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Guidance on Landfill Gas Flaring

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Statement of use

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The Environment Agency's National Landfill Gas Task & Finish Group commissioned the guidance, which is issued with the approval of the Environment Agency's National Waste Group and SEPA.

This revised document replaces Version 2.0, which was released for internal and external consultation, and has been amended in light of comments received. The guidance will be subject to further review as appropriate in light of future technical developments that may affect the guidance contained herein. A monitoring protocol for enclosed landfill gas flares is in preparation.

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Contents

Preface

Techniques for the combustion of landfill gas have undergone many changes over the last 15 years. From the initial pipe-flares of the early 1980s where vertical tubes were simply forced into the surface of a site and the emitting landfill gas lit with a burning oily rag, the technology employed has advanced significantly.

Techniques for the combustion of landfill gas have undergone many changes over the last 15 years. From the initial pipe-flares of the early 1980s where vertical tubes were simply forced into the surface of a site and the emitting landfill gas lit with a burning oily rag, the technology employed has advanced significantly.

In many ways the combustion of landfill gas may be seen as leading waste-gas flaring technology in other industries. This is largely because of the extremely difficult nature of landfill gas. As well as containing significant percentages of carbon dioxide and methane, landfill gas has been found to contain as many as 557 trace components.[1]

Higher standards demanded for the landfilling of wastes, including the need to control emissions rather than just migration, have added impetus for the flaring of landfill gas, where undertaken, to be carried out in an acceptable manner.

Key information contained in the appendices

The appendices contain information that may be viewed in isolation.

Topics covered include:

1 Flare component selection criteria
2 Flare maintenance checklist
3 Operational effectiveness checklist
4 Sample calculations
5 Flare siting criteria
6 Glossary and abbreviations

It is a publicly stated aim of the Government to reduce greenhouse gas emissions in the United Kingdom. Based upon a 1994 estimate, landfill gas was recognised to account for approximately 20% of total UK methane emissions. The general trend in this contribution however is reducing with the increased use of enclosed flares, greater landfill gas collection efficiency and an increased number of landfill gas utilisation schemes, particularly at modern engineered landfills. Large-scale passive venting of landfill gas is no longer considered an acceptable practice. To achieve pollution control and global atmosphere objectives relative to gas production, each landfill site must achieve the highest sustainable position outlined on the hierarchy in Section 1.4 during all phases of a site's operation and post-closure phase.

1 Environment Agency (2002) Investigation of the composition, emissions and effects of trace components in landfill gas. R&D Project P1-438.

Executive summary

Introduction

Waste Management Paper 27 *Landfill Gas* (WMP 27)[2] advises that landfill gas should be controlled, preferably by collection and burning in flares or energy recovery plant. The purpose of flaring is to dispose of the flammable constituents, particularly methane, safely and to control odour nuisance, health risks and adverse environmental impacts.

Consideration needs to be given to the environmental and health impacts associated with the combustion products resulting from flaring. The source document[3] for these guidance notes was commissioned to provide advice to regulators and others on landfill gas flaring, to recommend best practice for the design and operation of flares, and for controlling and monitoring their emissions.

A review of WMP 27 has been commissioned by the Agency's National Landfill Gas Group with the objective of producing a comprehensive guidance document on landfill gas management.

The R&D, upon which this guidance has been based, was undertaken by staff of AEA Technology, mainly in the National Environmental Technology Centre (NETCEN), with support from the National Physical Laboratory (NPL).[4]

Regulatory framework

The introduction of the Environmental Protection Act (1990), the Framework Directive on Waste (75/442/EEC as amended) and the Landfill Directive (1999/31/EC) extended the scope of waste regulation controls to a wider environment than before. Waste Management Paper 4 (WMP 4) *Licensing of Waste Management Facilities*[5] gives statutory guidance about the recovery of landfill gas in order to protect the global environment.

The Environment Agency and SEPA now wish to provide further guidance to regulators and others on landfill gas flaring and, with this objective, has prepared these guidance notes. The main emphasis is to provide guidelines for landfill gas flare operation and monitoring, based on best practice, taking account of relevant EU Directives. The EU Landfill Directive (1999/31/EC) came into force on 16 July 1999 and is having significant impacts on waste management in Europe. The following requirements are included:

- It provides targets for the reduction of biodegradable municipal waste disposed in landfill.
- It bans certain waste deposits in landfill.
- Most waste must be pre-treated prior to landfilling.
- It classifies landfills into those for hazardous waste, non-hazardous waste or inert waste.

The Landfill Directive will eventually result in a reduction in the volume of landfill gas generated from municipal waste. Changing waste composition may also result in significant changes in the composition of landfill gas.

Annex 1 of the Landfill Directive provides requirements for the operation of landfills, including landfill gas control requirements:

1. Appropriate measures shall be taken in order to control the accumulation and migration of landfill gas.
2. Landfill gas shall be collected from all landfills receiving biodegradable waste and the landfill gas must be treated and used. If the gas collected cannot be used to produce energy, it must be flared.
3. The collection, treatment and use of landfill gas shall be carried out in a manner which minimises damage to or deterioration of the environment and risk to human health.

Article 2 of the Landfill Directive defines landfill gas as *all gases generated from landfilled waste*. This definition therefore encompasses gas not only generated by the decomposition of biodegradable waste but also that generated by certain wastes in hazardous landfills such as VOCs from contaminated soils.

The Landfill Directive is implemented in England and Wales through the Pollution Prevention and Control (England and Wales) Regulations 2000 (SI 2000/1973) and the Landfill Regulations (England and Wales) 2002.[6] Separate systems will be introduced in Scotland and Northern Ireland.

2 Department of the Environment (1991) *Waste Management Paper 27* (WMP 27) *Landfill Gas*, 2nd Edition, 1991. The Environment Agency's National Landfill Gas Group has commissioned a review of WMP 27 under the Waste Regulation & Management R&D Programme to produce a comprehensive guidance document on the management of landfill gas.

3 See Section 2.4 for a definition of "open" flares.

4 *Guidance on the Emissions from Different Types of Landfill Gas Flares*, Environment Agency R&D Report CWM 142/96A, 1997. Available from the Environment Agency R&D Dissemination Centre, c/o WRc, Frankland Road, Swindon, Wiltshire SN5 8YF.

5 Under revision.

6 Statutory Instrument 2002 No.1559.

Objectives

The specific objectives of the guidance notes are as follows:

- to provide guidance for the review and evaluation of techniques and technologies that are available and are, or could be, used to control landfill gas flare emissions;
- to provide guidance for the review and evaluation of existing techniques for the measurement of the emissions from landfill gas flares and similar processes;
- to recommend best practice with regard to the setting up of landfill gas flare systems, operating conditions and monitoring;
- to provide the basic framework for guidance to control the output from landfill gas flares.

Main requirements

Existing waste management licences for landfill sites should be modified such that:

1. No more open[7] flares should be installed on UK landfills except for test and emergency purposes, and then only for limited periods of not longer than six months. Open flares should not be used as contingency flares associated with power generation or reticulation.
2. Open flares shall be replaced with enclosed flares (or techniques offering equivalent performance) by 31 December 2003 or when the site is permitted under PPC, if this is later.
3. 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 whatever the landfill gas composition and operational throughput. This is an indicative performance standard that is required to meet the emission standard. Alternative performance standards may be deemed more appropriate if compliance with the emission standard is suitably demonstrated.
4. To ensure that flare systems are operating correctly, they should not exceed the following emission concentrations when referred to normal temperature and pressure (NTP = 0°C and 1,013 mbar) and 3% oxygen:

   carbon monoxide (CO) – 50 mg/Nm^3

   nitrogen oxides (NO_x) – 150 mg/Nm^3

   unburned hydrocarbons – 10 mg/Nm^3
5. Inlet gas concentrations should be analysed annually to determine trace gases. Guidance is given below as to the level of monitoring that is recommended and the acceptable methods that may be employed. Easily accessible, safe and functional monitoring/sampling points should be retrofitted to enclosed flares as appropriate in instances where they are currently absent. This shall include a minimum of one emission representative monitoring location to be installed by 30 June 2003. All monitoring/sampling points should be provided in accordance with relevant health and safety legislation.

Recommended monitoring regimes to be applied to enclosed flares

Monitoring should be carried out as summarised below:

Level	Inputs (inlet gas)	Outputs
1st	CH_4, CO_2, O_2 and gas flow rate	Temperature
2nd	As above	As above, plus bulk components (O_2, CO, NO_x, CO_2, THC), trace components including HCl, HF and SO_2 and retention time

- First level monitoring should be carried out on a continuous and logged basis with telemetry since it provides the basic information needed for controlling the flare and demonstrates the degree of operation. The data obtained also allow the gas field to be balanced and controlled.
- Second level monitoring is necessary periodically or when there is some significant change in the composition of the landfill gas or method of operation of the flare. This may occur, for example, when a new phase of a site is brought on-line or the plant is newly commissioned or re-commissioned after a change of location. It provides more information about the completeness of combustion, the main combustion products and the major emissions. This should typically be carried out annually, dependent on risk and provided that the plant is maintained according to the manufacturer's recommendations. Second level monitoring is targeted at good combustion indicators of

7 See Section 2.4 for a definition of "open" flares.

potentially hazardous components in flare emissions. Such frequency and selection of trace species to be included in the emissions monitoring would also be subject to the findings of the environmental impact assessment from requirement No. 7.

A monitoring protocol for enclosed flares is being developed under a separate R&D project commissioned by the Environment Agency and in partnership with industry-sponsored research. Upon completion, it is expected that the protocol will succeed the recommended monitoring regimes contained in this guidance document.

6. Enclosed flare design should:
   - permit a homogeneous temperature distribution across the combustion chamber;
   - include lining with refractory material on the interior;
   - allow the flame to be contained within it;
   - allow the flare to be maintained in an effective condition.
7. Operators of landfill sites should undertake, or commission, an environmental assessment of the emissions from existing and proposed flares which:
   - should use either measured or reported emissions data, flow rate data and local meteorological data;
   - address the impacts of the dispersed emissions in the vicinity;
   - determine whether flaring is effectively controlling impacts of dispersed emissions;
   - addresses planning requirements;
   - be approved in writing by the Environment Agency or SEPA.
8. Flares should be positioned and sized so that potential health and environmental impacts are minimised.
9. Flares should be maintained in accordance with the manufacturer's recommendations. Full records should be available for inspection.
10. Each flare system shall have a designated flare manager who is formally identified to the Environment Agency or SEPA. All results obtained by flare system managers should be the subject of formal interpretation. This interpretation and a copy of the flare maintenance log must accompany results and reports when communicated to regulatory officers, on at least a monthly basis.
11. All landfill sites must have a risk-proportionate emergency response plan to be implemented within a site-specific response time following plant failure detection.

Structure of the guidance notes

These guidance notes provide basic information designed to assist regulatory officers in evaluating both existing and proposed flare systems suitable for combusting landfill gas on landfill sites. The guidance notes are structured to take readers through the logical build-up of know-how required to understand the principles involved in landfill gas combustion.

A selection of photographs from a range of flare manufacturers have been included throughout the document for illustrative purposes. These are not intended to favour or promote particular flare systems.

The guidance notes are structured in six chapters and are supported by references and six appendices. The appendices, including a glossary of terms and acronyms, are designed to provide quick access to key data and methods. The content of each chapter is summarised briefly in the following paragraphs.

Chapter 1 Background

Chapter 1 introduces some of the key concepts involved with landfill gas, including its production and composition. In order to facilitate an appreciation of the problem of combustion, it is necessary to have an understanding of the parameters that have led to the adoption by British industry, and the world landfill gas industry at large, of certain methods and technologies.

Chapter 2 Combustion basics

Chapter 2 is designed to provide the basics of combustion science and engineering. The objective is to provide an adequate basis from which to review the various technologies employed in landfill gas combustion.

Chapter 3 Environmental impacts

A working understanding of the environmental issues surrounding the use of flares for the combustion of landfill gas is required to assess specific applications. This chapter summarises the range of environmental impacts that are currently viewed as relevant to an assessment of landfill gas flaring. This covers such matters as fire and explosion as well as issues relating to local, regional and global issues.

Chapter 4 Operational requirements

Chapter 4 introduces the requirements for flare systems operating in the field. As with other elements of the guidance notes, it is not intended to be comprehensive with regard to detail. By addressing the important elements of operational flares, it will assist regulatory officers to assess installations, both planned and extant.

Chapter 5 Instrumentation

Chapter 5 is designed to provide guidance on the type of monitoring that may be undertaken and the equipment that may be employed. Owing to the extensive range of the latter, no attempt is made to provide an in-depth selection guide. Recommendations with regard to monitoring regimes are also provided.

Chapter 6 Emission standards

Prior to this document, there were no standards in the UK for landfill gas flares. Now part of the Environment Agency, HMIP provided some guidance on flare systems in the petrochemical industries, and there are other regulations that have to be taken into account. These, together with landfill gas flare emission standards in other countries, are briefly described.

Appendices

The appendices contain information that may be viewed in isolation. Topics covered include:

1. Flare selection criteria
2. Typical flare maintenance checklist
3. Site visit checklist
4. Sample combustion calculations
5. Flare siting criteria
6. Glossary of terms

1

Background

1.1 Introduction

The technology involved in the collection, combustion and utilisation of landfill gas in the United Kingdom is at a comparatively advanced stage. In many ways the United Kingdom leads the world in the scale of application of such technologies. More recently, research has commenced using low calorific burners and reticulation techniques which partition oxygen and carbon dioxide from the methane.

Landfill gas

- Is mainly composed of methane and carbon dioxide
- Has many small amounts of trace elements with potential health effects
- Is potentially explosive
- Is a potent greenhouse gas
- Can be used as a fuel
- Is legally considered a waste
- Is an asphyxiant

1.2 Landfill gas

Landfill gas is an end-product of the decomposition of biodegradable wastes in a landfill site and is itself legally considered to be a waste. The composition of the gas (**Figure 1.1**) varies according to the type of waste and the time that has elapsed since deposition within the site.

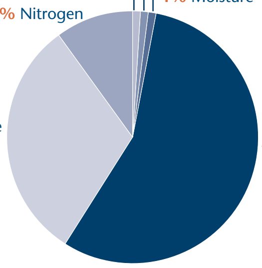

Figure 1.1 Typical gas composition at an engineered landfill site

Typically, the gas will have the following characteristics:

- The amount and composition of the landfill gas extracted from a landfill is variable[8] over both the long term and short term.
- In a site where entrapped air has been displaced, it is typically a mixture of up to 65% methane (CH_4) and 35% carbon dioxide (CO_2) by volume.
- It includes minor amounts of a range of organic gases and vapours, some of which may be malodorous, potentially harmful to health, and may produce corrosive compounds following combustion.
- The methane content is flammable, forming potentially explosive mixtures in certain conditions, resulting in concern about its uncontrolled migration and release.
- Methane has a high calorific value, and hence there is much current interest in burning landfill gas for power generation and process heating.
- The purpose of landfill gas flaring is to dispose of the flammable constituents safely and to control odour nuisance, health risks and adverse environmental impacts.
- Consideration needs to be given to the efficiency of destruction achieved during flaring and, hence, to the environmental impact and possible health risks associated with the combustion products resulting from flaring with systems of differing designs.

8 Numerous factors are influential: details are provided in Chapters 3 and 4 of WMP 27.

- Some components of landfill gas are also potent greenhouse gases, and recent studies have attributed about 20% of methane emissions in the UK and world-wide to landfills,[9] with 46% of man-made methane emissions in the UK being derived from landfills in 1996.[10]
- The global warming potential (GWP) of methane is between 21 and 62 (cf. CO2 has GWP of 1), depending on the period considered.[11]

Several factors cause the bulk composition to depart from the ideal:

- The wastes in a landfill are heterogeneous in composition, and they are deposited over an extensive period; hence, all the stages of decomposition can be present in a landfill at any given time.
- The rates of waste degradation vary because of local (site-specific) variations in conditions such as water content, temperature, leachate and waste compositions; again, this can result in all the stages of a landfill's decomposition cycle being present at any one time.
- Gas collection may draw in air that dilutes the gas generated within the landfill as well as facilitating some of the oxygen in this air to be consumed in the oxidation of materials within the landfill.
- The drawing in of air to a landfill may inhibit anaerobic activity, as well as lead to combustion within a landfill, and thereby affect the future generation and composition of landfill gas.
- Variations in barometric pressure and other atmospheric factors (e.g. precipitation) also influence the extent to which air is drawn into a landfill and the composition of the extracted gas.
- Landfill gas typically contains between 50 and 200 minor components at trace level concentrations. The compositional profiles of the gases generated at different sites tend to differ. The total number of minor constituents that can be found in landfill gas has been estimated as about 350, the vast majority being organic compounds. In total, these minor components can comprise 0.5% or more of the landfill gas emissions by weight. The USEPA advocates using a total non-methane organic compounds (NMOC) concentration of 8,000 ppm (by volume) as a default input to their Landfill Air Emissions Estimations Model. Of the inorganic constituents, hydrogen sulphide can be present at significant levels, and trace quantities of ammonia, mercury and volatile metallic compounds (as organometallic compounds or perhaps as metal hydrides) may also be present.

Minor constituents occur in landfill gas as the result of:

- their presence in, and subsequent volatilisation from, the wastes;
- their generation as by-products of waste degradation, and subsequent volatilisation.

The main factors that influence the minor component composition profiles are:

- the age of the landfill;
- the rate of degradation of the biodegradable matter;
- the range of wastes disposed of – whether, for example, they include aerosol products containing halogenated compounds.

1.3 Rates of landfill gas production

The quantity of landfill gas extracted from a landfill will also vary with time and between sites for the same reasons that account for compositional differences. Typically, extraction rates may vary from 25 to 100 m^3/h for small sites of 100,000 m^3 municipal solid waste (MSW) capacity up to 250 to 10,000 m^3/h or more for large sites with capacities of 1–10 million m^3.

The quality of the capping material will significantly influence the degree to which landfill gas escapes through the surface of the site to atmosphere and the quantities of water that may enter the body of the waste. For additional information, reference may be made to Environment Agency R&D Project P1-283, *A Framework to Model Health and Environmental Risks from Landfill Gas* – HELGA (R&D Technical Report P271).

As a landfill ages further and the intensity of anaerobic activity subsides, so the rate of gas generation will decline. It is expected that the rate of gas extraction will decrease proportionately, though relatively greater quantities of air might be drawn in. Landfill gas production may continue for several hundreds of years. Leachate recirculation can enhance landfill gas production, typically by a factor of 2, but too much moisture within the waste can also decrease gas production. When waste inputs and monitoring of a site indicate that a sufficient quantity and quality of landfill gas exist to sustain an enclosed flare, the landfill operator is required to carry out a representative pumping trial to assess the most appropriate landfill gas control option.

9 Williams, A. (Ed.) (1994) *Methane Emissions*. Report No. 28 Watt Committee on Energy.

10 Brown, K. et al. (1999) *Methane Emissions from UK Landfills*. Final report for the Department of the Environment, Transport and the Regions, March 1999. Report No. AEAT-5217.

11 Environment Agency (1999) *Methane Emissions from Different Landfill Categories*. R&D Technical Report P233a (CWM 141/97), Published July 1999.

1.4 Landfill gas management options

To achieve pollution control and global atmosphere objectives relative to gas production, each landfill site must achieve the highest sustainable position outlined on the hierarchy in **Figure 1.2** during all phases of a site's operation and post-closure phase.

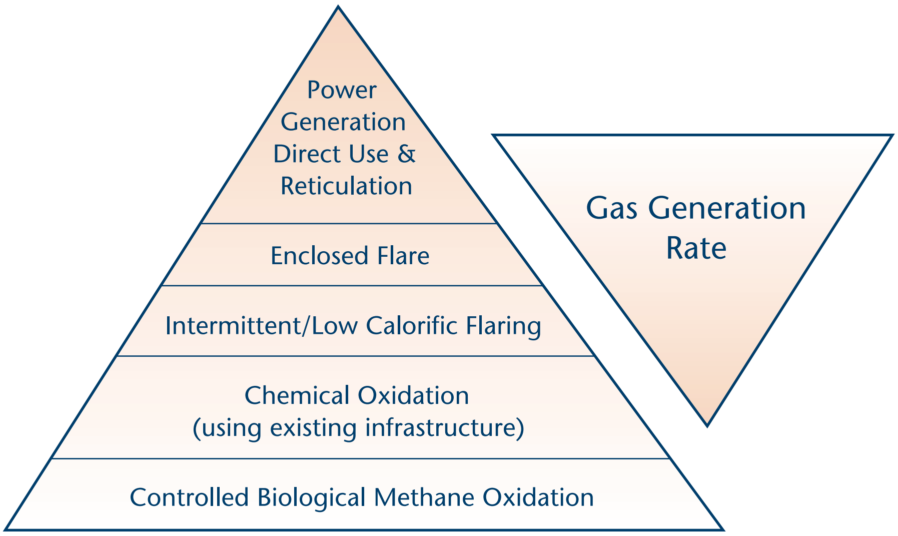

Figure 1.2 General relationship for landfill gas management options

In the landfill gas control hierarchy, gas collection with energy recovery is preferred to enclosed flaring. Controlled chemical or biological methane oxidation is at the base of the hierarchy and is appropriate for managing landfill gas in instances of lower gas generation when a flare cannot be sustained. Field trials of methane oxidation are being developed as part of the Environment Agency's Waste Regulation & Management R&D Programme.

2

Combustion basics

2.1 Introduction

Whilst the burning of gas may be seen as an easily achieved condition, the use of active gas extraction methods in a safe and environmentally sound manner requires a thorough understanding of the principles of combustion. The combustion of landfill gas is particularly difficult and requires that many aspects of the combustion process are properly accounted for and controlled. The three most important factors affecting combustion and emission control are time, temperature and turbulence (**Figure 2.1**).

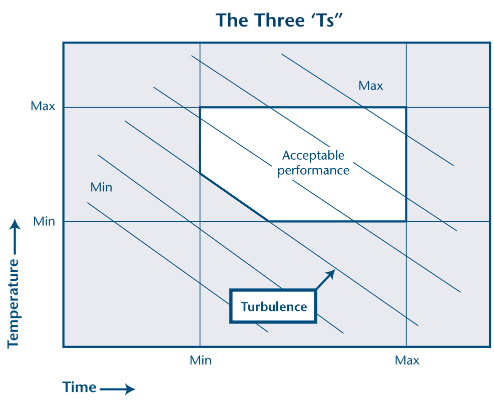

Figure 2.1 The three 'T's: time, temperature and turbulence

The three 'T's relationship for a non-specific burner is as follows. To maintain performance:

- 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;

and *vice versa*.

12 Department of the Environment (1991) Waste Management Paper 27 (WMP 27) Landfill Gas, 2nd Edition.

13 Passive venting is now being discouraged (WMP 4 and WMP 26B).

2.2 Gas control systems

The majority of landfill gas control schemes in the UK have been installed with the primary objective of preventing potentially explosive situations associated with subsurface gas migration. A number of systems have also been introduced to minimise odour pollution and vegetation stress. The objective of control systems is to ensure that landfill gas does not pose a risk to human health or pollution to the environment.[12]

An effective control system is defined tacitly in WMP 27 as one where, in any subsurface probe or borehole outside the area of influence of the gas control system (or outside the area of wastes, if greater):

- the concentration of flammable gas from the landfill gas is less than 1% by volume;
- the concentration of CO_2 from landfill gas is less than 1.5% by volume.

It is accepted practice to determine these figures with reference to established background levels, dependent on local geology.

A landfill gas control system is usually defined in waste management licences. Gas control systems are generally tailored to meet the specific needs of a site and, therefore, vary widely in design, management and operational philosophy. Options for controlling the local landfill gas include:

- controlled venting to air;[13]
- pumped extraction and flaring;
- extraction and utilisation in an energy recovery scheme, and flaring the surplus gas;
- biological or catalytic methane oxidation.

Where there are sufficient quantities of landfill gas, controlled venting is no longer acceptable practice because of the global impact of methane. In practice, it remains the case that many sites only have controlled venting or no control. Where flares are provided, they should be seen as a component of a 'system' for controlling landfill gas, and not in isolation. This matter is considered in more detail in Waste Management Papers 26A, 26B and 27.

Figure 2.2 Typical landfill gas wellhead

All landfill gas combustion plant and associated infrastructure must be maintained according to the manufacturer's specification by suitably qualified and trained personnel.

2.3 Gas collection infrastructure

All landfill gas transmission pipework should be pressure-tested to demonstrate its integrity. Retrospectively installed extraction wells are typically installed to a depth of 70% of the total waste depth, to allow for landfill settlement and to minimise the risk to landfill liners. All drilling should be undertaken in accordance with British Drillers Association guidance and relevant health and safety legislation.

Figure 2.3 Typical landfill gas pipework manifold arrangement, used to control flow

2.4 Types of flare

The nomenclature used by the waste management industry to denote the types of flare in use is frequently of a descriptive or historical nature, and can be confusing. Terms such as open, candle, elevated, diffusion, pre-aerated, conventional, enclosed, shrouded, muffled and ground are all used; it is often unclear whether these terms are used to differentiate between flares, or whether they are interchangeable. This report adopts the terms "open" and "enclosed" to denote two main categories of flare.

2.4.1 Open flares

Figure 2.4 A typical open flare

Open flares burn landfill gas as open flames, though a windshield is normally fitted. If provided, combustion control is rudimentary. Open flares are also known as elevated flares.

2.4.2 Enclosed flares

Figure 2.5 A typical enclosed flare

Enclosed flares burn landfill gas in a vertical, cylindrical or rectilinear enclosure. Some means of combustion control is normally provided, and the enclosure is often insulated to reduce heat losses and allow operation at higher temperatures. Enclosed flares are also known as ground flares.

2.4.3 Guidelines

Until now, there have been no specific guidelines for controlling emissions from landfill gas flares in the UK, with the exception of recommendations given in WMP 27 on the minimum combustion temperature (850°C), or planning and licence conditions imposed locally. As a result, flare designs range from simple off-the-shelf units to high-technology purpose-designed systems.

Whilst the combustion of landfill gas reduces the risks of uncontrolled landfill gas emission and explosion, the potential health and environmental impacts of emissions from flares (and from other combustion processes used for landfill gas utilisation) have to be taken into account. The reader is referred to Chapter 3 of the source document for further information.[14]

2.5 Combustion reactions

Combustion involves the reaction of a fuel and an oxidant, with the release of heat and visible radiation. Most fuels are principally composed of carbon (C) and hydrogen (H_2), the common exceptions being those with only one of these elements, in particular carbon monoxide (CO) and hydrogen itself. The oxidant is any substance that provides a source of oxygen (O_2) for the reaction. The ultimate products of combustion are carbon dioxide (CO_2) and water (H_2O). CO is the primary product of carbon oxidation, and it reacts with oxygen to produce CO_2, with the release of more heat. The presence of CO in the flue gases is indicative of incomplete combustion.

Landfill gas contains the hydrocarbon CH_4 and perhaps some small quantities of H_2. The main combustion reactions are:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{heat}$$

and

$$2H_2 + O_2 \rightarrow 2H_2O + \text{heat}$$

The calorific value is the heat liberated by the complete combustion of a unit quantity of fuel. The net values for CH_4 and H_2 are respectively 33.95 and 10.22 MJ/Nm^3.

2.6 Combustion air

In order to oxidise the fuel, it has to be mixed with atmospheric oxygen. Too little air, and combustion is incomplete; too much air, and the mixture will not burn at a sufficiently high temperature and combustion can be incomplete. The stoichiometric ratio is the theoretical minimum number of units of air required to burn completely a unit quantity of fuel. The values for CH_4 and H_2 are respectively 9.56 and 2.38 by volume. In practice, the air and fuel cannot be mixed perfectly. Excess air, being that air over and above the air required for theoretically complete combustion, is required to ensure that combustion is complete.

Figure 2.6 Example of a forced air enclosed flare

When gas is collected in a landfill, pumping may entrain air. As explained previously, bacteria in the landfill may use some of the oxygen in the air, but there may still be a significant amount of oxygen in the gas. This oxygen should be taken into account when estimating the required air supply to a flare.[15] For additional information on air supply, see Section 4.8.4 of this document and Section 2.5.5 of the source document.[16]

2.7 Burnout

Burnout, or complete combustion, may not be achieved in flares operating outside their design conditions, and partially burned fuel may show up as carbon (smoke, soot, particulates) and/or intermediate reaction products such as CO. Incomplete combustion may result from:

- at lack of O_2 caused by poor mixing of fuel and air or an overall air deficiency;
- at cooling of the flame by, for example, radiation or its impingement on cold surfaces;[17]
- at inadequate time at high temperature for the complete oxidation of carbon – the limiting factor for gases being the oxidation of CO to CO_2.

These deficiencies can be overcome by good design to allow their control. Open flares are not adequately controllable and lose a significant amount of heat by radiation and convection. Consequently, combustion is not usually as efficient as that from enclosed flares.

Temperature and retention time are two other important factors in the destruction of some of the minor species formed in the combustion process and will be discussed later.

14 *Guidance on the Emissions from Different Types of Landfill Gas Flares*, Environment Agency R&D Report CWM 142/96A, 1997.

15 See Appendix 4.

16 *Guidance on the Emissions from Different Types of Landfill Gas Flares*, Environment Agency R&D Report CWM 142/96A, 1997.

17 The same effect may be caused by large amounts of excess air.

Figure 2.7 Automatically controlled combustion air louvres (often located inside the flare)

2.8 Flammability and flame speed

Not all mixtures of air and landfill gas are flammable. The range of mixtures that burn is defined by upper and lower flammability limits, which are characteristic of individual gases. Flammability is particularly affected by CO_2 and N_2.

Flame speed (or burning velocity) can be defined as the speed, normal to the direction of the mixture flow, at which the flame front travels through a fuel gas/air mixture. It is greatest in the centre of the flammability range and decreases to zero at both limits. For efficient operation, burners should operate in the centre of the range.

If the mixing of landfill gas and air is non-uniform, then the flame speed may vary throughout the flame and the flame may become unstable or lead to incomplete combustion.

The mixing process can be improved by:

- increasing the exit velocity, and hence the turbulence, of the gas from the burner;
- discharging the gas through a number of orifices, rather than one (depending on the size of the combustion chamber and calorific value of the gas);
- increasing the velocity, and hence the turbulence, of the combustion air added to the burner.

2.9 Flame stability

In addition to producing a flammable mixture, the flame must be stable. The flame front is stabilised where the speed at which the mixture leaves the burner equals the flame speed (the speed at which the flame front travels through the mixture in the opposite direction). If the mixture speed is too low, then the flame may "flash-back"; and if too high, then the flame may "blow-off".

Good burner design can help to maintain flame stability. There are essentially two different types of burner: diffusion and pre-mixed.

- When the gas/air mixing takes place outside the gas pipe or nozzle, a diffusion flame is formed. This has the advantage that the flame cannot flash-back into the gas supply.
- Pre-mixed burners achieve more rapid contact of gas and air by mixing both together prior to the burner. In pre-mixed burners (often referred to as pre-aerated), up to 50% of the stoichiometric air requirement may be entrained in the gas flow. This mixture is then burned at the burner head or port(s), where additional (secondary) air mixes to complete combustion. Pre-mixed burners are very versatile, but precautions have to be taken to prevent flash-back. This usually involves fitting flame arrestors prior to the burner.

2.10 Draught

The buoyancy effect of hot gases is used to advantage in combustion systems by adding a chimney at the chamber exit. The hot gases rise up the chimney, inducing a negative pressure in the combustion chamber. The resulting pressure differential is used to draw in the air required for combustion in the so-called "natural draught burner". The advantage of this system is that no air-moving equipment is required. There may be a disadvantage with this approach if the height required (often in excess of six metres) causes difficulty with local planning requirements.

2.11 Maximum combustion temperatures

The temperature of the combustion gases depends upon:

- the landfill gas composition, in particular the concentrations of the flammable gases methane and hydrogen;
- the completeness of combustion;
- the quantity of air supplied;
- the convective and radiative heat losses.

The maximum flame temperature T_{AF} (K) may be calculated by assuming that all the fuel burns completely and that there are no heat losses. Then a simple energy balance gives:

$$\dot{m}_F H_F = \dot{m} C_p (T_{AF} - T_0)$$

where

$\dot{m}_F$ mass flow rate of the fuel, predominantly methane (kg/s),

$\dot{m}$ the total mass of the landfill gas and combustion air (kg/s),

H_F the calorific value of the fuel (kJ/kg),

C_p the specific heat of the combustion products (kJ/kg K),

T_{AF} maximum flame temperature (K),

T_0 ambient air temperature (K).

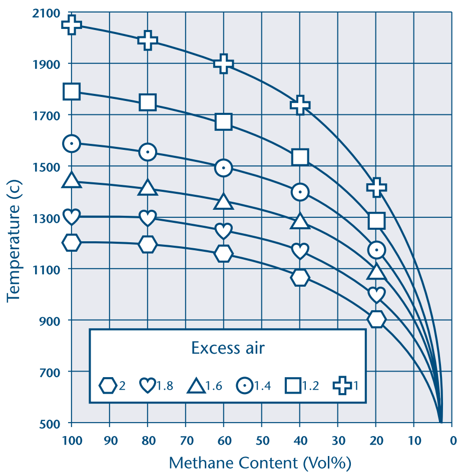

Figure 2.8 Flame temperature versus methane content

To simplify the calculation, it is here assumed that both the landfill gas and combustion air are at ambient temperature[18] and that the specific heat of the combustion products is independent of temperature.

The variation of the maximum achievable temperature with air supply and landfill gas composition, assuming it comprises only methane and carbon dioxide, is shown in **Figure 2.8**. The maximum temperature falls as the methane content decreases and also as the excess air increases. The latter is simply the result of there being more air to be heated from ambient temperature.

The ratio of CH_4:CO_2 in landfill gas typically lies between 50:50 and 65:35 v/v in practice,[19] a much narrower range than covered in **Figure 2.8**. Also, the optimum excess air supply for efficient combustion in an enclosed flare is generally considered to lie within the range 150–250%. Within this limited range of operation, the air supply is the main factor that affects the maximum gas temperature achievable.

Heat losses, even in enclosed flares, significantly reduce the temperature achieved in practice. In enclosed flares, the enclosure should be:

- sufficient to contain the flame and preferably lined with refractory material to promote radiant heat transfer and so ensure near-complete combustion;
- insulated to reduce outer wall temperatures and heat losses from it – this latter may be achieved by an inner refractory lining.

In an open flare the presence of cool zones at the flame's periphery results in incomplete combustion and, therefore, less heat release than is theoretically possible; radiative and convective heat losses are also substantial and uncontrollable.

Figure 2.9 The top of an enclosed flare showing the refractory lining

2.12 Retention time

By ensuring that combustion gases are held at the design temperature for a minimum duration, it is possible to ensure that near-complete burnout will occur.[20]

The minimum recommended retention time is 0.3 seconds at a minimum temperature of 1,000°C. This is an indicative standard that is likely to achieve the required emission standard. However, alternative criteria offering equivalent performance may also be acceptable – for example, a longer retention time combined with lower temperature. A simplified example retention time calculation is provided in Appendix 4.

Chapter 5 of the source document provides greater detail with regard to combustion principles.[21]

18 In some combustion plant, the hot flue gas is used to pre-heat the combustion air, and this needs to be taken into account in the energy balance.

19 Absorption of carbon dioxide into water or into soil may increase the relative methane content at some sites. At others, significant quantities of air may be drawn into the landfill and promote aerobic degradation processes in zones within the fill. The gas generated at such sites will tend to have a relatively lower methane and higher carbon dioxide content.

20 See Section 4.8.2 and Appendix 4.

21 *Guidance on the Emissions from Different Types of Landfill Gas Flares.* Environment Agency R&D Technical Report CWM 142/96A, 1997.

Environmental impact

3.1 Introduction

In order to determine how flares should be located on a landfill site, it is necessary to have an understanding of the environmental impact that the flare will have upon its surroundings.

One of the primary roles of a landfill gas flare is to protect people and the environment from landfill gas emissions. This brief review of the potential health and environmental impacts of landfill gas and the flaring of landfill gas, therefore, addresses two main issues:

- the range of potential environmental impacts;
- the conditions that need to be met for the emissions from landfill gas flaring to be acceptable.

3.2 Range of potential impacts

Many constituents of landfill gas are hazardous and pose potentially significant risks to human health and the environment. Some other risk factors result from the process of flaring.

For an in-depth review of health effects and odour threshold data, the reader should refer to Chapter 3 of the source documentation[22] and Appendix 6 of this document.

The damage that can be caused by uncontrolled migration of landfill gas is the main reason why landfill gas recovery and flaring are required, and should not be forgotten. Hence the minimum requirement of a landfill gas flare is that the flammable gases are burned and, in consequence, that the risk of their explosion is eliminated and environmental impact of combustion reduced.

Table 3.1 Potential health and environmental impacts

Scale	Potential impact	Source: landfill gas, flare, both	Main agents
Local	Explosion and fire	Both	CH_4, H_2
	Asphyxia	Both	CH_4, CO_2, N_2
	Human health	Both	NMVOCs, CO, NO_x, SO_2, PAHs, H_2S, PCDDs, PCDFs
	Odour nuisance	Both	NMVOCs, H_2S, NO_x
	Harm to flora and fauna	Both	CH_4, CO_2, NMVOCs, SO_2, NO_x, H_2S, HF, HCl
	Noise pollution	Flare	Landfill gas pumping and combustion
	Heat	Flare	Flare, flames, and flared gas
	Visual impact	Flare	Flare and visible flames
	Landfill gas condensate (pollution potential, risk to health, corrosion potential)	Both	Landfill gas extraction
Regional	Photochemical air pollution	Both	NMVOCs, NO_x
	Acidic precipitation	Both	Sulphur compounds, NO_x, HCl, HF
Global	Stratospheric ozone depletion	Both	CFCs, HCFCs
	Global warming potential	Both	CH_4, CO_2, CFCs

22 *Guidance on the Emissions from Different Types of Landfill Gas Flares.* Environment Agency R&D Report CWM 142/96A, 1997.

3.3 Emissions and their control

There are three principal mechanisms for the formation of gaseous pollutants in combustion systems.

- The first involves the oxidation of the chemical constituents of the fuel, particularly carbon, and leads to the formation of the oxides of carbon (CO and CO_2 and sometimes formaldehyde HCHO). The oxides of sulphur (SO_x) are also formed by oxidation, in this case from the oxidation of trace quantities of sulphur compounds in landfill gas.
- The second involves the pyrolysis, or thermal decomposition, of the fuel in oxygen-deficient regions, and this initiates reactions that can lead to the formation of polycyclic aromatic hydrocarbons (PAHs) and other trace species. Dioxins and furans can also be formed by this mechanism.
- Finally, the hot combustion gases produced in the combustion of any type of fuel at high temperatures, especially under fuel-lean or stoichiometric conditions, leads to formation of NO_x by oxidation of the nitrogen present in the air.

All of these mechanisms are considered in turn in the following subsections.

Just as there are reactions that form pollutants such as NO_x, so there are often others that destroy them. These, together with control of the excess air and temperature, can be used to reduce emissions from combustion plant. It should, however, be borne in mind that flares are small and inexpensive compared, for example, with power station boilers, and so some of the potential reduction strategies either cannot be applied or may be too expensive to employ.

3.4 Oxides of carbon

As already discussed, CO is the primary product of hydrocarbon oxidation, and its concentration decreases by a relatively slow reaction that forms CO_2. CO_2 is the ultimate product of carbon fuel combustion and its formation cannot be avoided.

Oxygenated organic compounds can also be emitted from combustion plant, as a consequence of incomplete combustion resulting from “quenching” of the hydrocarbon oxidation reactions by, for example, cool walls or dilution air. Foremost among these emitted compounds is formaldehyde (HCHO), but other aldehydes, ketones, cyclic ethers, alcohols and organic acids can be released. These compounds are formed by complex mechanisms in cool parts of the combustor (<700°C) and, to minimise them, such regions should be eliminated as far as possible.

3.5 Oxides of nitrogen

The principal oxide of nitrogen formed in combustion processes is nitric oxide (NO). Some NO may be converted to nitrogen dioxide (NO_2), the mixture being referred to as NO_x. Nitrous oxide (N_2O) may be present in small concentrations in exhaust products, but it is only of significance in relatively low-temperature combustors such as fluidised beds.

There are three mechanisms for the formation of NO_x:

- thermal NO_x results from the nitrogen in the combustion air and only becomes significant at temperatures above 1,200°C;
- fuel NO_x is formed from the nitrogenous species in the fuel;
- prompt NO_x occurs early in the flame and is caused by the attack of small hydrocarbon radicals (mainly CH) on nitrogen.

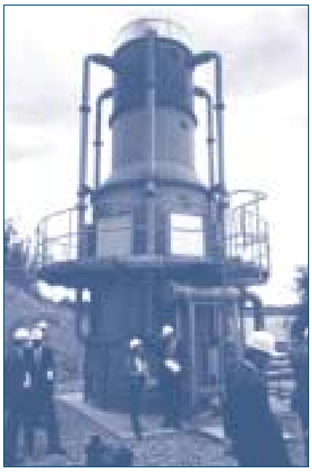

Figure 3.1 Experimental landfill gas flare using exhaust gas recycling to control NOx

NOx emissions can be reduced by careful control of the combustion process, the techniques being those which essentially limit the oxygen availability to the fuel and/or lower the peak flame temperature. There are three principal techniques that can be employed:

- air staging;
- fuel staging;
- flue-gas recirculation.

Advanced landfill gas flare systems employ one or a combination of the above.

3.6 Trace species

Landfill gas often contains small amounts of halogenated organic compounds[23] whose combustion will generate the acid gases HCl, HF and HBr. The concentrations of these gases in the emissions will depend upon the landfill gas composition.

The presence of chlorine-containing substances may give rise to the formation[24] of polychlorinated dibenzodioxins (PCDDs), termed "dioxins", and polychlorinated dibenzofurans (PCDFs), termed "furans". Several mechanisms exist for their formation, but that which is most likely to be of relevance to landfill gas flaring is their generation as products of incomplete combustion.

The conditions that favour the formation of dioxins and furans may also promote the formation of polycyclic aromatic hydrocarbon compounds (PAHs) from the products of incomplete combustion.

The above compounds may be formed in situations where there is a combination of low turbulence, low temperature and low oxygen content. Such conditions will be found at the periphery of an open flare, or in cooler zones around the walls of enclosed flares. This possibility is one of the key reasons behind the decision to recommend that the use of open flares be discontinued.

23 Organic compounds containing chlorine, fluorine, or bromine, or any combination of these.

24 Under certain conditions they may be formed either as products of incomplete combustion of chlorinated organic compounds, or by synthesis from non-halogenated organic compounds and inorganic forms of chlorine. The second of these mechanisms can be significant over the temperature range 200–450°C and is catalysed by metal-bearing particulate material.

4

Operational requirements

4.1 Introduction

The preceding chapters have provided a basis for understanding the design objectives for which landfill gas flares are intended. Many differing approaches are employed to achieve these objectives. Market forces have driven each particular line of technical development as much as the quality objectives followed by specific companies. It follows that some developments have a principal focus upon cost, with little concern for performance. By understanding the principles involved, it is possible to make a judgement about the nature of a particular piece of equipment.

4.2 Flares: common elements

The technology of a landfill gas flare is conceptually very simple: landfill gas is brought into contact with a supply of air and ignited. A variety of configurations of conduits and chambers can be used for the purpose. Whatever the exact design of the flare, however, it will comprise a number of basic elements, in addition to piping, valves and the body of the flare (**Figure 4.1**).

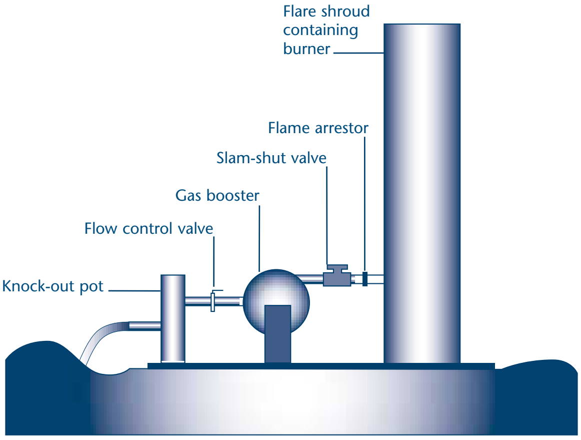

Figure 4.1 Basic flare arrangement

The basic elements common to open and enclosed flares are:

- *gas cleaning/conditioning* before the flare to remove moisture and possibly impurities, such as airborne debris, from the landfill gas;
- a *blower or booster* developing the head of pressure needed to feed landfill gas to the flare;
- one or more *flame arrestors* in the landfill gas feed line to prevent flash-back of the flame down the pipe;
- some method of *control* over the flow rate of landfill gas to the burner, and possibly over the supply of combustion air;
- a *burner* designed such that it maintains turbulent mixing of air and fuel and that the velocity of the gas is high enough to reduce the risk of flash-back of the flame down the feed pipe without blowing off the flame;
- an *ignition system* to light the gas mixture on start-up;
- a *flame detector* to check that ignition has been successful and combustion is taking place – this facility is normally provided with enclosed flares but it is more difficult for open flares since the location of the flame can be highly unstable.

4.3 Types of flare

The main division in the types of flare on the market is between open and enclosed flares. The original landfill gas flares were of the open design. These are still popular in the UK, owing to their simplicity and low cost. However, European and US legislation, which calls for high combustion temperatures and specific residence times, has developed the market for enclosed flares. In addition, the two basic categories can be further divided according to the way in which air is mixed with the landfill gas, and for operational reasons some flares may operate on a forced draught basis. This feature can be likened to the different modes of running a Bunsen burner.

4.4 Flame types

In a *diffusion flame* flare, air diffuses into the landfill gas leaving the burner. If there is no mechanism for increasing turbulence to provide rapid mixing of fuel and air, the flame will be deficient in air (reducing). Consequently, a long time is needed for completion of the reaction, and the flame is long, luminous and possibly sooty. This type of flare is similar to a Bunsen burner with the pre-aeration port closed.

The alternative design is the *pre-aerated* flare, which mixes primary air and landfill gas before the burner. Often the primary air enters through a venturi arrangement so that the rate at which it is drawn in depends on the flow rate of landfill gas. The aperture of the venturi can be adjusted manually or automatically. A pre-aerated open flare is akin to a Bunsen burner with the pre-aeration port open.

Figure 4.2 Duty/standby gas boosters after a moisture removal pot

4.5 Applications

The primary purpose of a flare is to burn landfill gas, collected by a control system to prevent migration off-site. Landfill gas is combusted to reduce the risk of fire and explosion, to reduce odours and to reduce the emission of methane globally. As noted in Section 2.2, this system may also include an energy recovery plant, in which case the flare will be on standby ready to dispose of landfill gas should the plant be unavailable, or as a back-up to burn surplus gas continuously. The back-up might be a large flare run at a low rate (subject to turn-down constraints), or a small flare might be provided to run at full load with a larger flare on standby in case of failure of the energy recovery system. The capacity of the energy recovery scheme will usually be less than the gas production rate since it is advantageous for it to run on full load. On the other hand, a flare might be the only disposal route and so may be running continuously at its operating capacity.

Some sites might operate solely with a flare. On others, an energy recovery scheme might be implemented once there is a sufficient gas supply, and so the use of the flare will change. As the gas production rate falls with increasing age, the required flare capacity decreases. This factor might be accounted for by the use of several small flares, the replacement of a large flare with a small flare, or running a flare intermittently. The frequency and duration of flare operation are dependent on the landfill gas migration status and the risk assessment. A further variant is the temporary installation of a flare if it is needed for only a short time in one place. The phasing of waste emplacement might make it impracticable to use a central flare compound, or there might be a very localised problem such as odour. Many manufacturers offer skid-mounted units to allow mobility. However, a generator may be needed for mobile flares to power the controls and gas pumping unit.

4.6 Requirements

From the above, and the discussions earlier in the guidance notes, it is apparent that there are several important features that a flare should offer in addition to low emissions. These are:

- flexibility, so that it can cope with a range of flow rates and methane concentrations;
- as a standby, the ability to respond quickly to a sudden increase or decrease in demand;
- to run for long periods unattended, particularly on a closed landfill – it is likely that staff with specialist combustion skills will not be immediately available even on an operational site.

In addition to the features associated with the day-to-day operation of the flare, other considerations relate to its location and ability to withstand exposure to all weather conditions, which will affect its long-term service.

A permanent flare system with its heavy base will place a large stress on the ground on which it is placed. Therefore, it is important to check the load-bearing capacity of the ground. Unless it is absolutely impossible, the flare should be located on original ground and not fill, which is likely to have an insufficient load-bearing capacity and be susceptible to differential settlement. If the flare must be located on waste, then a firm base should be provided.

Figure 4.3 Enclosed flare station

Ideally, the flare system should be located at a higher level than the gas collection system to minimise the risk of liquid draining into it. Condensate removal pots are not normally designed to accommodate large in-flows of liquid from the gas field.

As a flare is exposed to all weather conditions, it is important that the finish on the exterior of the flare is weatherproof as well as heat-resistant. Also the structure of the flare must be designed to withstand wind stresses. Ancillary items such as control and instrumentation equipment, including cabling, must be protected. Provision of housing makes maintenance tasks easier, but explosion hazards must be considered.

Figure 4.4 Low-height, low-emissions flare

Noise control is a relevant objective, and, where not adequately covered by the site planning permission, may be subject to control via waste management licence conditions. This issue will in future require to be more fully addressed as landfill sites fall within the remit of the PPC Regulations and environmental noise limits are imposed where deemed to be required.

The preference for locating flares on original ground will often lead to them being placed on the periphery of sites, hence increasing the probability that there will be trees and buildings nearby. The effect on these and on employees must be considered. Where there are residential areas nearby, noise from the flare may be a significant factor. Noise is generated both by the operation of equipment such as the blower and by combustion itself. Whilst there are conventional methods of providing sound insulation for plant items, it is less easy to reduce the impact of combustion noise, which tends to be low-frequency at around 17 Hz. Some manufacturers claim that their burner designs minimise noise production, and some include an acoustic lining in the flare stack.

Where the flare is near the general public, in addition to noise considerations, the local planning authority might wish to restrict the height of the flare to reduce its visual impact. However, they should be aware of the fact that some manufacturers have developed flare designs to overcome the problems caused by a height restriction by employing modified burner systems.

Support fuels for low-calorific-value landfill gas may be required in specific locations. It should be noted, however, that the use of high-grade energy to support the disposal of a waste gas should not be employed unless absolutely necessary, for example in close proximity to residential development, where flaring is essential. Such an approach will increase carbon dioxide emissions and, in view of the cost implications, have limited sustainability. As a guide, the Non-Fossil Fuel Obligation (NFFO) scheme[25] requires support fuels to be used on a <10% basis. As an alternative to support fuels, one or a combination of the following may deal with the presence of low-calorific-value landfill gas and still enable flaring to occur:

- Operating a flare on a timer to draw off gases only when the quality is adequate for combustion – care must be taken to ensure that off-site migration control objectives are not compromised.
- Employing a specially designed low-calorific-value gas burner.
- Paying closer attention to the question of gas well balancing to maximise the extracted methane content of landfill gas, to control oxygen ingress and to extract landfill gas at its production rate. It may be necessary to install more gas extraction wells (closer spacing) working under low pressure to avoid oxygen ingress. If oxygen is drawn into the waste mass by over-extraction, then landfill fires may result.[26]

25 NFFO is a scheme by which electricity companies are "obliged" to buy a fixed amount of power from non-fossil power producers.

26 Department of the Environment (1995) *Waste Management Paper 26B Landfill Design, Construction and Operational Practice*, HMSO.

In remote locations, or situations where the plant may run unattended for long periods, it may be appropriate to fit a telemetry system that will notify the responsible authorities of any operational failure that may affect plant operation. Telemetry systems can operate through the telephone line network, by means of radio waves or via a cellular telephone network. Such systems can advise by speech or digital communications of any monitored variable, whether digital or analogue, that is out of range.

4.7 Open flares

In the general case of diffusion and pre-aerated open flares, there is often a shield around the burner to protect the flame from the wind. The flame may, however, extend beyond the top of the shield by several metres. Good mixing of air and fuel at the burner shortens the flame and reduces its luminosity. Mixing is improved by good burner design and pre-aeration, which also allow some degree of combustion control through adjustment of the flow of air.

Open flares have the advantages of being inexpensive and relatively simple, which are very important factors when there are no emission standards. However, open flares are inefficient, resulting in very poor emissions compared with those from enclosed flares. Operators find it attractive to have equipment that can be relied upon to keep running with little or no attention. However, as noted in Chapter 2, good combustion depends upon maintaining a sufficiently high temperature for a certain length of time and also thorough mixing of the air and fuel. For a number of reasons, open flares cannot be relied upon to ensure good burnout and hence low emissions:

- An open flare with its unconfined flame cannot normally achieve high temperatures.
- Luminous flames, in particular, radiate heat and there is no means of reducing these heat losses.
- Ambient air cools the periphery of the flame and tends to quench the reactions.
- Without some method of containing the gases, residence times are very short and cannot be defined.

The radiation of heat from an open flare is, in itself, a health and safety disadvantage, in addition to its effect on the efficiency of combustion. The burner must be elevated sufficiently high to avoid excessive levels of radiated heat which could be experienced by operators working beneath the flare.

Emissions from an open flare are not easy to measure and interpret. Obtaining a representative sample of the combustion gases is very difficult, and is impracticable for routine monitoring. Sampling within or close to the flame will give high levels of unburned hydrocarbons and carbon monoxide. Recent measurements have demonstrated levels of 8–15% methane and 2% carbon monoxide. However, if the sample is collected away from the flame, the off-gases will have dispersed into the atmosphere. Also the location of the flame and the plume of off-gases will vary depending upon wind direction, thus making a permanent monitoring facility impracticable.

4.8 Enclosed flares

4.8.1 Structure

In an enclosed flare, the burner or burners are located at the base of a shroud, which is usually, but not always, circular in cross-section. Because of the shape of the flame, the height of a cylindrical shroud is often at least 2–3 times the diameter (the choice of height of flare is discussed in more depth later). Some manufacturers offer rectilinear-shaped chambers, but with a cylindrical shroud it is easier to maintain a uniform temperature across the chamber, eliminating cold zones where incomplete combustion can occur.

4.8.2 Retention time

The shroud may be designed to provide a certain retention (or residence) time and be insulated to maintain a particular combustion chamber temperature, or it might simply be used to hide the flame or reduce noise. The residence time required by Dutch and German (HMfUR)[27] regulations is in excess of 0.3 seconds, which is adequate for 98–99% destruction of hydrocarbons.[28] However, the regulatory authorities in the USA require a minimum residence time in the range of 0.6–1.0 seconds at 850°C to ensure the destruction of chlorinated trace components such as tetrachloroethylene and methylene chloride.

These guidance notes recommend a minimum retention time of 0.3 seconds at a minimum temperature of 1,000°C or similar standard offering equivalent performance.

4.8.3 Insulation

Good insulation and lining of the shroud can reduce heat losses so that temperatures of 1,000–1,200°C can be achieved in the combustion chamber and the

27 See Section 6.2.2.

28 Giles, D.L. (1989) *Landfill Gas Flare Design Basics*. Proceedings GRCDA 12th Annual Int. Landfill Gas Symposium, Monterey USA, 20–23 March. Governmental Refuse Collection and Disposal Association, Publication GLFG No. 0017, pp. 165–172.

temperature of the outer skin reduced to about 80–100°C. In these conditions, a mild steel construction with a paint finish is possible. However, in windy conditions the top 0.5–1 metre of shroud may be exposed to high temperatures, caused by down-wash of the hot combustion gases induced by the low pressure on the downwind side. In such circumstances, this part of the flare is better made of stainless steel.

A ceramic fibre, in modular or blanket form, is often used for insulation rather than refractory bricks, since it is not damaged by variations in temperature, and does not spall. However, very high temperatures, in excess of about 1,200–1,300°C, which might be found particularly in the vicinity of the burner, can destroy the metal retaining clips. A further disadvantage of using clips is that they conduct heat to the outer shell and create hot spots there. To avoid these problems, some manufacturers bond the fibre to the shroud.

To reduce heat losses further, some manufacturers provide a refractory-lined disc, or 'hat', above the top of the flare that reflects heat back into the combustion chamber. It also helps to keep rain out of the flare stack. The disadvantage of this item is that it prevents the free upward movement of the exhaust gases and so is not recommended.

4.8.4 Air supply

In most cases, combustion air is drawn into the flare under natural draught. As the theoretical draught is directly proportional to the height of the shroud, height may be an important factor in determining the flow of air. Where other mechanisms are employed to entrain air, height is of less significance.

There can be problems with a supply of air under natural draught. Under very windy conditions, in a bottom-entry flare with no surround, the air may bypass the inlet. Baffles may need to be incorporated below the base to encourage the diversion of air into the flare. It is also possible that, in high winds, one side of the shroud may receive too much air and the other too little, so that one side runs too cold and the other too hot. Consequently there is the danger of combustion being incomplete on one side, whilst on the other excessive NOx might be formed and the refractory damaged.

It is possible to install a blower to supply air under forced draught, so avoiding any problems that may be associated with natural draught. This leads to additional capital and running costs.

Tall flares are preferable to shorter flares as:

- they are better able to induce sufficient combustion air;
- they are more likely to provide an adequate retention time for the entire gas stream;
- the temperature distribution is more uniform – with short, wide stacks there is an increased risk of poor mixing of gases near the walls, and tall flares are less likely to develop cold spots where combustion will be poor;
- they allow better dispersion of the off-gases into the atmosphere.

4.8.5 Process control

Combustion control consists of automatically adjusting the total air intake according to the combustion temperature (commonly measured by a thermocouple located at some point within the shroud). In a natural draught flare, the intake of air is often through sets of louvres (see **Figure 2.7**), their position determining the flow rate.

Where automatic flame temperature control is not provided, it should be noted that the maintenance of minimum flame temperatures across a range of operating conditions cannot be assured.

4.8.6 Burners

Enclosed flares can contain a single burner with several tips, or an array of multiple burners each with its own gas supply. Where multiple burners are used, it may be possible to operate the flare over a different range of flow rates of landfill gas by activating only a selection of burners at any one time. This is achieved by manual control, though it could be achieved through an automatic feed-forward control loop. However, such flares should be designed to ensure that there are no cool zones within the shroud under any burner on/off conditions.

Manufacturers offer a variety of burner designs to create turbulent mixing of landfill gas and combustion air. Some also include baffles within the shroud, but these cause an additional pressure loss that restricts the flow of air induced under natural draught. The velocity at which the gas leaves the burner tip is very important; to prevent flash-back, this velocity must be greater than the flame propagation speed.

4.8.7 Turn-down

Turn-down is the ratio of minimum gas flow to maximum gas flow under which satisfactory operating conditions will be maintained. Turn-down depends upon the range of rates of heat release for which the flare is designed, and permissible exit velocities from the burner tip. The turn-down ratio will therefore affect the flare emission significantly. In general, manufacturers quote ratios of 4:1 or 5:1, based on heat release, for a flare operating under good combustion conditions and a range of methane concentrations of around 20–60% by volume.

It is possible to turn a flare down to achieve a 10:1 turn-down, or greater, but the emission standard is unlikely to be met and such a turn-down is difficult to achieve because of the variability in methane content. The optimum requirement is a chamber that can take the maximum turn-down without overheating and the minimum turn-down without being too cool. A low rate of heat release will not allow high combustion temperatures to be achieved.

4.8.8 Start-up and shut-down

Start-up consists basically of turning on the supply of landfill gas to the burner, attempting to ignite it and checking for ignition by means of the flame detector. If ignition is unsuccessful, then the flare might shut down or ignition might be tried again after a set time. Care has to be taken to avoid the risk of explosion caused by an accumulation of gas (there has been a recorded instance of this occurring).

Where a flare is operated on a timer, being switched on and off at pre-programmed intervals during the day, it is important to ensure that the timing sequences selected facilitate reliable operation. It may be, for example, that gas must be vented from a long pipeline prior to ignition being attempted. Sufficient time, dependent on plant design, must be allowed for the explosive mixture of gases to dissipate in order to optimise the concentration of methane before ignition proceeds.

4.8.9 Applications

Enclosed flares are needed to meet strict operating and emission standards. In the past, in the UK, enclosed flares have been selected only where a landfill operator wishes or is required to meet TA Luft emission standards,[29] or the local planning authority stipulates that the flame must not be visible. It is recommended that, in the future, they are required as standard. A site-specific risk assessment should be used to determine the most appropriate landfill gas control option.

4.9 Individual elements

A number of items, identified in Section 4.2, are included in most flaring systems. A selection of the different design components available are described below and their relative merits discussed.

4.9.1 Gas conditioning

Conditioning is usually carried out using a condensate knock-out vessel, or two vessels in series, in conjunction with demister pads. The conditioning equipment might remove solid debris in addition to moisture from the gas. Some manufacturers supply cyclones as part of the conditioning system. Solids can be:

- particles of plastic, present in newly installed gas pipelines;
- dust from intermediate cover material or fines from other waste;
- deposits of ash.

4.9.2 Gas booster

The gas booster or blower is designed to develop a head of around 3–15 kPa to provide the required discharge pressure at the burner tip. Centrifugal blowers, which readily allow variable flow rates, are generally used and are equipped with temperature and pressure gauges on the inlet and outlet sides. They can be belt-driven or have a direct drive. Belt-driven blowers may cost less to buy but require more frequent attention to maintain the belts and bearings. Whatever type of equipment is used, it is essential that it is suitable for operating in a potentially explosive atmosphere. In addition, since landfill gas contains corrosive vapours and some particulate matter, it is desirable to protect the blower from these aggressive constituents in case they are not completely removed by the conditioning unit. To maximise the availability of the flare, a second blower can be provided as a back-up in case of routine maintenance or failure of the primary unit.

4.9.3 Flame arrestor

Flame arrestors are normally located in the flare feed line. Sometimes they are also located in the landfill gas supply on one or both sides of the gas blower, as this item is a potential source of sparks. Flame arrestors should be fitted with a high-temperature switch, to provide an alarm indication if a flame is burning on the element and cut off the supply of gas. They must be cleaned regularly, and it is normal

29 See Section 6.2.2.

practice to have a spare available. Pressure differential measurement across flame arrestors can be used to assess maintenance requirements.

4.9.4 Ignition

There are two main types of automatic ignition system. One uses a propane pilot burner, and the other a landfill gas pilot burner. Propane ignition may be more effective in cases where the methane concentrations are as low as 20%, but it should be remembered that frequent ignition attempts would result in a greater consumption of propane. Where this is brought to site in bottles, the cost of running such an ignition system may be appreciable. It is also possible to put the ignition system on a timer so that it sparks for a set length of time within a certain period.

Within the two categories of ignition system there are further choices of technique. For example, regarding propane ignition, one manufacturer favours the use of a torch rather than flame-front ignition. Torches give a smoother start-up, but cannot withstand temperatures above about 1,200°C, whilst with flame-front ignition there is a danger of explosion should ignition fail several times and an explosive mixture accumulate in the flare.

4.9.5 Flame detection

There are two principal methods of flame detection, thermocouples and ultraviolet (UV) light sensors. Owing to the heat capacity of a thermocouple, there is a lag between the extinction of the flame and its registration. A UV sensor responds rapidly, but the lens can easily be fouled, and so regular cleaning is necessary. The frequency with which a thermocouple must be replaced ranges from six months to two years, depending partly on the extremes of temperature or the corrosive environment to which it is exposed. The bulb, which is the sensing component in a UV sensor, costs in the order of £100. Bulb manufacturers recommend replacement once a year, but they can last up to five years.

5

Instrumentation

5.1 Introduction

There exists a wide range of instruments for monitoring landfill gas flare systems. Some of these have an operational requirement, in that they are required to enable the equipment to be run correctly. Others are employed to monitor the performance of the equipment. Within this latter category are instruments that give useful information to assess what is happening with the plant and the gas field as well as instruments to ensure compliance with performance specifications and environmental requirements.

5.2 Requirements for monitoring techniques

A monitoring technique should be designed to meet several criteria. These include:

- suitability for the type of monitoring required, i.e. compliance or process control;
- measurement of important parameters;
- collection of data representative of all emissions, accounting for variations within the gas composition and volume and with time, i.e. from appropriate points spatially and temporally;
- provision of accurate and reproducible data, which can be referred to standard conditions;
- sufficiently reliable and robust equipment for the conditions involved;
- safety.

It is also important that the technique complies with relevant standards. Several standards already exist world-wide for the monitoring of stationary emission sources. They tend to be designed for stack monitoring, and so are applicable to enclosed rather than open flares. Some of the standards that can be referred to for monitoring of landfill gas flares are listed in Section 6.2.

5.3 Problems associated with monitoring flares

Monitoring of landfill gas flares to provide a representative result is not straightforward. The problems faced vary with the type of flare. All emissions from landfill gas flares will be variable in terms of flow rate and composition as a result of the nature of the gas source. There are the overall trends that result from the ageing of the waste, on top of which are superimposed the fluctuations arising from inhomogeneities in the waste and changing meteorological conditions. Consequently, combustion conditions and the products of combustion vary over time. Thus a fully automatic combustion control system is required.

It is also very difficult to ensure that measurements are representative of emissions from the flare as a whole. In the case of *open flares*, in particular, this is due to the instability in the location of the flame, which varies with wind speed and direction, and the gas flow rate. In addition, regardless of flare type, the flame itself comprises a number of zones, depending upon the way in which air is mixed with the landfill gas and the quality of the gas as a fuel, and it is important to sample from a point at which combustion is complete. It is doubtful that meaningful emission results can be obtained from open flares at all.

In *enclosed flares* there will be variations in gas composition across the stack. This is known as stratification and results from poor mixing in large-diameter ducts at low gas velocities. Unlike a chimney stack, the duct through which the flared gases flow can be of several very different designs, and representative sampling points need to be determined for each. There are additional factors arising from variations in the flow of landfill gas which affect the flow regime in the duct and thus how well mixed the gas is at any one point. The flare may contain many burners, with only some in operation at any one time, and there may be a variable flow of induced air from just below the burners.

Monitoring conditions in a landfill gas flare can be very severe. The temperature should be 1,000°C or more; some modern flares operate at up to 1,200°C. Also the atmosphere is corrosive, containing acid gases such as SO_2 and, particularly in the case of young waste, HCl and HF in the presence of moisture.

Monitoring of open flares presents several health and safety problems. Safe access to the elevated discharge point is difficult. In addition, the environment near the flame is dangerous owing to the instability of the location of the flame, the explosive and noxious atmosphere, and the radiative heat emitted.

The general conclusions of the study project upon which these guidance notes are based were as follows:

- Even under stable test rig conditions, combustion is an unsteady process producing unavoidable temporal variations. In such circumstances, "single-shot" measurements may be misleading. Time-averaged readings are, therefore, essential.
- Differences in the results obtained may be important, especially if a plant is close to exceeding the emissions limits against which it performance is being monitored.
- Discrimination between NO and NO_2 can be a problem.
- NO_x tends to be overestimated and SO_2 underestimated.

Further research has been commissioned by the Environment Agency's Waste Regulation & Management R&D Programme on analytical techniques and monitoring of landfill gas flares.

5.4 Monitoring locations

Easily accessible, safe and functional monitoring/sampling points should be retrofitted to enclosed flares as appropriate in locations where they are currently absent. These should be easily accessible in accordance with all relevant health and safety legislation.

In addition to the choice of equipment to use, there are two approaches to monitoring emissions: single-point and multi-point. The extent to which each, with careful selection, will obtain a representative measurement is discussed below.

5.4.1 Single-point monitoring

For an enclosed flare, it is necessary to ensure that the sample is indicative of the whole emission and has not been compromised by stratification. A preliminary monitoring exercise should be carried out to examine the velocity, oxygen and temperature profiles across the width of the combustion chamber. The parameters should be measured simultaneously.

Monitoring of open flares is vulnerable to great uncertainties due to instabilities in the position of the flame, uncontrolled addition of air and rapid dilution in the ambient atmosphere.

5.4.2 Multi-point monitoring

Multi-point methods are designed to overcome the problems of single-point monitoring and are recommended for use with enclosed landfill gas flares. The gas is monitored at several locations in a two- or three-dimensional array, either simultaneously or consecutively. In a closed flare, it is possible to employ established stack monitoring techniques with allowance for the very high temperatures and the variety of configurations of combustion chamber. These may include the use of an averaging pitot-tube type of probe, which allows sampling simultaneously from a series of points along its length. Alternatively, a multiple-sample-point array may be used. This would be based on the guidance in BS 6069[30] or the simpler BS 3405,[31] which specifies only four sampling points for ducts with a diameter less than 2 m (enclosed flares usually have diameters of about 1–2 m).

5.5 Recommended monitoring regimes

Monitoring should be carried out as summarised in **Table 5.1** according to site circumstances.

Table 5.1 Recommendations for monitoring regimes to be applied to enclosed flares

Level	Inputs (inlet gas)	Outputs
1st	CH_4, CO_2, O_2 and gas flow rate	Temperature
2nd	As above	As above, plus bulk components (O_2, CO, NO_x, CO_2, THC), trace components including HCl, HF and SO_2 and retention time

30 BS 6069–4.3 (1992) *Characterisation of Air Quality. Stationary Source Emissions*. Method for the manual gravimetric determination of concentration and mass flow rate of particulate material in gas-carrying ducts.

31 BS 3405 (1983) *Method for Measurement of Particulate Emission Including Grit and Dust* (Simplified method).

- First level monitoring should be carried out on a continuous and logged basis, with telemetry, since it provides the basic information needed for controlling the flare and demonstrates the degree of operation. The data obtained also allow the gas field to be balanced and controlled.
- Second level monitoring is necessary periodically or when there is some significant change in the composition of the landfill gas or method of operation of the flare. This may occur, for example, when a new phase of a site is brought on-line or the plant is newly commissioned or re-commissioned after a change of location. It provides more information about the completeness of combustion, the main combustion products and the major emissions. This should typically be carried out annually, dependent on the presence of population centres or other environmentally sensitive areas and provided that the plant is maintained according to the manufacturer's recommendations. Second level monitoring is targeted at good indicators of potentially hazardous components in flare emissions. Such frequency and selection of trace species would also be subject to the findings of the environmental impact assessment from requirement No. 7.

A monitoring protocol for enclosed flares is being developed under a separate R&D project commissioned by the Agency[32] and in partnership with industry-sponsored research. Upon completion, it is expected that the protocol will succeed the recommended monitoring regimes contained in this guidance document.

5.6 Monitoring techniques

Monitoring techniques associated with landfill gas flares may be divided into four basic categories: extractive, in-stack, cross-stack, and remote. For a full discussion of the relative merits of each, the reader should refer to the source documentation.[33]

The actual cost of the monitoring system required for a particular purpose will depend upon the number of parameters specified, the accuracy required, the instrument's robustness and its specified availability. One option is for the operator to have a maintenance contract tailored to the availability required. All electrical equipment should comply with appropriate relevant standards. Due regard should be given to the corrosive and aggressive properties of combusted landfill gas and effective particulate and moisture filtration used to minimise the effect on monitoring equipment.

5.6.1 Extractive monitoring

Extractive monitoring differs from other types in that it involves the collection of a sample of combusted gas and transport away to an analyser. It can be run as either a continuous or a periodic method. The most important consideration in setting up an extractive system, apart from the selection of appropriate sampling locations, is ensuring that the gas sample integrity is maintained and not altered by chemical reaction. It is also essential that chemically resistant probes and associated tubing are used. Temperature must be maintained above dew point to prevent condensation from occurring.

Some of the above potential interference effects can be overcome by passing the gas through a column or solution of an appropriate chemical medium. The likely effect of interference gases should be considered prior to employing a particular instrument. Sample components such as acid gases and hydrocarbons may damage equipment, including sensors, pumps and flow meters. Particular care must therefore be taken in this regard.

5.6.2 In-stack monitoring

These are sometimes referred to as *in-situ* techniques. The key feature is that the sensing device is in the stack and the results are conveyed as an electronic signal. There are two main configurations: the equipment can operate in "cross-stack" mode using the duct itself as the measurement cell, or the sensor may employ a shorter cell length and be supported within the hot gas in the stack. An "in-stack" technique can produce real-time, continuous data but may inherently be less reliable than extractive analysis because interferences cannot be removed *in-situ*.

5.6.3 Cross-stack monitoring – optical sensors

Cross-stack optical techniques measure gas concentrations in a stack by measuring the change in spectrum of a beam of light as it travels across the stack between a transmitter unit and a receiver unit. They are an example of an integrated-path measurement technique. The four methods of cross-stack monitoring that may be relevant for use on landfill gas flares are as follows:

- dual-wavelength;
- gas filter correlation;
- DOAS (differential optical absorption spectroscopy);
- FTIR (Fourier transform infrared).

32 *Monitoring Protocol for Landfill Gas Flare Emissions*, Environment Agency R&D Project P1-405.

33 *Guidance on the Emissions from Different Types of Landfill Gas Flares*, Environment Agency R&D Report CWM 142/96A, 1997.

Table 5.2 Extractive gas sampling techniques

Technique	Component	Gases with cross-sensitivity to target component
Infrared	CO_2	H_2O, particulates, SO_2, NO_2
Non-dispersive infrared	SO_2	H_2O, CO_2, CO, NO, NO_2, SO_3, particulates
	NO, N_2O	
	CH_4	H_2O, particulates, NO_2
	CO	H_2O, particulates
	HCl	H_2O, CO_2, aldehydes, NO
Ultraviolet	SO_2	UV absorbers
Non-dispersive ultraviolet	SO_2	CO_2, CO, NO, NO_2, SO_3, hydrocarbons, particulates
Electrochemical	SO_2	H_2O, NH_3, H_2S
	HCl	SO_2, NO_2, SO_3, NH_3, H_2O, CO_2, Cl_2
	HF	SO_2, NO_2, SO_3, NH_3, H_2O, CO_2, Cl_2, metal fluorides, hydroxides
	O_2	SO_2, NO_x, acid gases
	CO	
	NO	
	NO_2	
Fluorescence	SO_2	NO_2
Flame photometric	Total sulphur	H_2O, SO_3
Flame ionisation	Hydrocarbons	Other hydrocarbons, reduced response for hydrocarbons containing O, N, Cl
Mass spectrometry	CO	N_2
Paramagnetic analyser	O_2	
Chemiluminescence	NO, NO_x, NO_2	
Traditional wet chemistry	SO_2, SO_3, HF, HCl	
Filtration	Particulates	

Table 5.3 In-stack monitoring techniques

Technique	Component	Interferences
Infrared	Hydrocarbons	H_2O, NO_2
	CO	H_2O, particulates
	HCl	H_2O, particulates, CO_2, aldehydes, NO
Non-dispersive infrared	SO_2	H_2O, CO_2, CO, NO, NO_2, SO_3, particulates
	NO_x	H_2O, particulates
Ultraviolet	SO_2	H_2O

Figure 5.1 In-stack enclosed flare monitoring with grid of probes (right) for emissions monitoring

5.6.4 Remote sensing

Remote sensing techniques measure gas concentrations by monitoring the extent to which radiation (either optical or microwave) is scattered and absorbed as it travels through the measurement path. They do not require any physical contact with the measurement region. Remote sensing techniques that require equipment at both ends of the measurement path were covered above under cross-stack monitoring. This section is restricted to techniques that do not require access to both ends of the measurement path. All of the remote sensing techniques of relevance make use of the interaction of optical radiation with the gas. Three different principles are used, namely:

- COSPEC (correlates absorption spectra with reference spectra);
- passive FTIR (Fourier transform infrared);
- DIAL (differential absorption LIDAR).

5.6.5 Other monitored parameters

Other parameters that may require to be monitored include the following:

- temperature of the gas entering and leaving the gas booster;
- temperature of the flame;
- temperature of the combustion chamber;
- pressure of the gas at various stages through the collection and combustion system;
- landfill gas flow.

5.7 Quality management

Another related factor is the quality of the monitoring being carried out, whether in-house or by external consultants. Stack emissions monitoring is a very competitive business, and consultants vary from those with purpose-designed and -built mobile laboratories to some with a few portable instruments that can be put in the back of a car. The general standards being applied are being improved, particularly by the launch of the Source Testing Association (STA).

One of the main objectives of the STA is to improve auditing and so increase confidence that operators' emissions data are reliable. The main criteria may be summarised as follows:

- the use and strict adherence to recognised standard methods (BSI, CEN and ISO);
- the use of non-standard methods only after approved validation;
- participation in proficiency testing;
- the use of approved measurement protocols;
- the use of standard reporting forms, which would include process measures as well as emission data;
- accreditation of all relevant on-site sampling and laboratory analytical methods with the UK Accreditation Service (UKAS, formerly NAMAS);
- certification and registration of stack testing personnel or consultants under a professional competency scheme, preferably based on a BSI standard – such certification should be specific to landfill gas flares.

6

Emission standards

6.1 Introduction

The recommendations contained in these guidance notes comprise the first approach to providing a set of standards for landfill gas flares. This chapter reviews relevant emission standards and concludes with a brief statement of the principles behind the recommendations for emission standards contained in this document.

6.2 Existing national flare emission standards

6.2.1 France

There are no regulations at present, but it is likely that there will soon be standards requiring a flame temperature of >900°C and limits on emissions of SO_2, NO_2, CO, dust and HCl.

6.2.2 Germany

Limits are specified at national and state level. Limits given in the national Technical Directive for Air Pollution Abatement (TA Luft) and by the Hessisches Ministry for Environmental Protection and Reactor Safety (HMfUR) are summarised in **Table 6.1**.

Table 6.1 German emission limits (mg/Nm^3, dry gas at 3% O_2 [24 h average] unless stated otherwise)

Component	TA Luft		HMfUR
	1986	1996*	1989
Particulates	5	10	5
CO	100	50	100
NO_x ($NO + NO_2$)	500	200	200
SO_x ($SO_2 + SO_3$)	35		
SO_2		50	500
HCl	30	10	30
HF	5	1	5
H_2S	5		
C(org)	20	10	20
Cd	0.2	0.05	–
Hg	–	0.05	–
Total metals	–	0.5	–
PCDD/PCDF I-TEQ (ng/m^3)	–	0.18	0.18

* Unadopted.

6.2.3 The Netherlands

Dutch standards are contained in the Nederlandse Emissie Richtlijn Lucht (NER). Chapter 3 of that document provides requirements and restrictions for landfill gas flaring, and in particular paragraph 3.3 details 47 special guidelines for specific processes. Amongst these guidelines is G1 *Treatment of gases from landfills, waste fermentation and anaerobic wastewater treatment plant*. The Dutch regulators recognise that measuring emissions is difficult; therefore standards relate to the operation of the flare. Flaring requirements contained in Section G1 are that the exit temperature must be 900°C and the retention time must be at least 0.3 seconds. The flare must be of the enclosed type unless it is intended only as back-up for occasional maintenance or disruption of utilisation, in which case an open flare will suffice.

The sulphur content (H_2S + organic sulphur compounds) of landfill gas to be treated in a flare must be lower than 0.0050% (50 ppm). If this value cannot be met, a sulphur removal efficiency of 98% is required.

By using an enclosed flare with control over the combustion temperature and a sufficiently long retention time, the operator complies with the requirement to minimise dioxins as specified in paragraph 3.2 of the NER (unless the halogenated hydrocarbons content deviates from "normal").

6.2.4 Switzerland

The Clean Air Act of Switzerland (LRV, 1992) stipulates the limits in **Table 6.2**.

Table 6.2 Swiss emission limits (mg/Nm^3, dry gas at 3% O_2)

Dust	CO	NO_x	SO_2	HCl	HF	C(org)	Cd	Hg	Total other metals
20	60	80	50	20	2	20	0.1	0.1	1

6.2.5 United States

The details of regulation differ from state to state. Typically, a destruction and removal efficiency (DRE) of 95, 98 or 99% is required, and emissions of NO_x and CO are limited according to the thermal output (expressed as MJ) of the flare. Limit values for NO_x and CO are expressed in terms of thermal capacity and lie in the ranges 25.8–34.4 mg NO_x/MJ and 51.6–120 mg CO/MJ, respectively.

6.3 Incineration and combustion plant in the UK

Table 6.3 compares UK emission limits for both large and small incineration plant, and combustion plant. In making this comparison, it is important to note the following:

- The limits cited relate to plant burning different fuels, including waste oils, municipal solid waste, general waste, natural gas and chemical waste.
- The size of the plant for which the regulatory limits apply is important. To allow an approximate comparison, illustrative thermal ratings of the different systems are quoted.
- The concentration data are *not directly* comparable because the limits for different plant are related to different standard conditions (excess oxygen values from 3 to 11% apply in different cases).

Flares may also be considered through the planning process, controlled by local authorities. Factors such as the National Air Quality Strategy (NAQS) and Air Quality Management Areas (AQMA) as well as the General Development Procedure Order (GDPO) may all be brought to bear.

Table 6.3 Selected UK emission limits for other combustion and incineration plants

Plant/reference	Capacity (MW thermal)	Emissions limit (mg/Nm^3)					
		CO	Organic C	NO_x as NO_2	SO_2	HCl	HF
Waste oil burner, PG 1/1 (91)	<0.4	–	–	–	–	–	–
Waste oil burner, PG 1/1 (91)	0.4 to <3	–	–	–	–	–	5
Waste oil burner, PG 1/1 (91)	3 and more	–	–	650	2,250	100	5
MSW-derived fuels, PP 1/5	>3	100	20	–	300	50	2
Natural-gas-fired boilers, PG 1/3 (91)	20–50	–	–	200	35	–	–
Chemical incineration, IPR 5/1	20–30	50	–	650	50	30	2
MSW incineration, IPR 5/3	10–150	100	20	350	300	30	2
Clinical waste incineration	<1 t/h	100	20	–	300	100	–
Clinical waste incineration	>1 t/h	50	20	350	300	30	2
Sewage sludge incineration	<1 t/h	100	20	–	300	100	4
Sewage sludge incineration	>1 t/h	50	20	650	300	30	2

34 *Emissions from Landfill Gas Energy Recovery Plant – Monitoring Protocols.* Environment Agency R&D Technical Report P248 (in preparation).

A current R&D project commissioned by the Environment Agency is under way to provide guidance on emissions from gas engines running on landfill gas.[34]

6.4 Discussion of standards

Given the intrinsic difficulties of measuring the emissions from landfill gas flares, the approach of regulating the design and operation standards adopted in the Netherlands has its attractions. Such a standard is readily achievable and should provide an adequate degree of protection to the public and to the environment.

Most future sites in the UK are likely to fall into a larger size range, flaring typically 1,000 cubic metres per hour (1,000 m^3/h; circa 5 MW_{th} with 50% methane) or more. The net thermal energy of such systems is substantial and equivalent to those of processes for which standards are set by the Environment Agency. The constituents of landfill gas and the emissions from its flaring include:

- oxides of sulphur, and other sulphur compounds;
- oxides of nitrogen;
- oxides of carbon;
- organic compounds and partial oxidation products;
- halogens and their compounds.

Given the above, it is, therefore, considered reasonable that waste management licences should impose maximum emission concentrations on landfill gas flares in addition to a design and operational standard. It should be borne in mind, however, that flaring landfill gas disposes of a hazardous gas with a high global warming potential that will otherwise leak directly to the atmosphere over many years.

Such emissions standards might be set more tightly with increased thermal rating, for example, as for waste oil burners (see **Table 6.3**). If standards are set in this way, site operators might be tempted to opt for a multi-flare system if this is cheaper. To guard against this, standards should be set on a site basis rather than on the basis of an individual flare.

In practice, it is possible to obtain both a combustion chamber temperature of 1,000°C and a minimum retention time of 0.3 seconds whilst having a flame burning with inadequate combustion air and/or turbulence to ensure adequate mixing. To guard against this, the approach taken in these guidance notes is to combine that taken in the Netherlands, stating the design and operation standards, with bulk-component emission limits. These latter parameters will indicate that the plant is operating correctly.

To overcome any practical difficulties in monitoring flares, especially small ones, under field conditions, the adoption of "process type approval" may be considered in specific circumstances. It is not considered that such compliance could be guaranteed at present. On the other hand, this approach would be cost-effective and would facilitate the modelling of sites with multiple flares and assessing their impact on health and the environment.

The performance of a flare system should be verified upon first use to ensure that it complies with the standards required herein. Thereafter, monitoring and verification should follow the procedures outlined in requirement No. 5.

6.5 The UK emission standard

The interim standard to be adopted by the Environment Agency and SEPA in controlling the emissions from flare stacks is outlined below.

The combustion air supply should be controlled so as to achieve a minimum temperature of 1,000°C and 0.3 seconds retention time at this temperature whatever the landfill gas composition and throughput within the design parameters. Alternative performance criteria may be deemed more appropriate if they offer equivalent performance and meet the desired emission standard detailed in the paragraph below.

To ensure that flare systems are operating correctly, they should not exceed the following emission concentrations when referred to normal temperature and pressure (NTP = 0°C and 1,013 mbar) and 3% oxygen:

carbon monoxide (CO)	–	50 mg/Nm^3
oxides of nitrogen (NOx)	–	150 mg/Nm^3
unburned hydrocarbons	–	10 mg/Nm^3

Compliance with the above emission standard has been demonstrated at a number of UK landfill sites as being achievable.

7

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7.1 Further reading

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Simulation of methane oxidation in soils. CWM Report 021/91

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The Controlled Waste Management (CWM) R&D Programme of Wastes Technical Division (Department of the Environment) transferred into the Agency on its creation in April 1996 and became the Waste Regulation and Management Research Programme (P1).

All published CWM R&D reports in additional to those published by the Agency are available from the Environment Agency R&D Dissemination Centre, c/o WRc, Frankland Road, Swindon, Wiltshire SN5 8YF

Tel: 01793 865000 Fax 01793 514562
Email: publications@wrcplc.co.uk

7.4 Environment Agency Waste Regulation & Management research programme – published reports

Methane emissions from different landfill categories. R&D Technical Report P233a (CWM 141/97), Published July 1999

The evaluation of possible health risks to landfill site workers from exposure to gaseous waste emissions (landfill gas). R&D Technical Report P257 (CWM 140/96), Published March 2000

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Emissions from landfill gas energy recovery plant – monitoring protocols. R&D Technical Report P248 (CWM 181/99)

A framework to model health and environmental risks from landfill gas (HELGA). R&D Technical Report P271, Published February 2000

7.5 Environment Agency Waste Regulation & Management research programme – current R&D projects relevant to landfill gas

The following is a list of current projects with project number, status and contractor details.

Measurement of gas potential for landfilled material (biological methane potential test). R&D Project P1-219, active contract – Minton, Treharne & Davies

Landfill methane measurement protocols (flux box). R&D Project P1-271, active contract – WS Atkins

Gassim – landfill gas risk assessment tool. R&D Project P1-295, completed project (Software and User Manual) – Golder Associates & LQM. Details and demonstration version available at **www.gassim.co.uk**

Development of guidance on the effects of gas cleanup on the emissions from landfill gas utilisation equipment. R&D Project P1-330, active contract – LQM

Guidance on best practice management of landfill gas (review of WP27). R&D Project P1-343b, active contract – Entec

Minimising methane emissions from municipal landfills. R&D Project P1-357, active contract – in collaboration with Biffaward and Shanks.fIRSt – WS Atkins led consortium

Development of a monitoring protocol for landfill gas flare emissions. R&D Project P1-405, active contract – AEA Technology

Monitoring protocol for emissions from landfill gas utilisation systems. R&D Project P1-406, active contract – Entec

Investigation of landfill gas trace components: composition and emission. R&D Project P1-438, active contract – Komex

Quantification of trace components in landfill gas. R&D Project P1-491, active contract – Komex

Appendix 1:

Flare component selection criteria

As will be evident from the contents of these guidance notes, the selection of a flare stack involves attention to a great many diverse, and often very site-specific, requirements. The following tabulation of some of the key matters that should be considered by landfill operators is provided more as an *aide-mémoire* than as a definitive statement of selection criteria. The detailed design is the responsibility of the flare manufacturer.

A landfill gas flare system will typically comprise four principal sections, centred around the main gas booster. These are as follows:

- inlet pipework, including a valved inlet manifold and dewatering facilities;
- a gas booster (also referred to as a suction fan, an extraction fan or gas blower), which places a negative pressure or suction on the gas field and delivers the gas under pressure to the flare system;
- interconnecting pipework between the gas booster and the flare, sometimes including filters, valves and pressure regulators;
- the landfill gas combustion plant.

The following sections highlight some of the key aspects within these four sections that will be involved in an assessment of fitness-for-purpose.

Table A1.1 Inlet pipework

Item	Factors involved	Comments
Materials of construction	Strength and corrosion resistance	Inlet pipework will be typically subjected to wet, corrosive gases. Both material type and surface finish may play a part in the selection process
Valves	Size, durability and design	It is often the case that larger valves will offer less control than smaller valves. Valve materials must be suitable for a wet corrosive environment. It is the design/method of operation rather than the size of the valve that governs the degree of flow control
Condensate removal	Corrosion resistance and duty	Provision for leachate removal should be made at all low points in the system. At each point, the rate of condensate removal should be capable of preventing line blockage
Condensate collection	Volume and corrosion resistance	Vessels should be of a suitable material to withstand prolonged submersion in a corrosive environment, and of a size capable of dealing with all the condensate produced
Liquid level switches	Reliability and durability	Level switches, for advance warning about the build-up of condensate, must be capable of working in a dirty environment where solids may interfere with moving parts
Instrumentation	Zoning and durability	Instrumentation should be robust enough to operate with minimum servicing and operation in a harsh environment. All electrical feeds to the devices located on or in the pipework should comply with relevant standards pertaining to their use in potentially explosive atmospheres

Table A1.2 Gas boosters

Item	Factors involved	Comments
Materials of construction	Corrosion resistance and quality	Impellors and fan casings will be operating in moist, corrosive gas. Preferably they should be made in stainless steel or other suitable material, such as carbon steel and cast iron, but these materials can fail
Total pressure head	Field pipework size and gas end-use	Field pipework will dictate the amount of pressure loss experienced at the flow rate required to deal with the gas produced. Some end-uses, such as generation schemes, may require specific outlet pressures
Motor specification	Zoning and fan weight	Higher flow rates require bigger fans and so bigger motors. The motor needs to be correctly zoned for the application: zone 2 – where an explosive mixture may occur, or zone 1 – where an explosive mixture will occur
Drive connection	Flexibility and durability	The choice is between direct drive and belt drive. Direct drive fans require less maintenance and provide a tidier, quieter unit. The belt drive unit is easier to maintain, as the motor is separate from the fan, and different sized pulleys allow for variation in fan speed
Shut-down signals from continuous monitoring	Safety and operational requirements	Most shut-downs are safety-related and occur to prevent harm to personnel or components. Panels should be flexible enough to allow for all customer requirements to be met. An automatic shut-down on all plant is required

Table A1.3 Interconnecting pipework

Item	Factors involved	Comments
Materials of construction	Strength and corrosion resistance	Inlet pipework will be typically subjected to wet, corrosive gases. Both material type and surface finish may play a part in the selection process
Length of run	Gas conditioning requirements	Some flow meters require a minimum amount of straight, uninterrupted pipe
Flare type and operational requirements	Slam-shut	Flares with a pilot line will require an actuated main control valve, and enclosed flares will require it to be fail-safe ("slam-shut") for safety reasons. The operator may require a slam-shut valve to prevent passive venting when the flare is not burning
Manual control valve	Size and function	Some valves provide good flow control and poor isolation, and some provide good isolation and poor flow control. Ideally, flow control should involve both types of requirement

Table A1.4 Flare stack

A flare stack is selected primarily to meet health and safety concerns. These concerns are defined in terms of the impact that the unit will have on the environment, both positive and negative. In circumstances where landfill gas is generated in excess of 2,000 m^3/h, it is usually necessary to utilise more than one flare.

Item	Factors involved	Comments
Open or enclosed flare?	Period and purpose of use	See requirement No. 1
Are duty/standby gas boosters required?	Maximum permitted downtime prior to issuing an alert	In locations of high sensitivity to lateral migration, it is essential to have established emergency procedures and to fit standby equipment
Are monitoring facilities available?	Requirements of the site licence	Adequate sampling points, particularly in the stack, will assist with monitoring compliance. These must be safe, functional and easily accessible. Provision of continuous monitoring and suitable telemetry link
Flame temperature control	Exhaust gas requirements	Combustion chamber temperature control is essential if a minimum burn temperature is stipulated. The amount of air allowed into the burn zone should be automatically controlled through a motorised unit such as a damper, thus maintaining optimal fuel/air ratio
Method of achieving turn-down	Wide range of gas production rates	Maintaining high temperatures across a wide range of flow rates is best achieved using individually valved burners, potentially capable of reacting to changes in delivery pressure automatically
Shroud materials	Flare type and duty	High-temperature flares can be adequately protected from corrosion by hot dipped galvanising. At least the top 1 m of the shroud should be fabricated from stainless steel
Thermal insulation materials	Desired burn temperature	Ceramic blanket lining should be of an adequate thickness to prevent damage to the shroud. All high-temperature fixings should be ceramic or better
High-temperature shut-down	Safety	High-temperature shut-downs should be fired from at least three positions inside the stack. Duty/standby thermocouples are recommended to prevent heat damage on a thermocouple failure
Flare height	Planning permission	Flare height is dictated by the residence time required to achieve complete burn. As the flow rate increases, so do flare diameter and height. The technology is in place to reduce flare height and maintain residence time using internal exhaust gas recirculation. Plume dispersion from wide-diameter flares is less effective than from the equivalent taller, narrow flares
Exhaust gas quality	Environmental impact	The four main controls available are temperature control, combustion air control, exhaust gas recirculation and staged burning
Safety	Applicable British and European standards	Manufacturers should be ISO 9001 accredited, fabrication should be carried out by coded welders, and all electrical work should be to IEE Regulations, 16th edition (or subsequent)

Appendix 2:

Flare maintenance checklist

Routine maintenance of a flare should only take three to four days each year. Manufacturers generally offer service contracts to carry out this work.

The checks most frequently cited by manufacturers and operators include:

- checking the liquid level in the knock-out pots;
- checking belts and bearings on the gas booster;
- checking the pressure drop across filters and flame arrestors, as this indicates fouling;
- cleaning the lens on a UV flame detector.

If the flare is a standby to an energy recovery scheme, then it is important to check the regulators that control the switch-over of gas supply to the flare.

An example maintenance schedule for a high-temperature flare with electrical ignition and a UV flame detector is shown below. Not all of the components referenced will be present on all flares.

Specific guidance must be sought from the manufacturer of individual flaring systems. Flares can operate uninterrupted and unattended for several days, provided that suitable telemetry links are established and maintained.

Table A2.1 Flare maintenance schedule frequency (subject to site-specific needs)

Task	Weekly	Monthly	Quarterly	Annually
Check flow rate, pressure, temperature and monitor inlet gases	x			
Check electrical control panel		x		
Check temperature control loop components			x	
Check control of ignition electrode		x		
Replace ignition electrode				x
Clean UV lamp		x		
Replace UV lamp				x
Check/clean filter in inlet knock-out pot			x	
Check/clean/replace filters in gas sampling lines			x	
Check operation of all alarm functions			x	
Check operation of telemetry system			x	
Clean flame arrestors			x	
Check/clean motorised valves				x
Check condition of air throttle or damper		x		
Check thermocouples			x	
Check condition of terminal boxes		x		
Check condition of thermal insulation			x	
Check infrastructure integrity to assess balancing and perimeter boreholes to ensure the gas control system is operating optimally	x	x		
Check maintenance log	x			

Appendix 3:

Operational effectiveness checklist

Every visit to an operating extraction and flare system by both regulators and contracted technical/maintenance staff will have a specific number of objectives, principal amongst which is to ensure that the system is performing as is required by the dictates of the situation.

A checklist cannot be a substitute for understanding, but the following table is offered as a guide to the type of matters that should be verified during a routine visit. The topics of importance may be subdivided as follows:

- Flare operational requirements
- Extraction system
- Site operational requirements
- Environmental compliance
- Health and safety

Table A3.1 Site visit checklist

Item	Factors involved	Comments
Flare operational requirements	Flame/combustion process	Temperature, excess air and retention time
	Maintenance record	Available for inspection
	Operations manual	Available for use
	Operator training	Competent personnel on-call
	General condition	Is the system fully operational?
Extraction system	Well balancing	Effective balancing will be evident from gas quality and site records. Well balancing must be carried out by technically competent and trained staff
	Well installation programme	Is this designed effectively?
	Oxygen content	High O_2 implies a leaking system or over-extraction. This might also be detected with a high N_2 content, determined by deducting CH_4, CO_2 and O_2 percentages from 100
	General condition	Is the system operational?
	Liquid in gas collection pipework	Condensate blockages characterised by a “sloshing” sound and indicated by rapid fluctuations in gas flow rate, temperature and increasing negative pressure
Site operational requirements	Are day-to-day site-works and gas management coordinated?	Lack of planning will lead to excessive downtime
	Is the well installation programme designed to control migration effectively?	
	Do the extraction system and its operation meet the requirements of site licence?	Insufficient or poorly installed wells may meet the letter, but not the intention, of a licence

Item	Factors involved	Comments
Site operational requirements	Are the operating instructions available for use by the operators?	
Environmental compliance	Is the emission standard being achieved?	Instrumental monitoring for verification
	Are there odours?	
	Is there excessive noise?	
	Do flames or black smoke appear from the top of the flare?	
	Monitoring records of inlet and outlet gas quality	Available for inspection and up-to-date, complete with regular written reviews
	Is the surrounding radiative heat excessive?	
	Does the flame temperature match the specification?	
	Can the residence time be ascertained?	
	Are there low-temperature spots within the chamber?	Within the section designated as meeting the design requirement
Health and safety	Is casual access by the public prevented?	
	Are clear instructions on how to stop and isolate the unit readily available?	
	Are emissions monitoring requirements being complied with?	
	Is the type and design of flare suitable for the location?	
	Are emergency procedures in place and effectively dis-seminated and understood?	

Appendix 4:

Sample calculations

There are many indicative calculations that can be made with regard to the combustion process. The sample calculations provided below derive key data for assessing whether or not a flare will meet technology performance criteria. The calculations include the following:

1 Combustion air requirement

2 Normalised exhaust gas flow rate

3 Temperature-corrected exhaust gas flow rate

4 Stack exit velocity

5 Retention time

6 Gas normalisation

7 Combustion heat release

8 Landfill gas yield calculation for indicating when to commence extraction

To assist with understanding of the method employed, a hypothetical flare operating with a flow rate of 1,000 normalised[35] cubic metres per hour (Nm^3/h) of landfill gas with 50% methane and at a temperature of 1,000°C is used as the basis for the calculations unless otherwise stated.

A4.1 Combustion air requirement

Combustion air is employed both to oxidise the methane and to cool the flame. The exact amount of air required is a function of the heat losses in the specific flare considered. Where, for example, more insulation is employed on the walls of an enclosed flare's combustion chamber, the air requirement may be greater and vice versa.

The below table provides typical air requirements for an enclosed flare. These may vary from flare to flare as a function of heat loss control. To calculate the air requirement at NTP:

Combustion air requirement at

1,000°C = 1,000 Nm^3/h x 0.50 (%age CH_4) x 22.3

= 11,150 Nm^3/h

The combustion equation is:

$CH_4 + 2O_2 = CO_2 + 2H_2O$

- Nitrogen is 78.084% of air
- Oxygen is 20.946% of air
- The balance is 0.97%

On this basis, the amount of air required for stoichiometric combustion is 9.55 parts per part of methane.

A4.2 Normalised exhaust gas flow rate

Total exhaust gas flow rate

= 1,000 Nm^3/h (landfill gas) + 11,150 Nm^3/h (air)

= 12,150 Nm^3/h

Table A4.1 Typical combustion air requirements[36]

Exhaust temp. (°C)	750	850	1,000	1,100
Excess air (air/CH_4)	32	27.4	22.3	19.55
Excess air (%)	236	187	133.5	105.5

35 Normalised temperature and pressure (NTP) = 0°C and 1,013 mbar absolute pressure.

36 Kalani, L. and Nardelli, R. (1996) *Landfill Gas Flare Emissions*. SWANA 20th Annual Landfill Gas Symposium, Monterey, CA, USA, 25 March 1996. Original in Imperial units. Air volumes extrapolated to

A4.3 Temperature-corrected exhaust gas flow rate

Actual exhaust gas flow rate (corrected for temperature)

$$= \frac{12{,}150 \times (1{,}000 + 273.15)}{273.15}$$ [37]

$= 56{,}631$ m^3/h at 1,000°C

A4.4 Stack exit velocity

Assume the internal diameter of the flare is 1.5 m.

Cross-sectional area of combustion chamber

$= p r^2$ (p = 3.142; r = radius)

$= 1.767$ m^2

Stack exit velocity at a temperature of 1,000°C

$$= \frac{56{,}631}{1.767}$$

= 8.9 m/s

It should be remembered that exhaust gases will cool as they leave a flare. The cooling process usually begins before the gases reach the exit point. The actual exit temperature, therefore, will be less than the design temperature. It is prudent to allow one half-diameter for loss of design temperature. In practice, the point for loss of design temperature should be measured.

A4.5 Retention time

Retention time is the period that exhaust gases are held at the design combustion temperature, or above. Assume the height of the flare at the design temperature is 4 m.

$$\text{Retention time} = \frac{\text{height of flare at design temperature (m)}}{\text{stack velocity at design temperature (m/s)}}$$

$$= \frac{4}{8.9}$$

= 0.45 s

A4.6 Gas normalisation

$$\text{Gas normalisation} = \frac{\text{(gas reading)} \times (20.8 - O_2 \text{ normalisation})}{20.8 - O_2 \text{ gas reading}}$$

O_2 normalisation to 3% for flares.

A4.7 Combustion heat release

The potential net thermal energy input (capacity) of a landfill gas control system is given approximately by

capacity = $V \times (H_{methane} \times F_{methane} + H_{hydrogen} \times F_{hydrogen})/3{,}600$ (MW)

where

V = rate of landfill gas extraction (Nm^3/h)

$H_{methane}$ = net calorific value (CV) of methane, 35.9 MJ/Nm^3

$F_{methane}$ = fractional methane content of landfill gas

$H_{hydrogen}$ = net CV of hydrogen, 10.8 MJ/Nm^3

$F_{hydrogen}$ = fractional hydrogen content of landfill gas

For the hypothetical flare of this worked example:

combustion heat release

= 1,000 Nm^3/h x 35.9 MJ/Nm^3 x 0.50 (%age CH_4)/3,600

= 4.99 MW

A4.8 Landfill gas yield calculation for indicating when to commence extraction

Landfill gas generation	5–10 m^3 CH_4/t yr (in municipal solid waste)
Example 100,000 t landfill	dimensions 100 m x 100 m x 10 m deep (assuming 1 t = 1 m^3)
	= 500,000 m^3 CH_4/yr
	= 57.1 m^3 CH_4/h
At 60% CH4 (x 1.666)	= 95.1 m^3 landfill gas/h provides a conservative estimate

100 m^3/h is a practical threshold for flaring (i.e. 500 m^3 flare on maximum turn-down).

37 Absolute zero in Kelvin = –273.15°C.

Appendix 5:

Flare siting criteria

Environmental factors involved in the siting of flares on specific landfill sites are largely to do with the hazards to the environment that exist from both landfill gas and flares, as delineated in Chapter 3 of these guidance notes, coupled with the operational needs of the specific circumstance.

The main factors involved are placed under the following headings.

A5.1 Explosion and fire

It must not be forgotten that flares are burning comparatively large amounts of fuel gas. Ready access should be available for the emergency services, and standard fire prevention measures must be taken. Flares must not be located within enclosed spaces, such as within buildings, unless the building is properly designed to operate according to the relevant British and European Standards governing the use of electrical equipment in potentially hazardous atmospheres. Flares should also not be located near to trees or other structures that may actually ignite in high temperatures. Manufacturer's recommendations must be sought and followed with regard to the minimum spacings required.

A5.2 Asphyxia

Where enclosures are used to prevent nuisance from noise or to offer protection from the weather, and human access is possible, it must not be forgotten that landfill gas is an asphyxiant. There must be adequate ventilation or systematic safeguards to ensure that atmospheres that could asphyxiate are not given the opportunity to so do. For similar reasons, it is also advisable to avoid the location of flares in hollows, or other such locations where venting gases may collect.

A5.3 Human health

Human health is at risk from many factors. As well as the points covered above, the question of hazardous emissions is addressed here. Studies in Germany[38] indicated that at one site landfill gas was travelling 3 km in a plume, with as little as only 10% dilution. It may well be that in sites of particular sensitivity detailed dispersion analysis should be carried out to validate safety assumptions. Every attempt should be made to ensure that the plume from a flare, no matter how high a quality, should not be allowed to pass directly to a dwelling or human habitation under prevailing wind conditions.

A5.4 Odour nuisance

As has been recorded elsewhere,[40] with open flares it is possible with some models to have a large unburned fraction passing straight through a flame. It is for this reason that some open flares can actually cause odour problems, often resulting in complaints being made to landfill operators and regulators by the general public. Such odours are generally caused by trace components of landfill gas, which nevertheless exceed their associated low-odour threshold values. The source table documents the more significant compounds and their adopted odour thresholds relevant to landfill gas or flare emissions.[41]

The table also demonstrates the overall efficacy of flaring in achieving significant reductions in odorant concentrations through a combination of destructive oxidation and dilution (with combustion air). Even so, the potential for odour nuisance from flaring remains, although it is generally to a lesser extent and the character of the odour may be different:

- The process of gas collection results in a concentrated point source of emission, in contrast to the diffuse emissions from uncontrolled landfill gas.

38 Gerhardt, H.J. Model studies on gas dispersion from landfills. *Proceedings Sardinia 1993, 4th International Landfill Symposium*, 11–15 October, vol. I, pp. 669-679.

40 Gerhardt, H.J. Model studies on gas dispersion from landfills. *Proceedings Sardinia 1993, 4th International Landfill Symposium*, 11–15 October, vol. I, pp. 669–679.

41 *Guidance on the Emissions from Different Types of Landfill Gas Flares*, Environment Agency R&D Report CWM 142/96A, 1997.

Table A5.1 Highest observed concentrations and adopted odour thresholds (AOTs) for selected compounds[39]

Compound	AOT (mg/m3)	Highest observed concentration (mg/m3)		Compound	AOT (mg/m3)	Highest observed concentration (mg/m3)	
		LFG	Flare			LFG	Flare
hydrogen sulphide	0.0001	20	0.9	ethanal	0.1	12	2.7
propane thiol	0.00014	29.8	ND	ethyl butanoate	0.28	350	ND
methane thiol	0.0002	430	ND	ethyl propanoate		136	ND
diethyl disulphide	0.0003	19.8	ND	ethyl ethenoate	0.4	240	ND
ethane thiol	0.00046	24*	0.0002	ethyl benzene	0.4	428	0.5
butanoic acid	0.001	210	0.06	xylenes	0.54	1,100	1.0
pentane thiol	0.003	6.6	ND	pentenes	0.6	210	3.4
dimethyl sulphide	0.0037	135	1.7	toluene	0.7	1,700	0.7
dimethyl disulphide	0.004	40	0.14	carbon disulphide	0.7	48	7.9
furfural	0.008	3.2	ND	undecanes	0.8	290	0.64
diethyl sulphide	0.01	3.1	0.13	sulphur dioxide	1.0	ND	53
chlorotoluene	0.01	7.7	ND	octanes	1.0	675	0.05
butyl benzene	0.012	160	0.6	decanes	1.0	650	1.5
phenols	0.02	1.6	ND	heptenes	1.0	103	ND
limonene	0.02	470*	0.4	butenes	1.2	170	5.7
butyl ethanoate	0.03	60	ND	butan-2-one	2.0	160	0.2
hydrogen fluoride	0.03	ND	5.5	nonanes	2.0	400	0.5
butane thiol	0.04	16.1	ND	heptanes	2.1	1,054	ND
propyl benzene	0.04	490	1.2	trichloroethylene	3.0	182	0.9
methyl butanoate	0.05	305*	ND	propan-2-one	3.0	4,300	0.1
naphthalene	0.05	21	0.01	octenes	5.0	144	ND
styrene	0.07	150	ND	methanol	6.0	400	3,580
dipropyl ether	0.07	220	ND	benzene	9.0	114	0.8
butan-1-ol	0.077	170	0.1	propanol	10	210	0.07
hexenes	0.08	316	ND	chloromethane	21	1,300	0.1
nitrogen dioxide	0.1	ND	256	chloroethene	39	264	ND
butan-2-ol	0.1	210	0.6	ethanol	100	3,200	2.3

* Concentration as ppm.
ND not detected.

- A few potent organosulphurous and other odorants can be produced in flaring, probably as a result of inefficient combustion and residence time (see Chapter 5), although overall their concentration is reduced.
- Some of the products of combustion – SO_2, HF and NO2 – have low to medium AOTs. The AOTs of some odorous organic compounds are below their limits of analytical detection, and hence, even if not detected in flare emissions, they might contribute to malodour.

39 *Guidance on the Emissions from Different Types of Landfill Gas Flares*, Environment Agency R&D Report CWM 142/96A, 1997.

A5.5 Noise pollution

Flares can be very noisy. As well as the noise of the mechanical equipment involved, there may also be an element caused by the combustion process itself. Preferably a flare should be located away from buildings. Where this is not possible, it may be necessary to employ extensive sound attenuation measures. These may include brick buildings with sound baffles on ventilation ports. Noise levels are the subject of local planning requirements, and due regard should be given to background noise levels on a site-specific basis when designing flares, particularly at landfill sites in close proximity to residential development. The gas booster may be encapsulated in a soundproof box as a noise reduction measure. Noise levels in the order of 45 dB(A) at 10 m from a flare can be achieved. A noise reduction of 3 dB(A) can be expected if the distance from source is doubled, e.g. the noise level at 1.3 m above ground level at a distance of 20 m from an enclosed flare is measured at 70 dB(A) and 67 dB(A) at 40 m from the flare.

Under rare conditions the low-frequency vibration derived from the turbulence within enclosed flares can induce resonance within nearby structures such as buildings and vehicles. The effects of the vibration can include nausea and headaches. The effect is attenuated with distance, so extreme care must be taken to ensure that flares are not sited within the range of such receptors.

Figure A5.1 High-temperature, low-emissions enclosed flare within a brick enclosure to reduce noise impact

A5.6 Heat

All flares produce heat. The first source is radiative heat from the flame. This is only present in open flares or enclosed flares operating above their design point. With an enclosed flare, the unit should be operated within its performance limits, whatever they prove to be. The second source of heat is through the walls of a combustion chamber. Where the combustion chamber has inadequate insulation, the outside surface temperature may be an actual danger.

Manufacturers should be asked to demonstrate the control of heat built into their flares. Radiative effects are typically evident within a 10 m zone from a flare, dependent on height.

A5.7 Visual impact

Whilst combustion engineers and individuals with an eye for *art nouveau* may appreciate the structural form of flare stacks, it is rare that they might be considered to have contributed to the natural beauty of a locality. For this reason, it is best to avoid the siting of flares on high points within a site, unless there is no other alternative location. The responsibility for visual impact rests with local planning authorities, who may specify individual requirements.

A5.8 Ground type

A flare should preferably be located on firm original ground. Flares will often need to be in position for many years, and there is a temptation to place them on the landfill itself. Whilst this can be done with the proper civil engineering precautions in place, these will probably include piles and concrete rafts. Over the longer term, the surface of a landfill will settle, often significantly. Even a modest amount of differential settlement can result in an unsafe installation.

A5.9 Operational requirements

A flare should be easily accessible for operation and maintenance. Where a flare is to be located on the far side of a site, for example, an access road should be provided.

Landfill gas often emerges from the ground in a warm saturated condition. As the gas cools, large quantities of condensate can be formed.

It is generally preferable to have this condensate falling away from the inlet to the flare, rather than into the flare condensate knock-out pot. The flare condensate knock-out pot is designed to collect water from the gas that is formed in the pot itself rather than to deal with large quantities that flow into the flare from the pipeline. Where a low point cannot be avoided, the unit should be designed to cater for large condensate flows.

A6

Appendix 6:

Glossary and abbreviations

A6.1 Glossary of terms

Adiabatic	Occurring without loss or gain of heat.
Aerobic	In the presence of oxygen.
Air-staging	The input of air into a burner at different levels to manage flame temperatures and control the formation of NO_x.
Anaerobic	In the absence of oxygen.
Asphyxiation	The lack of oxygen in the blood due to restricted oxygen intake.
Blow-off	A combustion condition in which the flame front moves away from the burner to a point where it is terminally unstable and extinguished.
Burnout	Completeness of combustion.
Calorific	value The heat liberated by the complete combustion of a unit quantity of fuel. The gross (or higher) calorific value is the total heat available after the water formed as a combustion product has condensed. The net (or lower) calorific value signifies that the water formed is still vapour.
Combustion air	The air supplied to burn the fuel.
Condensate	The condensed water and associated soluble compounds derived from the landfill gas stream.
Diffusion flame	Flame in which no combustion air contacts the fuel upstream of the burner head or stabiliser.
Emission	A material that is expelled or released to the environment. Usually applied to gaseous or odorous discharges to the air.
Environmental impact	The effect of any operation on the surrounding environment.
Excess combustion air	The air, above the stoichiometric requirement, that is supplied to assist the combustion of a fuel.
Flame speed (burning velocity)	The speed, normal to the mixture flow, at which the flame front travels through a fuel vapour/oxidant mixture.
Flammability limits	The limits, expressed as the concentration of fuel in oxidant, within which the fuel/oxidant mixture will ignite. The upper (rich) limit is the point above which there is too high a concentration of fuel to ignite. The lower (lean) limit is the point below which there is not enough concentration of fuel.
Flammable	A substance capable of supporting combustion in air.
Flash-back	A combustion condition in which the flame front moves upstream and into the burner body, where it may or may not extinguish (applies to pre-mix burners).
Flue gas recirculation	The function of removing exhaust gases from a burner exit and feeding them back into the burner with combustion air to control NOx formation.
Forced draught	Air supplied by external mechanical means such as a fan or blower.
Fuel	Any substance that will react with an oxidant with the release of heat energy.

Fuel staging	Passing fuel into a combustion chamber at different locations to spread flame intensity and control NOx.
Gas migration	The movement of gas from the wastes within a landfill site to adjoining strata, or emission into the atmosphere.
Landfill	The engineered deposit of waste into or onto land in such a way that pollution of the environment is minimised or prevented and, through restoration, provides land that may be used for another purpose.
Landfill gas	All the gases generated from landfilled waste.
Leachate	Polluted water emerging from a landfill, originating from water ingress or biological degradation.
Lower explosive limit (LEL)	See "Lower flammability limit".
Lower flammability limit (LFL)	The lowest percentage by volume of a mixture of flammable gas with air that will propagate a flame.
Monitoring	The physical examination, measurement by portable instrument, and analysis of samples to provide information for assessment of conditions.
Natural draught	Air induced into the burner by the pressure differential generated across the burner due to gas temperature changes and chimney height.
Odour	The smell of a material or collection of materials.
Odour threshold value	Lowest concentration of an odorous substance that can be detected by sense of smell.
Operational sites	Sites that are not completely filled, operating under a licence, including sites that are temporarily closed for whatever reason.
Oxidant	A substance (usually oxygen in air) that reacts with the fuel in the combustion process.
Photochemical air pollution	Pollution resulting from the effects of light and other electromagnetic radiation on airborne chemicals.
Pre-mix burners	A class of burner in which the combustion air and fuel are mixed to varying degrees before they leave the burner nozzle.
Primary air	A proportion of the combustion air that initially mixes with the fuel prior to exit from the burner port. See also "Secondary air".
Retention time	The time period at which the gases are at a specified temperature.
Reticulation	The process of stripping out unwanted gases.
Sampling point	Sampling points are at the centres of equal areas for circular and rectangular ducts. Sampling points should not be located within 3% of the sampling line length (if d or l > 1 m) or 3 cm (if d or 1 < 1 m) from the inner duct wall.[42]
Secondary air	Combustion air introduced into the flame after the burner port or exit. See also "Primary air".
Soot	Submicrometre particles of carbon that arise from gas-phase combustion with inadequate air.
Stoichiometric	The exact proportions in which substances react. For combustion, the theoretical minimum amount of air or oxygen required to consume the fuel completely.
Stratosphere	The atmospheric layer in which temperature increases with height.
Sub-stoichiometric	When there is insufficient air or oxygen to allow complete combustion of the fuel.
Tertiary air	An auxiliary air supply in addition to primary and secondary air, which may be added downstream of the flame to stage the combustion process.
Toxic	A substance or material that can produce a detrimental effect on human, animal or plant life.
Turn-down ratio	The ratio of the maximum firing rate of a burner and the minimum. A 2:1 ratio means that the minimum is half the maximum fuel firing rate.

42 Environment Agency Technical Guidance Document (Monitoring) M1 *Sampling and Safety Requirements for Monitoring Releases to Atmosphere.*

Upper explosive limit (UEL)	See "Upper flammability limit"
Upper flammability limit (UFL)	The highest percentage by volume of a mixture of flammable gas with air that will propagate a flame.
Volatilisation	Release of constituents in waste as gases when the temperature is raised.

A6.2 Abbreviations

AOT	adopted odour thresholds
AQMA	Air Quality Management Area
CFC	chlorofluorocarbon
COSPEC	correlated spectroscopy (correlates absorption spectra with reference spectra)
CV	calorific value
DIAL	differential absorption LIDAR
DOAS	differential optical absorption spectroscopy
DRE	destruction and removal efficiency
FTIR	Fourier transform infrared
GDPO	General Development Procedure Order
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HCl	hydrogen chloride
HF	hydrogen fluoride
I-TEQ	international toxicity equivalent (a normalised expression of concentration for PCDDs and PCDFs)
LEL	lower explosive limit
LFG	landfill gas
LFL	lower flammability limit
LIDAR	light detection and ranging
MJ	megajoules
MSW	municipal solid waste
MW	molecular weight
NAQS	National Air Quality Strategy
ND	not detected
NFFO	Non-Fossil Fuel Obligation
NMOC	non-methane organic compound
NMVOC	non-methane volatile organic compound
NO_x	oxides of nitrogen, including nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O)
NTP	normal temperature and pressure (0°C and 1,013 mbar)
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCDD	polychlorinated dibenzodioxin
PCDF	polychlorinated dibenzofuran
PTFE	polytetrafluoroethylene
SO_x	oxides of sulphur, including sulphur oxide (SO) and sulphur dioxide (SO_2)
STA	Source Testing Association
THC	total hydrocarbons
TLV	threshold limit value
TOC	total organic carbon
UEL	upper explosive limit
UFL	upper flammability limit
UKAS	UK Accreditation Service
UV	ultraviolet
VOC	volatile organic compound
WMP	Waste Management Paper

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