured pressure (kPa) and 101.3 (kPa) is atmospheric pressure
V_r = gas volume at reference conditions (273K)(m^3).
V_m = measured volume (m^3)
C = concentration (subscripts ‘r’ and ‘m’ indicate reference and measured conditions, respectively).

Mass emission calculation

The mass emission rate (ER) calculation, which is outlined below, combines the measured concentration and flow rate data.

To convert to:

$$ER = C_m \left(\frac{mg}{m^3}\right) \text{ x } Flowrate \left(\frac{m^3}{s}\right)$$

This gives an emission rate in mg/second.

g/second	Divide by 1,000
kg/second	Divide by 1,000
kg/hour	Multiply by 3,600.

It is essential that the emission concentration and emission flow rate are expressed at the same conditions (temperature, pressure, water content and oxygen content).

Appendix E:

Example flare emissions report

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 and 101.3 kPa) 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)

Appendix F:

Detection principles of instrumental methods of analysis

Spectrophotometric methods

These methods are based on the identification of an element or compound by observing the characteristics of its absorption or emission of electromagnetic radiation (IR, UV, etc.). The absorption and emission characteristics depend on the atomic and molecular structure.

As well as analysis, spectrophotometric techniques can be used for quantitative measurement. For example, molecules such as carbon monoxide, carbon dioxide and sulphur dioxide have specific absorption frequencies in the infrared, and this absorption can be used to measure their concentrations in a flare exhaust stream.

Instruments for the continuous measurement of gaseous emissions compare the transmission of radiation through the sample gas with the un-attenuated radiation through a cell containing clean air. The Beer–Lambert Law relates the absorption of radiation to the concentration of the gas in question:

$$I = I_0 e^{-Ecl}$$

where:

I_0 = intensity of radiation from the source entering the flue gas
I = intensity of the radiation at the receiver
E = extinction coefficient of the substance
c = concentration of the emission
l = path length of the light beam in the duct.

Ideally, only one gas would absorb at any one frequency and the optical filters would be capable of selecting very narrow frequency ranges very accurately. Unfortunately, this is not the case and some gases interfere with the measurement of others due to the proximity of their specific frequencies. Thus, errors may be introduced by the presence of other compounds. Perhaps the best example of this is the interference of water in the determination of carbon monoxide and carbon dioxide. The problems of known interferences can be overcome by appropriate pretreatment but, in many cases, such treatment is not possible and errors may remain undetected.

Infra-red absorption spectrometry

The simplest form of spectrometer consists of a source, an optical filter, the sample cell and the detector; this type of instrument is known as a single beam non-dispersive analyser. The filter selects that part of the spectral range most characteristic of the substance to be measured.

As with all continuous monitors of this type, regular zeroing and calibration are required to overcome zero and range drift caused by small changes in the optical/spectral properties of the optical filter and the detector sensitivity. Some of these problems may be overcome using twin beam instruments. In a twin beam instrument, the radiation from the source is split by means of mirrors so that one part passes through the sample cell and the other through the reference cell. The two beams are then brought together onto a half silvered mirror or chopper rotating at a constant speed, which allows each beam alternately to reach the detector cell.

In an instrument operating on the ‘Luft’ principle, the central membrane of the detector cell forms one plate of a variable capacitor and the concentration of the gas being measured is proportional to the capacitance of the detector cell. With no emission in the measuring cell, the intensities of the two beams are equal and therefore the radiation reaching the two halves of the detector are equal and the heating effect on the gas within the two halves of the cell is the same. Thus, the capacitance of the detector is at its baseline level. With higher concentration in the measuring cell, the radiation reaching the sample half of the detector will be less, the heating effect on that half of the detector will be less, the central membrane will move and the capacitance of the cell will change.

The twin beam type of instrument is most commonly encountered in on-line measurement of gaseous emissions. Two other types are used – the dispersive analyser and the correlation spectrometer. In dispersive instruments, the radiation source has a wide spectrum and the band of interest is selected by means of a diffraction grating or prism.

Ultra-violet spectrometry

When molecules absorb ultraviolet radiation, outer electrons are excited to a higher energy state. The spectra of vapours and gases at low pressures show broad bands at low resolution, but fine structure at high resolution. 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.

Non-dispersive UV analysers are very similar to their IR counterparts and they can be of single or twin beam construction. Glass components cannot be used in the optical system because glass is opaque to UV radiation and quartz is used instead.

Instead of using direct absorption of the UV radiation, an alternative method known as second derivative UV photometry exists. This technique measures the shape of the narrow characteristic absorption bands of components such as sulphur dioxide and nitric oxide. Measurement of the second derivative is achieved by modulation of a specific spectral line (by means of a tuned monochromator). This modulation with respect to time enables the second derivative to be measured directly. This technique is designed to eliminate interference problems, as the second derivative is not affected by other UV components.

UV fluorescence

This technique is commonly used for measuring gaseous sulphur dioxide concentrations. UV radiation from a xenon lamp passes through a 210 nm band pass filter before reaching the measurement cell. Molecules of SO_2 in the test gas become excited and move to a higher energy state. On return to the stable ground state, energy is radiated and emitted at a characteristic wavelength of 350 nm. The UV radiation leaving the cell passes through a 350 nm band pass filter before being measured by a photomultiplier. The electronic system translates the photomultiplier signal into concentration terms.

Chemiluminescence

Fluorescence can also take place as a result of a chemical reaction and, in this case, it is called chemiluminescence. In a chemiluminescence analyser, two gases are made to react together. The resultant energy emitted (hn) can be measured and, under carefully controlled conditions, it can be related to the concentrations of the reacting gases. With one gas present in excess, the chemiluminescence is proportional to the concentration of the other gas and, at low concentrations; the relationship conforms to the Beer-Lambert Law.

An example of chemiluminescence is the reaction between ozone and nitrogen dioxide. This reaction is also of environmental importance as it is a component of the photochemical production of ozone in the atmosphere. Analysers available for the determination of nitrogen dioxide use the following reaction:

$$NO + O_3 = NO_2 + O_2 + hv$$

As the chemiluminescence reaction is between nitric oxide and ozone, the sample is passed through a catalytic converter to change any nitrogen dioxide to nitric oxide. The sample then passes to the reaction chamber, which is under reduced pressure, where ozone is introduced. Excited nitric oxide molecules are formed, which results in chemiluminescence in the visible region of the spectrum (light) as they return to the ground state. The light passes through an appropriate bandwidth filter in front of the photomultiplier tube. The light intensity measured by the photomultiplier is converted electronically to give a direct readout of the total nitric oxide concentration including that resulting from the catalytic conversion of NO_2. A second reading can be obtained by bypassing the catalytic converter; this allows the concentration of nitric oxide, excluding that equivalent to the NO_2, to be obtained. The concentration of NO_2 is obtained from the difference between the two readings.

Flame ionisation detector measurement

Covalent organic carbon molecules are easily ionised in a hydrogen flame. An electric field applied across the ionised gas cloud causes a current to flow between the electrodes depending on the charged species present and the structure of the molecule. This current is approximately proportional to the mass flow rate of the carbon atoms and varies slightly for a given type of compound and the carbon number.

A cell contains the fuel and air burner and the sample is introduced into the flame together with the fuel gas. Orifices that have been calibrated to give the correct flow at an indicated gas pressure control the flow rates of fuel and combustion air. The burner itself forms one electrode of the measurement circuit, and the second electrode is situated in the optimum position to collect the maximum ionisation current. With a constant flow of sample gas containing hydrocarbons, a current is generated which can be suitably amplified to give a direct readout in parts per million (ppm) methane or propane equivalents (depending on whether propane or methane was used as the calibration gas).

All continuous hydrocarbon instruments have facilities for the permanent connection of cylinders of zero gas, which may be synthetic hydrocarbon free air or nitrogen, and a span or calibration gas. The calibration gas is usually a known concentration of methane in nitrogen. The mode of operation of the detector (zero, span or measure) is selected using a series of valves. The detector has a high sensitivity to many organic molecules and has little or no response to carbon dioxide and water. It is less sensitive to carbon compounds containing sulphur, oxygen and halogens, and other techniques may therefore be necessary when these compounds are of interest.

In more sophisticated instruments, it is possible to measure methane and non-methane hydrocarbons. Such instruments incorporate a catalytic converter, which oxidises all hydrocarbons except methane – thus making the two readouts possible.

The flame ionisation detector (FID) was originally developed as a detector for samples that had been subjected to chromatographic separation into their constituent gases. The response is linear over seven orders of magnitude, i.e. it can be used over a concentration range of about 10–12µg/ml to 10^{-5} g/ml of sample.

The output of the FID can be affected by a change in oxygen levels. Consequently, if the system is being used in a flare exhaust, it is normally necessary to overcome the ‘oxygen synergism’ effect by employing a hydrogen/helium fuel gas mixture. However, new FID systems are becoming available which overcome the synergism effect by other means.

Photoionisation detection

Photoionisation detection (PID) uses the ionising effect of a beam of photons to detect organic compounds in a sample of exhaust gas. Unlike flame ionisation detection (FID), this system does not need a fuel or a zeroing gas, as there is no residual voltage. Hence, PIDs are relatively portable.

PIDs will respond to most organic solvents, including chlorinated compounds. The response varies from compound to compound; thus, knowledge of the species present and their relative proportions is required for a quantitative analysis of emissions.

PIDs do not respond well to methane and therefore are typically not suitable for monitoring emissions from landfill gas flares as the main determinand is methane. However, they can be used for some of the other trace compounds found in landfill gas.

Response factors for VOCs

FIDs are normally calibrated in terms of methane and therefore the calculation of the result in terms of carbon is not subject to large errors if measuring methane or other saturated hydrocarbons. However, the FID’s response is different for different types of organic compound.

Its response is reduced if the organic compound is unsaturated or, for example, contains oxygen, nitrogen or chlorine. For solvents such as carbon disulphide, it has no response at all. Thus in the presence of these compounds, the calibration of the FID response directly to mg carbon per m^3 using methane does not accurately represent the emission of VOCs in terms of mg/m^3 carbon even though it may meet the requirements of the standard.

In the case of flare emissions, however, the complex composition of the exhaust gases makes it impractical to measure of the carbon content of the exhaust gases by any other technique. Where the particular VOC is known, a response factor for the FID can be determined by parallel measurements with a reference method such as trapping followed by gas chromatography. The response factor can then be applied to all measurements made using the FID.

More often than not, the emission is of a mixture of VOCs and, in such cases, it is necessary to determine a composite response factor. This approach is valid only if the relative proportions of the different compounds in the mixture remain constant. If the process changes so that a different mixture is produced or the proportions of the various solvents change, the composite response factor will change. Parallel measurements should reflect possible changes in the composition of the emission. Manufacturers of FID equipment may be able to provide details of the response factors of their instrument for different VOCs.

Photoionisation detectors may be more appropriate for some VOCs and particularly chlorinated compounds. However, PID has the same drawbacks as a FID if mixtures of compounds are involved; for example, it does not respond to saturated hydrocarbons and it has a variable response to other organic compounds.

Gas chromatography

This method separates the components in the sample gas by passing it through a column with a high surface to volume ratio. The surface can either be a solid or a liquid dispersed on a solid. The separation of the mixture depends on the selective absorption of the various components onto the column medium. The components are carried through the column by an inert carrier gas. A suitable detector for hydrocarbons, such as a FID, or an electron capture device for chlorinated species, is used after the column to measure the components. An unknown sample is characterised by comparison with known concentration of known standard components.

Mass spectrometry

The mass spectrometer has been used as a laboratory tool for many years. The molecules in the sample are ionised by bombardment with a high-energy electron beam or fast atom bombardment, and decomposition/ fragmentation often follows. The fragments are separated by use of a magnetic/electric field. The instrument displays the charge to mass ratio, which is used to identify components and their relative abundance. This provides a measure of concentration of the component in the sample.

Separating components initially using gas chromatography and then analysing the mass spectra mathematically is a powerful method of identifying an unknown sample.

Electrochemical cell

These analysers make use of two different techniques:

- allowing the emission to pass through a selective semi-permeable membrane into an electrolytic solution;
- measuring the current due to the oxidation/reduction of the dissolved gas at an electrode.

These processes generate electrons giving a current proportional to the concentration of the emission present.

UV/visible diode array

The analyser consists of a UV/visible spectrophotometer with a linear photodiode array detector, a diffraction grating and a deuterium lamp source. The system's modular design allows a variety of configurations to cope with different gas conditions such as high sample temperatures (e.g. 230°C). In addition, accurate analysis of low levels is possible using computing software.

Paramagnetic devices

Most gases are diamagnetic, i.e. they are repelled from the strongest part of a magnetic field. Oxygen, however, is paramagnetic and is attracted. Oxygen meters utilise the movement of oxygen within a sample due to the influence of magnetism. Oxides of nitrogen also exhibit paramagnetism, but to a lesser degree, and are present in much lower concentrations; their effect is therefore negligible.

Glossary

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 a substance collect on the surface of a solid or liquid.

Biodegradable waste
Any organic waste that is capable of undergoing anaerobic or aerobic decomposition, e.g. food, garden waste, paper and paperboard.

Chemiluminescence
The emission of light during a chemical reaction.

Deposition
Removal of particles or gases from a gas stream through surface adsorption, impaction, etc. In the context of the flare gas emissions, this includes dry deposition –- direct absorption or uptake on soil and vegetation. It may also include wet deposition – removal in rainfall passing through the plume as it disperses.

Design capacity
The maximum gas flow rate the flare is designed to burn at.

Dew point
Temperature at which the water vapour contained within a gas mixture will condense to form liquid water.

Dispersion
The tendency for components of the flare/stack emission to spread out from the path they would be expected to follow as a result of mechanical mixing and thermal kinetic energy. It causes dilution of the components in the free atmosphere.

Duct
An enclosed structure through which gases travel.

Electromotive force
Electromotive force (or voltage), the potential difference in charge between two points in an electrical field. The greater the voltage, the greater the flow of electrical current.

Enclosed flare
Flare in which combustion conditions are improved by enclosure of the flame in a shroud.

Flame photometry
Method for determining concentrations of trace constituents in which the sample is aspirated in a flame and trace constituents determined by their optical absorption/emission.

Flare
Structure designed to facilitate combustion of landfill gas under controlled conditions.

Flue
See Duct.

Fugitive gas
Proportion of emissions of landfill gas that are not accountable by known point sources on site. Typically, diffusive loss or leaching through the surface of a landfill generates fugitive losses.

Gravimetric
Method for determination of particle concentrations in air by direct weighing of the mass present in a collected sample.

Greenhouse gas
A gas when present in the atmosphere that contributes to global warming because of its radiative properties.

Homogeneous
A homogeneous mixture is uniformly and completely mixed.

Impinger
Sampling device in which the sample is collected directly into a liquid medium.

Incoloy
Incoloy alloy 825 is a nickel-iron-chromium alloy with additions of molybdenum, copper and titanium. This has high resistance to thermal stress and degradation up to 1,300°C

Ionise
To convert wholly or partly into ions.

Isokinetic sampling
Condition required when sampling particles at which the gas entering a sampling nozzle is at the same velocity and direction as the bulk flow of gas in the sample duct or stack. This condition minimises any sampling error that might arise due to inertial properties of the particles.

Landfill gas

All gases generated from the landfilled waste.

Paramagnetic

Property whereby substances develop magnetic properties when subject to a magnetic field.

Pitot tube

A probe designed to measure gas velocity in a moving gas stream with minimal disturbance of the flow.

Radicals

A term usually applied to species that have one or more free valences.

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 on the wall of the stack, duct or flue through which access to the emission gas can be gained.

Semi-volatile organic compounds

The volatility of a pure organic compound depends on its vapour pressure. The form in which a substance is present in air is dependent upon the vapour pressure. Typically, in air, an organic compound with a vapour pressure greater than 10–7 atmosphere will be gaseous. At a vapour pressure below 10–11 atmosphere, the compound is almost exclusively in the particle phase. In between these ranges, compounds can be present in both gaseous and particle phases depending upon temperature and pressure; these are referred to as semi volatile organic compounds.

Stack

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

Stoichiometric

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

Stratification

Condition that can develop in a flare. May occur across the sampling plane through poor mixing or incomplete combustion, whereby significant differences in the concentrations of components of the flare gases may occur without the sampling plane.

Tenax

Proprietary medium used for the adsorption and collection of organic compounds from sample gas streams or air. Subsequent desorption of the collected material allows determination in the laboratory.

Ultraviolet (UV)

A form of electromagnetic radiation, shorter in wavelength than visible light.

NMVOCs (Non-methane Volatile organic compound)

Organic compounds that can be measured in the gas phase at ambient temperature (VOCs) but excluding methane, the predominant VOC in landfill gas.

VOCs (Volatile organic compound)

Organic compounds that can be measured in the gas phase at ambient temperature

Intra-red (IR)

A form of electromagnetic radiation, longer in wavelength than visible light

UV fluorescence

Process by which some substances emit radiation when excited by radiation of shorter wavelength (UV). The emitted radiation can be used to determine concentrations of the particular substance.

Acronyms

BSI	British Standards Institution
CEMS	Continuous emission monitoring system
CEN	Comité Européen de Normalisation
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Defra	Department for Environment, Food and Rural Affairs
EN	Norm Européenne (European Standard)
FID	Flame ionisation detector
FTIR	Fourier transform infrared spectrometry
GC	Gas chromatography
GC-MS	Gas chromatography–mass spectrometry
HCl	Hydrogen chloride
HF	Hydrogen fluoride
HSE	Health and Safety Executive
IR	Infra-red
ISO	International Organisation for Standardization
I-TEQ	International Toxicity Equivalent
MCERTS	Environment Agency's Monitoring Certification Scheme
MS	Mass spectrometry
NDIR	Non-dispersive infra-red spectrometry
NDUV	Non-dispersive ultraviolet spectrometry
Nm	Nanometer (10–9 of a metre)
NMVOC	Non-methane volatile organic compound
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides (sum of NO and NO_2)
PCDDs	Polychlorinated dibenzo-p-dioxins
PCDFs	Polychlorinated dibenzo furans
PID	Photoionisation detector
PM_{10}	Particulate matter of 10 microns (10^{-6} of a metre) or less in diameter
ppb	Part per billion (1 ppb is 1 volume of gas in 10^9 volumes of air)
PPE	Personal protection equipment
ppm	Part per million (1 ppm is 1 volume of gas in 10^6 volumes of air)
PTFE	Polytetrafluoroethylene
PUF	Polyurethane foam
SO_2	Sulphur dioxide
STA	Source Testing Association
STP	Standard temperature and pressure (0^{o}C and 1 atmosphere pressure)
UK	United Kingdom
UKAS	United Kingdom Accreditation Service
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
VDI	Verein Deutscher Ingenieure (German national standards body)
VOCs	Volatile organic compounds

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