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Control of landfill gas containing low concentrations of methane

Science Report – SC030305/SR2

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SCHO1008BOUU-E-P

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Steve Killeen

Head of Science

Executive summary

Landfill gas with a high methane content is relatively straightforward to burn and on modern landfill sites is often used to generated electricity. This avoids local pollution problems and significantly reduces the potential impact on global warming from the landfill site. However, once the methane content of the landfill gas falls below a certain level it cannot be used to generate electricity and the gas will need to be flared instead. When the methane content falls again, there is simply not enough methane to keep a flare alight. At this point the gas is known as low calorific landfill gas and it is currently vented untreated into the atmosphere where it acts as a greenhouse gas over 20 times more potent than carbon dioxide.

It is not known exactly how much methane is released from this source, however figures from the Department for Environment, Food and Rural Affairs (Defra) show that methane releases from landfill sites accounted for approximately three per cent of the UK's total greenhouse gas emissions in 2006 (Defra, 2008). Defra has estimated that a minimum of 25 per cent of these emissions come from old, closed landfill sites likely to be emitting low calorific landfill gas.

Unfortunately, these figures are based on a model of the UK's methane emissions rather than direct measurements and it is therefore hard to quantify the extent of emissions and the type of site from which they come. The Environment Agency is planning work to investigate this issue, but at present it appears that old, closed sites are contributing a significant proportion of the UK's methane emissions from landfill. Reducing emissions of low calorific landfill gas should therefore be a priority for industry and government.

In the past it has proved difficult to treat the methane in low calorific landfill gas by burning it in a flare. Low calorific gas does not contain enough methane to sustain a flame, which is why standard flares cannot burn it. Specialised low calorific flares have now been developed to counter the problem and this report reveals the results of trials of two such flares.

The trial results show that the technology exists to flare low calorific landfill gas in a safe manner that complies with Environment Agency guidance on the minimum temperature and residence time for the destruction of landfill gas. However, care will need to be taken in the design and operation of the gas field within the landfill site, as the extraction of low calorific gas will require a different approach to that for standard landfill gas.

Overall, this technology shows significant promise as a way of reducing emissions of methane, both in the UK and worldwide.

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1 Landfill gas and methane

1.1 Production of landfill gas

Micro-organisms present in municipal solid waste (MSW) degrade the organic content of the waste as part of their normal metabolic process. In a landfill site, where airflow is limited, the conditions quickly turn anaerobic as the available oxygen is exhausted by microbial action. Under anaerobic conditions the micro-organisms present degrade the organic content of MSW and release carbon dioxide and methane, as well as a range of trace gases and vapours, which are collectively termed landfill gas. Where anaerobic conditions prevail, over 90 per cent of the energy available in the organic MSW will be converted to carbon dioxide and methane. In the early life of a landfill, for example years five to 15, a significant amount of methane-rich landfill gas is often produced (see Figure 1.1 below) - typically 5 to 10m^3 per tonne of waste each year. If uncontrolled, this would represent a significant safety problem (as methane and air mixtures can be explosive), a massive greenhouse gas (GHG) problem (as methane is a potent GHG), and local pollution problems. Consequently, modern engineered landfill sites are required to collect the gas generated and to control its emission.

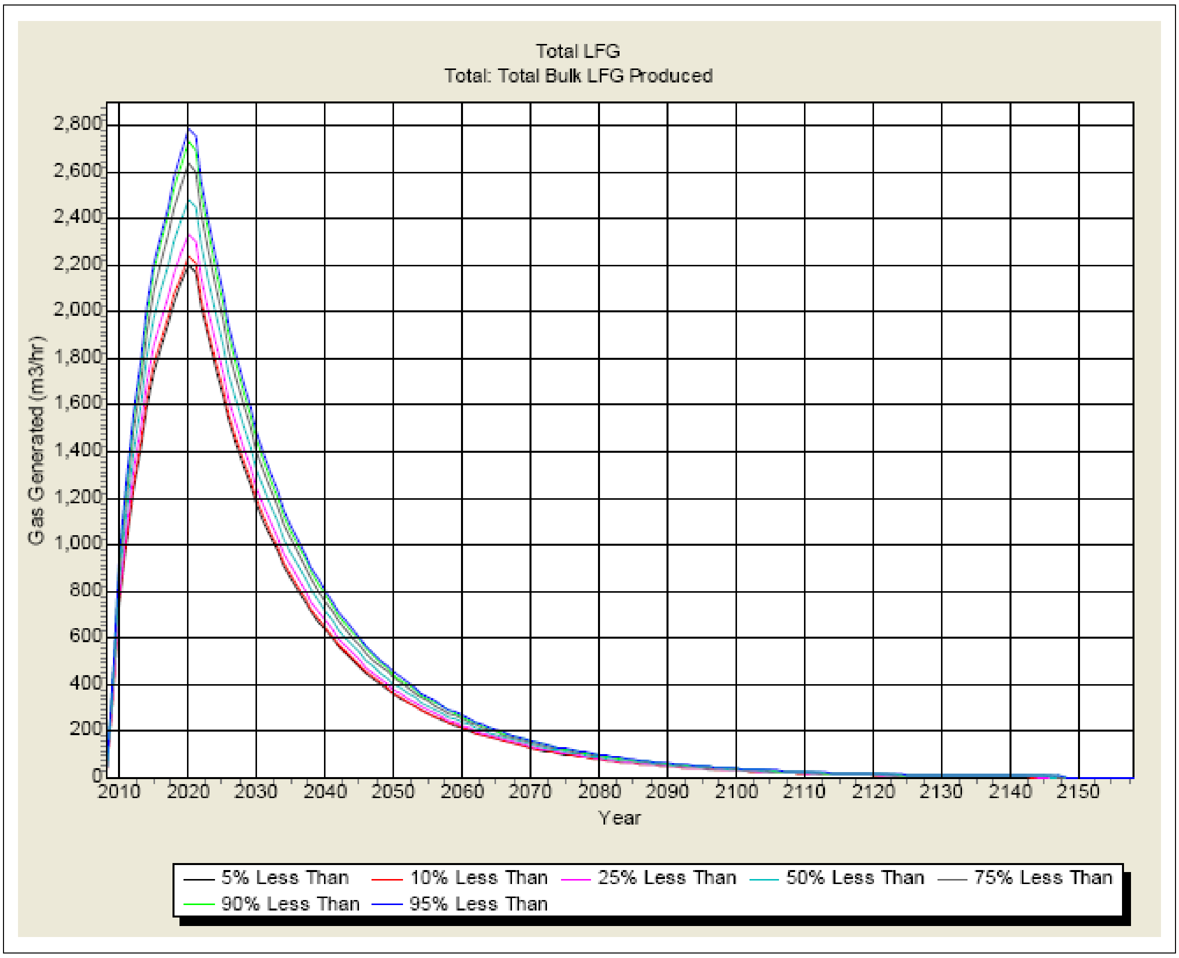

Figure 1.1 Model output of estimated landfill gas emissions for an individual site

Figure 1.1 shows a typical output from the GasSim model used to estimate emissions of landfill gas as part of the Environmental Permitting process for landfill sites. While the vertical axis shows total gas generated rather than methane concentration, the curve would look very similar if methane concentration was plotted against time. The area under the lines represents the total amount of landfill gas emitted over the lifetime of the landfill site. Low calorific flares would tend to be used at around the 200-400 m^3/hr point, depending on site conditions, which gives an indication of the proportion of methane that could be captured by the installation of low calorific flares. It should be noted though that there are concerns that the outputs from GasSim may not accurately reflect on-the-ground emissions.

During peak landfill gas production, the typical composition of landfill gas will be 50-65 per cent v/v methane and 30-40 per cent v/v carbon dioxide. As a landfill ages, gas generation deteriorates, producing gas with reduced methane content and sometimes with an intermittent flow. The quantity and rate of production of landfill gas, as well as the level of methane present within it will decline for a variety of reasons. These may occur together resulting in a cumulative effect and include:

- Dilution with air. Air is often drawn into a landfill as a result of gas pumping, changes in the relative pressure within the landfill, or deterioration of the extraction infrastructure. The introduction of air results in a nitrogen/carbon dioxide/oxygen/methane gas mixture.
- Dilution with nitrogen from air. Where air is introduced into a system, aerobic micro-organisms are able to use the oxygen present in that air to oxidise methane, which is generated in areas of the landfill that remain anaerobic. This results in a nitrogen/carbon dioxide/(residual) methane gas mixture.
- Reduced methane production. In older landfills the amount of methane generated decreases as the organic content of the waste is reduced following microbial action. This results in a carbon dioxide-rich gas mixture.

The timescale of this decline will depend on a number of site-specific factors, such as moisture content and the types of waste in the landfill. However, this low-level gas production can continue for decades and, cumulatively, could represent a significant source of GHG that requires control.

Landfill gas with a high methane content (40-60 per cent v/v) is relatively straightforward to burn, thus alleviating local pollution problems and significantly reducing the global warming potential of the gas emitted. As a general rule, once the methane content of the landfill gas falls below approximately 30 per cent v/v then difficulties sustaining combustion in engines can occur. At this point landfill gas would normally be flared through a high temperature flare. However, once the methane content falls further, to approximately 20 per cent v/v, difficulties can occur in sustaining combustion within the flare. This is low calorific landfill gas and it is currently vented untreated into the atmosphere.

1.2 The scale of the problem

The Department for Environment Food and Rural Affairs' (Defra) published figures for UK GHG emissions show that the main source of methane emitted to the atmosphere in 2006 was landfill, which accounted for 39.5 per cent of all methane emissions. Weighted by a global warming potential of 21, methane accounted for 7.5 per cent of total UK GHG emissions in 2006, which means that methane releases from landfill accounted for approximately three per cent of the UK's total GHG emissions (Defra, 2008).

Defra estimated overall emissions of 927,000 tonnes of methane from landfill sites in the UK in 2005. This figure comprises: 239,000t from 'old' sites (closed before 1980 and without gas collection systems); 351,000t from 'middle aged' sites (closed between 1980 and 1986 with limited or no gas collection systems); and 337,000t from 'young' sites (closed after 1986, or currently operational with comprehensive gas collection).

Unfortunately, these figures are based on a model of the UK's methane emissions rather than direct measurements, and it is therefore hard to quantify the extent of emissions and the type of site from which they come. The Environment Agency is planning work to investigate this issue, but at present it appears that closed sites are contributing a significant proportion of the UK's methane emissions from landfill. Reducing emissions from old landfill sites should therefore be a priority for industry and government.

1.3 Low calorific value landfill gas

The most common sources of low calorific value landfill gas are:

- Older closed landfills.
- Perimeter gas collections.
- Leaky landfill gas collection systems.
- Over-pumped landfill gas collection systems.
- Poorly balanced landfill gas collection systems.
- Shallow waste deposits subject to atmospheric conditions.

1.3.1 Closed landfill sites

There are three key challenges to overcome in the control of landfill gas originating from older closed landfill sites:

- Variable gas flow rates make it awkward to maintain the feed to a combustion process.
- Low gas flow rates make it harder to maintain an optimum combustion temperature in a normal flame.
- Low methane levels produce a gas which, when mixed with air, is below the lower flammability level.

1.3.2 Perimeter gas collections

Gas is collected from the perimeter of some landfill sites in order to prevent it migrating off site. Perimeter gas tends to have a low methane content and a high oxygen content as ambient air is pulled into the system and dilutes the collected gas.

1.3.3 Collection system leaks

Ambient air can be pulled into the system via leaks and through the site cap. This will have the effect of increasing the oxygen content of the collected gas, while proportionally reducing the methane content. When the oxygen level reaches five per cent, this creates an explosive gas, which does not require mixing with air prior to combustion, but presents risks of explosion and fires within the waste or gas collection pipework.

1.4 Landfill gas composition

The composition of landfill gas varies widely between sites, over time and with different gas collection regimes. Typical composition ranges for a methane-rich landfill gas are seen in Table 1.1. As methane generation declines over time, so does the generation of the other gas components. As landfills evolve, landfill gas also often becomes diluted with air or the products of air (nitrogen). The precise composition of a site's landfill gas will need to be determined to assist in the selection of an appropriate control technique.

Table 1.1 Typical landfill gas composition

Constituent		**Typical concentrations (percentage v/v)**	**Trace components**
Methane	CH_4	50 – 60	Hydrogen sulphide, non-methane volatile organic carbons (NMVOCs) and halo-carbons
Carbon Dioxide	CO_2	30 – 50	
Nitrogen (from air)	N_2	0 – 15	
Oxygen (from air)	O_2	0 – 2	
Hydrogen	H_2	0 – 2	
Trace components		0 – 1	
Water vapour	H_2O	Saturated	

Source: IEA Bioenergy, 2000.

1.5 Biofilters

There are two basic approaches to the control of generated methane: thermal oxidation and biological oxidation. Thermal oxidation is the reduction of methane to carbon dioxide and water vapour in a flame, and has been the traditional method of controlling landfill gas in the UK. Biological oxidation is the reduction of methane to carbon dioxide and water through the normal metabolic process of micro-organisms, and is an emergent technology still under development.

Biofilters consist of a packed bed (typically compost, peat moss or wood chips) on the surface of which is a biofilm (micro-organisms, including bacteria and fungi). Air or gas flowing through the packed bed transfers organic pollutants onto the biofilm, which is able to absorb and metabolise them. This type of system has been used successfully to remove low concentrations of odorous compounds from landfill gas and other odorous gases generated at waste water treatment works, food factories, and so on. The micro-organisms present in existing systems have the ability to metabolise methane. This type of system has been demonstrated in the laboratory to oxidise 90 per cent of the methane content of a 20 per cent methane in air gas mixture at $50m^3/hr$ (Stachowitz, 2003). However, this success has yet to be repeated in operational systems.

Biofilters are live colonies of micro-organisms and require careful control of pH, temperature, oxygen and nutrient level. One of the key operational challenges is to prevent drying of the packed bed, which results in biofilm die off and loss of gas treatment. This can be avoided by wetting the gas fed into the filter. Because of the careful control required for optimum gas treatment, biofilters are regarded as high maintenance systems. Large airflows may be treated with this type of system (which has been demonstrated for odour control), although a large area is required to house the process. This has been a key drawback to widespread adoption of the technology.

Details of the micro-organisms involved and the physical phenomena which underpin biofilter systems are not yet fully understood. Further development of these systems is required if they are to be used for methane abatement in the future.

1.6 Combustion basics

Understanding the combustion process provides an insight into the challenge of burning low calorific gas. The basic reaction that releases the majority of heat energy from landfill gas is the oxidisation of methane:

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

and:

$2H_2 + O_2 \rightarrow 2H_2O$ + heat

During combustion processes, fuel is admixed and reacted with an oxidant to produce heat and visible radiation. In landfill gas utilisation and flaring systems, landfill gas is used as the fuel and air (containing approximately 21 per cent oxygen) used as the oxidant. The stoichiometric ratio of air to methane (at standard temperature and pressure, STP) for idealised combustion is 9.52:1. In practice, excess air is used to ensure complete oxidation of the methane and other flammable components within landfill gas.

1.7 Ignition temperature and flammability

The ignition temperature of a mixture of combustible gas and air is the lowest temperature at which the combustion is self-propagating. At this temperature the rate of heat release from the combustion process just exceeds the rate of heat loss to the surroundings, and no external heat is required to maintain the combustion process. The ignition temperature for methane in air at atmospheric pressure is 925-945K (625-672°C).

A mixture of landfill gas and air cannot achieve self-sustaining combustion if there is either too little or too much methane present. All combustible gases have upper and lower limits of flammability, and a specific range of fuel and air mixtures that can be ignited. Flammability limits for methane are shown in Table 1.2, with figures for other fuel gases. These figures are approximate for mixtures of gas and air at standard temperature and pressure. Both the upper and lower flammability limits will be dependant on the specific conditions in the combustion chamber, including temperature, pressure, volumetric composition of the fuel gas, size and shape of the combustion chamber and the direction of flame propagation. For example, the levels of nitrogen and carbon dioxide present in the fuel gas (landfill gas) will affect the range of flammability for methane. Where a gas mixture is above the upper flammability limit, it may be diluted with air to bring it into the flammable range.

Table 1.2 Flammability/explosive limits

Constituent		Lower limit or lean limit (percentage v/v)	Upper limit (percentage v/v)
Hydrogen	H	4.0	75.6
Methane	CH_4	5.0	15
Ethane	C_2H_6	3.0	15.5
Propane	C_3H_8	2.0	9.5
Butane	C_4H_{10}	1.5	9.5
Ethylene	C_2H_4	2.7	34

Source: Environment Agency, 2008.

Flammability limits are key when considering low calorific gases because they dictate that very low calorific gas cannot be burnt as a normal self-sustaining flame. The technologies developed for burning low calorific gases aim to maintain an adequate combustion temperature by introducing energy to the combustion process and by reducing heat loss from the combustion chamber, so reducing the cooling effect of gas flow at ambient temperatures

The main problems with the combustion of low calorific landfill gas are therefore ensuring that:

- There is adequate heat or energy within the process to sustain the combustion.
- There is adequate oxygen to ensure complete combustion.
- A high enough temperature can be achieved to ensure destruction of trace components of the landfill gas without forming polluting by-products.
- The risk of low concentrations of methane leading to potentially explosive mixtures of methane of 5-15 per cent v/v may exist in pipework is recognised.

1.8 Optimum combustion

The design of a combustion process should aim to maximise the conversion of methane, so minimising releases of unburnt methane, other unwanted by-products of incomplete combustion and temperature dependant formation of oxides of nitrogen. This is the case for established landfill gas control techniques, which are subject to strict emissions standards. By-product formation varies in relation to the air to fuel ratio, the temperature of combustion and the residence time in the flame. Typical by-products and their formation are noted in

Table 1.3 below.

Table 1.3 By-product formation

By-product/pollutant		Formation
Carbon monoxide	CO	Complete oxidation of CO requires temperatures in excess of 850°C and a residence time of >0.3s.
Partially oxidised hydrocarbons		Temperatures in excess of 850°C throughout the flame prevent the formation of these unwanted molecular combinations.
Dioxins and furans		
Poly-aromatic hydrocarbons	PAH	
Nitrogen oxides	NO_x	Oxidation of nitrogen to give NO_x occurs at temperatures above 1,200°C. Oxidation of nitrogenous NMVOC also occurs within the flame to give NO_x.

Source: IEA Bioenergy, 2000

An optimum combustion process would therefore maximise the desired reactions and minimise unwanted reactions. In order to do this the combustion process should provide a temperature range between 850°C and 1,200°C with a minimum residence time of 0.3s.

1.9 Calorific value

Calorific value (CV) is the amount of heat energy liberated by the combustion of a fuel, expressed as work potential for that heat, per unit of gas - MJ m^3. For landfill gas, which is predominantly carbon dioxide and methane, the main combustible component is methane (other combustible molecules will be present at trace levels), so the CV is closely related to the methane content of the gas. High methane concentration gas (rich gas) will burn rapidly in air and with a hot flame. Low calorific concentration gas (lean gas consisting of less than 20 per cent methane) will burn less rapidly in air, with a low temperature flame. Methane concentrations and calorific values are illustrated in Figure 1.2 below. The net value for methane (CH_4) is 35.88 MJ/m^3, which equates to 9.97 KWh/m^3 or ~10 KWh/m^3. If the typical concentration of methane in landfill gas extracted from a site is 50 per cent v/v, it would give a fuel with an energy content of 5 KWh/m^3.

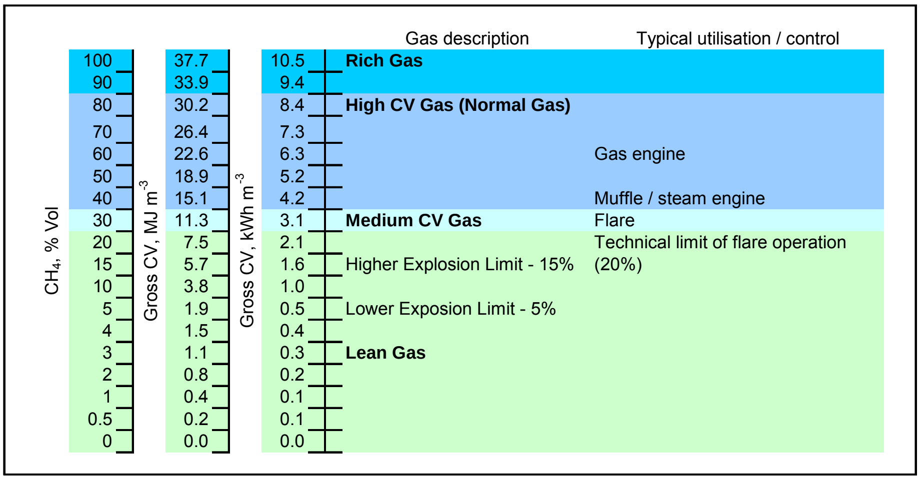

Figure 1.2 Methane content and calorific values for landfill gas

Source: Based on Haase Energietechnik Gruppe, 2008.

1.10 Amendments to standard flares

Traditional flare systems can be adapted to deal with a low or intermittent gas flow at old landfills with the use of timed cycles. This gas flow control method allows a build up of landfill gas in the collection system. A period of gas build up is followed by a period of flaring in a normal flare. A standard flare may be fitted with a re-ignition system for this type of gas control.

Standard flare systems may also be adapted for the combustion of low calorific gas generated in old landfills. However, as methane concentrations fall below 20 per cent, these measures cease to be effective. Alternative control techniques are required for this very lean landfill gas.

1.11 Flare rating

Traditionally, flares in the UK are described in terms of the volumetric capacity or the flow rate of landfill gas that they are capable of burning. It is common to hear flares described as having a capacity of 1,000 m^3 per hour with a turn down ratio of 5:1 to reduce the volume of gas burnt. Turn-down is the ratio of minimum gas flow to maximum gas flow under which satisfactory operating conditions of temperature and complete combustion will be maintained. Thus the above flare would be expected to satisfactorily burn between 200 m^3 and 1,000 m^3 of landfill gas per hour. The achievable turn-down actually depends upon the range of energy release or power rating the flare is designed for and permissible exit velocities from the burner tip. 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 per cent v/v.

However, during discussion of low calorific flare sizing, the design power rating is more appropriate than volumetric flow. This describes the energy needed to achieve satisfactory operating conditions during combustion and can be related to the methane content of the landfill gas. As we have seen, methane has an energy content of ~10 KWh/m^3. Therefore landfill gas with a methane content of 10 per cent v/v will have an energy content of ~1 KWh/m^3. A flare rated at 200kWth will therefore need $200m^3/h$ in order to operate at design specification. However, if the methane content is higher, for example 20 per cent v/v, then the flare would only be able to deal with $100m^3/h$. In this manner, low calorific flares have the capability to operate over a range of conditions, either a small volume of relatively high gas quality or a larger volume with low methane content. The sizing of the flare needs to be carefully matched to the expected quantities and quality of gas from the site to ensure maximum operational life.

2 Results of low calorific flare trials

2.1 HAASE Energietechnik AG/Clarke Energy Limited

Clarke Energy Limited has been the sole UK distributor for HAASE Energietechnik AG equipment since 1995/96. HAASE is a German company specialising in the manufacture of flare stacks, gas processing equipment, anaerobic digestion plant, mechanical and biological treatment plant and reverse osmosis equipment.

HAASE produces a range of conventional high temperature flares that are suitable for gases with methane content in the 25-80 per cent v/v range. A range of modified high temperature flares are also available, suitable for a 20-60 per cent v/v operating regime. The HAASE low caloric value, or lean gas, flare has recently been introduced to the range and is capable of treating gases with methane content in the 10-50 per cent v/v range.

The principle differences between the HAASE lean gas flares and their standard high temperature cousins are that:

- The combustion air is preheated through the use of an internal heat exchanger.
- Special lean gas burners are used in the flare system.
- The combustion of the ignition and start-up phase of the flare is supported by a propane or natural gas burner.

Other key features of the lean gas flare range are:

- Sizes from 100kWth to 1,800kWth, translating to a gas flow rate of 100-1,800m^3/hr at 10 per cent v/v methane concentration.
- A modular design. They can be applied in adapted versions for higher methane levels and subsequently retrofitted for operation with 'leaner' gas.
- The burning temperature of the flare is controlled to 1,000°C, thus ensuring that the emission concentrations for carbon monoxide and oxides of nitrogen are below UK limits.
- Dimensioning of the flare is such that the 1,000°C temperature is maintained for a minimum of 0.3 seconds.
- Thermal load regulation (turn-down ratio) of 3:1.

A prototype HAASE flare has been installed at a closed municipal waste landfill in Northern Germany since 2006. Figure 2.1 below shows the input gases to the flare and confirms that it is able to combust gas with a methane content of below 20 per cent v/v. The original chart is attached in Appendix 1, with a more detailed report contained in Appendix 2.

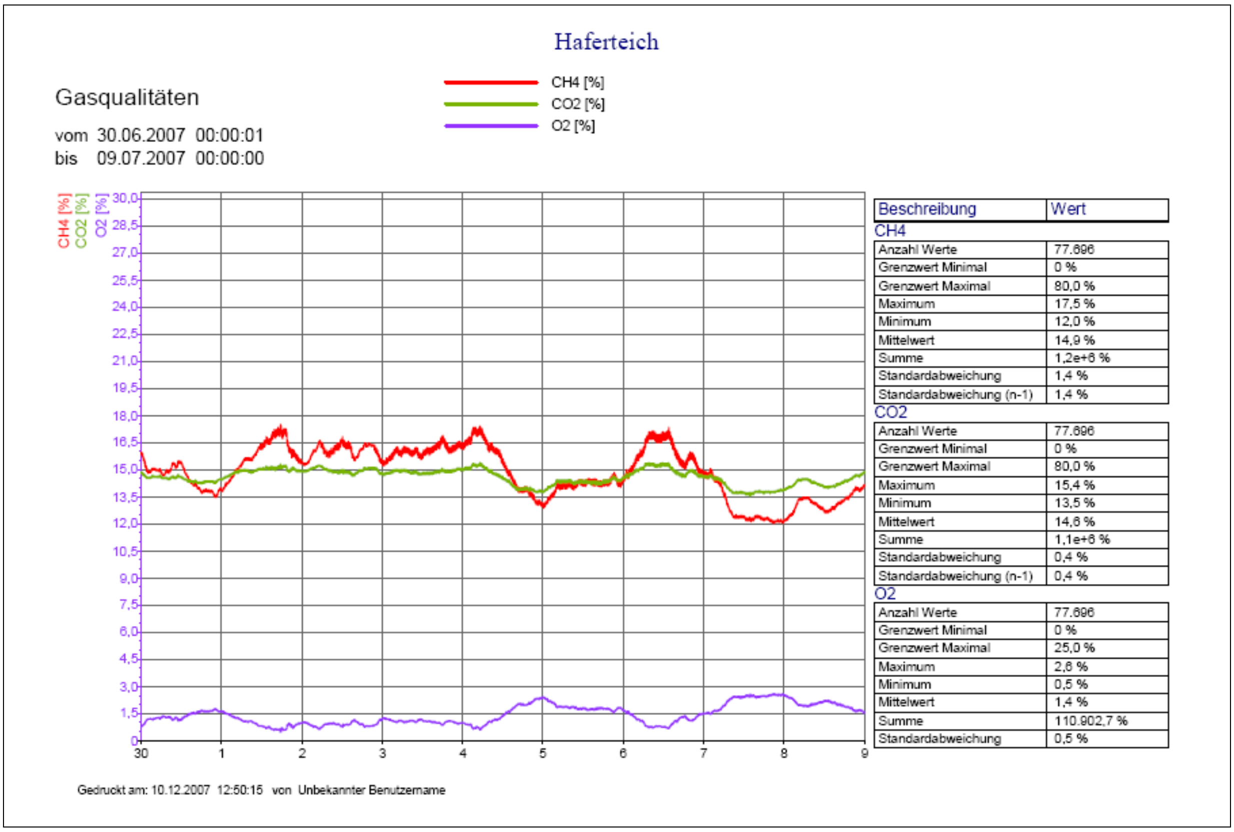

Figure 2.1 Levels of methane, carbon dioxide and oxygen entering HAASE's trial low calorific flare

The flare was designed to meet the TA Luft emission standards, the German emission standards for stationary engines, which are widely referred to by flare manufacturers in Europe. Emissions from the flare have also been tested using a handheld combustion meter, which demonstrated that the flare would meet UK emission standards.

HAASE has not yet fully developed the range of lean gas flares, so at present each flare is made to site-specific requirements, which means that exact costs are not available. However, indicative costs are in the region of £70-80,000, with an annual maintenance cost of £2,250.

2.2 Hofstetter Umwelttechnik AG / ENnate Limited

ENnate Limited is a subsidiary company of Infinis Limited and is the sole UK distributor for Hofstetter high temperature flares in the UK. Hofstetter is a Swiss company specialising in combustion systems for landfill gas. As well as a range of conventional high temperature flares, Hofstetter has also recently developed the **HOF**GAS® Lowcal flare, which is able to combust gas down to a minimum of 15 per cent v/v methane and still meet the Environment Agency's standards for flare emissions.

These flares use a specialised burner and control of the air to fuel ratio to ensure that combustion is optimised and that a minimum temperature of 1,000°C is achieved. During development of the low calorific flare, emissions testing was carried out on a prototype. A report detailing the testing is attached in Appendix 3.

The specific features of Hofstetter **HOF**GAS® Lowcal flares are:

- Designed to operate between 15-30 per cent methane v/v.
- A range of four models (XS-L) with sizes from 120-1,800 KWh and flow range of 40-600 m^3/hr.
- A turn-down ratio of 5:1.
- A combustion temperature of 1,000-1,200°C with retention time of at least 0.3 seconds.

Further details of the Hofstetter **HOF**GAS® Lowcal range of landfill gas flares are contained in Appendix 3. Cheshire County Council has recently installed Hofstetter **HOF**GAS® Lowcal flares at five closed landfill sites in its area.

3 Other considerations

3.1 Extraction system design

The extraction system for a low calorific flare will comprise essentially the same elements as a conventional flaring system. A network of extraction wells within the waste is connected to a booster fan, which applies negative suction pressure to the wells to draw the gas into the system. The fan then ‘boosts’ the gas pressure to deliver the gas to the flare at an appropriate pressure and flow for the flare to burn the gas. The design of the extraction system will need careful consideration, although the following principles should be observed.

The low calorific flare systems are designed to be deployed on sites where there is a comparatively low level of gas production, but where there are advantages in collecting and burning the gas both in terms of preventing migration and reducing the impact of methane as a greenhouse gas. The design of the extraction system needs to take account of the reduced gas production and must closely balance the extraction to low gas generation rates. If the gas is over extracted, there is a risk that air ingress will turn the waste aerobic and stop the methanogenic process. It is therefore envisaged that any extraction would take place under low suction pressure both at the wellhead and the gas booster. Typical values for extraction pressure would be around -10 mbar at the booster and around -3 to -5 mbar at the wellhead. As the system will operate at low pressures, it is important that transmission pipe work is correctly sized to minimise pressure loss. In addition, as higher flow rates of low calorific gas may need to be accommodated, redundancy should also be built in by designing the system to operate at low gas velocity within the pipe work. This gives the option of increasing flow rate by increasing gas velocity without increasing pressure losses within the system.

The spacing of the gas wells will need to be considered on a site-to-site basis. In practice, gas wells are normally installed at 40-metre centres, however for a low calorific system a tighter well spacing should be considered. As the system will be operating at a lower suction pressure, the zone of influence of the extraction wells will be smaller and therefore more wells will be needed to ensure coverage of the site. This also enables some redundancy to be built into the system. Due to the costs of installing and maintaining the flare it is important that the system is operational over several years to make it worthwhile. Conventionally, flexibility in terms of the quality and quantity of gas burnt is achieved through the flare’s turn-down range. As discussed above, maintaining the energy content of the fuel near the design power rating is more critical with low calorific flares. Therefore, building redundancy into the system by allowing gas to be extracted from additional wells will prolong the life of the system without placing undue stress on gas production within the site. Similarly, the sizing of the flare and booster to accommodate a range of flows and gas quality will need careful consideration.

It can also be expected that as the majority of settlement on the site will have taken place by the time low calorific flares are deployed, the usual problems with settlement disrupting wells and condensate problems in transmission pipe work will be minimised. Leachate levels may be higher than expected in these older sites due to a lack of control infrastructure or deterioration in the control systems. As the gas extraction system operates at relatively low pressure, this should minimise leachate interference with gas extraction. The design and location of the condensate management system also needs to consider the increased density of older waste and its lower potential attenuation capacity.

The low calorific flares can also be used in conjunction with an existing gas extraction system, when the existing conventional flare is no longer capable of burning the gas. However, an assessment of the existing extraction system would need to be carried out to ensure that the poor gas quality at the gas compound is a result of declining gas production rather than problems and air ingress in the extraction system diluting the gas.

3.2 Gas field balancing

Balancing the gas field is an important part of effective landfill gas management. Normally, gas balancing protocols look to optimise the methane content – and hence calorific value – of the gas and minimise air ingress into the system. This is done by adjusting the suction to the well and hence increasing or decreasing the amount of gas extracted. However, as suction is applied to the extraction system there is inevitably some degree of air ingress, either into the waste or the extraction pipework. This leads to dilution of the landfill gas by oxygen and nitrogen by the time it reaches the gas engines or flare.

Generally, during the main phase of gas production the gas field is balanced to maintain methane at >40 per cent v/v, the ratio of methane to carbon dioxide at >1:1.2, oxygen levels at <5 per cent v/v and nitrogen (or balance gas) at <20 per cent v/v. Excessive air ingress into the waste can re-establish aerobic conditions within the waste and kill anaerobic methanogenic bacteria, thus reducing landfill gas production.

The ratio of methane to carbon dioxide landfill gas is normally 1:1.2. A ratio less than 1:1 in an extraction well would generally be cause for concern, as this could indicate aerobic conditions in the well. However, at this stage of declining gas production, the ratio of methane to carbon dioxide will be lower than 1:1.2 anyway. Similarly, concentrations of nitrogen at >20 per cent v/v would normally indicate signs of air ingress and the possibility of fires occurring. Again, with the lower rates of gas production, levels of nitrogen may naturally be higher as there will be some air ingress due to the effects of atmospheric pressure.

This also means that higher levels of oxygen may be detected within the gas wells. It is important that levels of oxygen do not lead to explosive mixtures of landfill gas within the gas extraction system. The minimum amount of oxygen required for an explosive mixture is approximately 12-14 per cent v/v depending on the temperature and pressure. It is recommended that the field should be balanced such that oxygen concentrations are kept below three per cent v/v anywhere within the system. Where higher levels of gas extraction are required to prevent migration, consideration should be given to installing additional wells rather than increasing suction from existing wells.

The risk of over-extraction leading to air ingress and fires remains even though the low calorific flare system is operating at lower pressures. The normal methods of preventing this through looking at the nitrogen concentration and methane/carbon dioxide ratio are not valid in these systems. It is therefore important that the levels of carbon monoxide are monitored to detect any early signs of a fire. This can be easily done using commonplace handheld instruments, although these are prone to interference and any suspicious result must be confirmed by a laboratory sample. Monitoring the temperature of the landfill gas at the wellhead, manifold, or flare inlet could also provide early indication of a fire.

4 Technology suppliers

4.1 Flare manufacturers close to testing at the time of writing

Contact was made with two other flare manufacturers who are known to be developing flares capable of dealing with low calorific landfill gas.

CBT Limited, based in Rugby, manufactures a Surface Burner NIT-type flare that has been adapted from the petrochemical industry. The flare works on the premise that the landfill gas is fully mixed with air in a metal mesh before ignition and combustion takes place on the surface of the mesh. Unfortunately no information was available on the performance of this flare during the timescale of this report. However, this technology does seem to have potential for future development.

Uniflare Limited, based in Kenilworth, is also in the process of developing a low calorific flare. However, this product is still at the development stage and no prototype had been trialled on site at the time this report was compiled. It is understood that a prototype is now available.

4.2 Other flare manufacturers

We have found the following suppliers advertising the ability to supply emission control solutions for low calorific landfill gas generation. We would like to emphasise that this is not an exhaustive list nor does inclusion within it constitute any form of recommendation by the Environment Agency.

4.2.1 Biogas Technology Limited

This company is based in Cambridge. It supplies and installs a range of flares for a wide range of gas control requirements. The company website does not detail the specific technologies that its flare systems use.

The CEN flare range starts at very low flows, $50m^3\ hr^{-1}$, and extends to a maximum standard capacity of $2,000m^3\ hr^{-1}$. The lower end capacity is specifically designed for older, closed landfills that require compliant combustion of landfill gas at low flow. To meet another requirement of closed landfills, the complete range of CEN flares are fitted with telemetry and remote access control. This ensures operator efficiency and accountability through the provision of logged operating data (Biogas Technology Limited, 2008).

4.2.2 Organics

This company is based in Coventry. Its primary product ranges are systems and equipment for the collection, use and/or disposal of landfill gas and the treatment of leachate. The company supplies high quality, low emission flare stacks as well as a range of dedicated leachate treatment plant designs, including unique thermal technology for the stripping of ammonia from leachate and general wastewaters. The company's LHC flare can operate at five per cent methane in air (Organics, 2008).

4.2.3 Roedinger Bioenergie GmbH

This company is part of Bilfinger Berger Umwelttechnik, based in Aarbergen, Germany. Along with a wide range of landfill gas collection and treatment systems, the firm supplies the Depotherm system designed to run on low calorific gas (Roediger BioEnergie GmbH, 2008).

4.2.4 3Ts International

This company has an office in Chepstow. Its main business activities are the design, manufacture and marketing of pyrolitic incinerators, rotary kilns, regenerative thermal oxidisers, liquid and sludge incinerators, waste gas flare stacks, thermal treatment systems and process ovens.

For landfill gas applications, the company markets 'a unique prime gas support system [that] can be offered for very low CV or poor quality gases where combustion may be unreliable. This system uses a small volume of either Propane or Natural gas as a pilot and support fuel. Controls are suitable for outside location and provide automatic operation. They could be configured to activate by pressure or run constantly' (3Ts International Limited, 2008).

5 Conclusions

From the limited data supplied to the Environment Agency and observations during site visits carried out as part of the production of this report, the following conclusions can be drawn:

- The technology exists to flare low calorific landfill gas in a safe manner that complies with Environment Agency guidance on the minimum temperature and residence time for the destruction of landfill gas.
- The two flare manufacturers that have produced low calorific flares have produced products that meet the Environment Agency emission limits.
- The design and operation of the gas field to extract low calorific gas will require a different approach due to low gas production rates.
- Low calorific gas could be flared for a significant time resulting in reductions to methane emissions and consequent local safety and global warming benefits.

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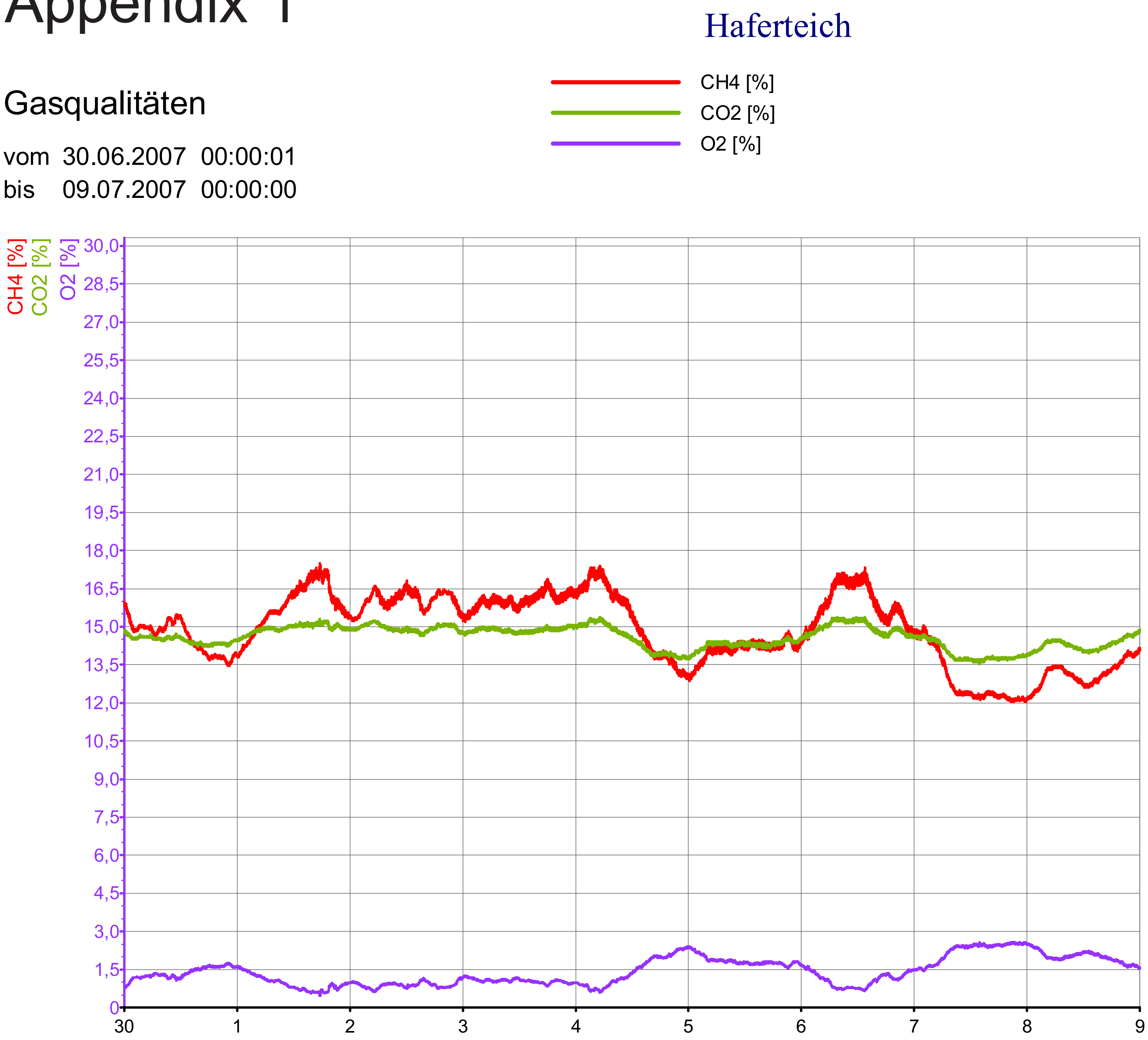
List of abbreviations

v/v	On a volume per volume basis; the per cent of the volume of a constituent in 100 units of volume
MJ/m^3	Megajoule per metre cubed
KWh/m^3	Kilowatt hour per metre cubed
K	Kelvin
KWth	Kilowatt thermal
mbar	Millibar
m^3/h	Metre cubed per hour

Appendix 1

Gasqualitäten

vom 30.06.2007 00:00:01
bis 09.07.2007 00:00:00



Beschreibung	Wert
CH4	
Anzahl Werte	77.696
Grenzwert Minimal	0 %
Grenzwert Maximal	80,0 %
Maximum	17,5 %
Minimum	12,0 %
Mittelwert	14,9 %
Summe	1,2e+6 %
Standardabweichung	1,4 %
Standardabweichung (n-1)	1,4 %
CO2	
Anzahl Werte	77.696
Grenzwert Minimal	0 %
Grenzwert Maximal	80,0 %
Maximum	15,4 %
Minimum	13,5 %
Mittelwert	14,6 %
Summe	1,1e+6 %
Standardabweichung	0,4 %
Standardabweichung (n-1)	0,4 %
O2	
Anzahl Werte	77.696
Grenzwert Minimal	0 %
Grenzwert Maximal	25,0 %
Maximum	2,6 %
Minimum	0,5 %
Mittelwert	1,4 %
Summe	110.902,7 %
Standardabweichung	0,5 %

Appendix 2

Low Calorific Value Flares

1. Introduction

Clarke Energy Limited has been the sole UK distributor for HAASE Energietechnik AG equipment since 1995/96. HAASE are a German company specialising in the manufacture of flare stacks, gas processing equipment, anaerobic digestion plant, mechanical and biological treatment (MBT) plant and reverse osmosis (RO) equipment.

Clarke Energy Limited has provided and installed many HAASE flares in the UK, in particular on landfill gas applications where Clarke Energy has historically had a strong presence through the installation of GE Jenbacher gas engines to produce power from the methane based gas. Clarke Energy has often provided turnkey solutions for these applications with a HAASE flare installed to support the operation of the GE Jenbacher engines.

However, closed landfill sites gradually but constantly lose 'quality' – i.e. the methane content of the gas falls. As the methane in the gas is the source of energy a gas engine uses to produce electricity a point will be reached where the methane percentage is too low to support the operation of an engine. Although the GE Jenbacher gas engine is particularly effective in operation with low methane content gases, and landfill gas with below 30% methane can still support these engines, landfill sites will ultimately produce gas of such low quality that flaring becomes the only option.

As the methane level falls further the energy in the gas becomes insufficient even to support a 'standard' flare stack. HAASE's high temperature flares are suitable for gases with methane content in the 25-80% by volume range. A range of modified high temperature flares are also available suitable for a 20-60% operating regime.

At lower methane contents it is still extremely important that the gas is treated. A build up of this gas could still constitute an explosion hazard, and as methane is such a potent greenhouse gas it cannot be allowed to vent to atmosphere. Hence, at methane contents below 20% by volume HAASE provides two options for the treatment of these gases:

i) For extremely low methane content gases in the range of 0.4-10% the HAASE VocsiBox system is recommended, and unlike biofilters is capable of degrading up to 99% of the methane.

ii) The HAASE low caloric value, or lean gas flare, has been recently introduced to the range and is capable of treating gases with methane contents in the 10-50% by volume range.

It is the low calorific value flare which is the focus of this report.

2. Features of the HAASE Low Calorific Value Flares

The HAASE low calorific value flares are suitable for use with gases with methane content in the 10-50% by volume range and with capacities from 100kWth to 1800kWth. This relates to a gas flow rate of 100-1800Nm^3/hr at 10% methane concentration.

These HAASE lean gas flares are also modular in design and therefore can be applied in adapted versions for higher methane levels and then retrofitted subsequently for operation with 'leaner' gas.

The burning temperature of the flare is controlled to 1000^{o}C thus ensuring that the emission concentrations for CO and NOx are below required limits for landfill, sewage and biogases. The dimensioning of the flare is such that the 1000^{o}C temperature is maintained for a minimum of 0.3 seconds.This flare will combust hydrogen sulphide and V.C's

The principle differences between the HAASE lean gas flares and the standard high temperature flares are:

i) the combustion air is preheated through the use of an internal heat exchanger

ii) special lean gas burners are used in the flare system

iii) the combustion of the ignition and start-up phase of the flare is supported by a propane or natural gas burner.

3. Control System

3.1 Temperature Regulation

The combustion temperature is continuously monitored and controlled through the automatic regulation of combustion air-flow.

3.2 Load Regulation

The landfill-gas blower is inverter controlled. The load regulation controls the landfill gas flow to maintain a constant power and hence a constant preheated combustion air temperature. The first lean gas flare prototype offered a thermal load regulation for a range of 2:1, but thermal load regulation of 3:1 is now available.

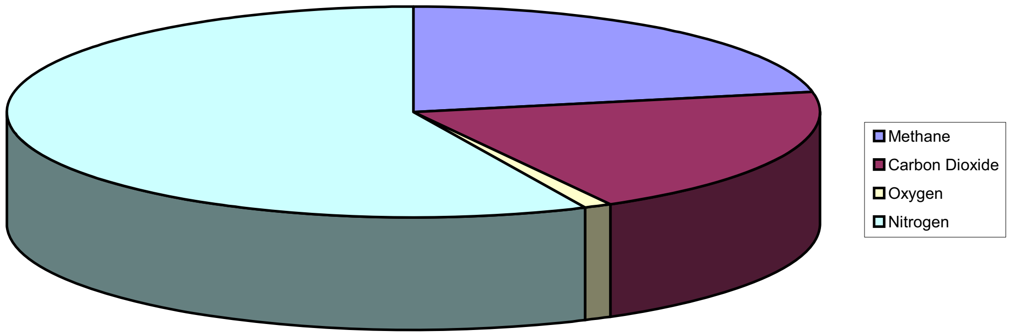
3.3 System Shutdown

On system shutdown the main landfill gas valve closes. All methane will burn out and air is blown through the flare until a low temperature is achieved. There is no risk of explosions.

4. Prototype Flare

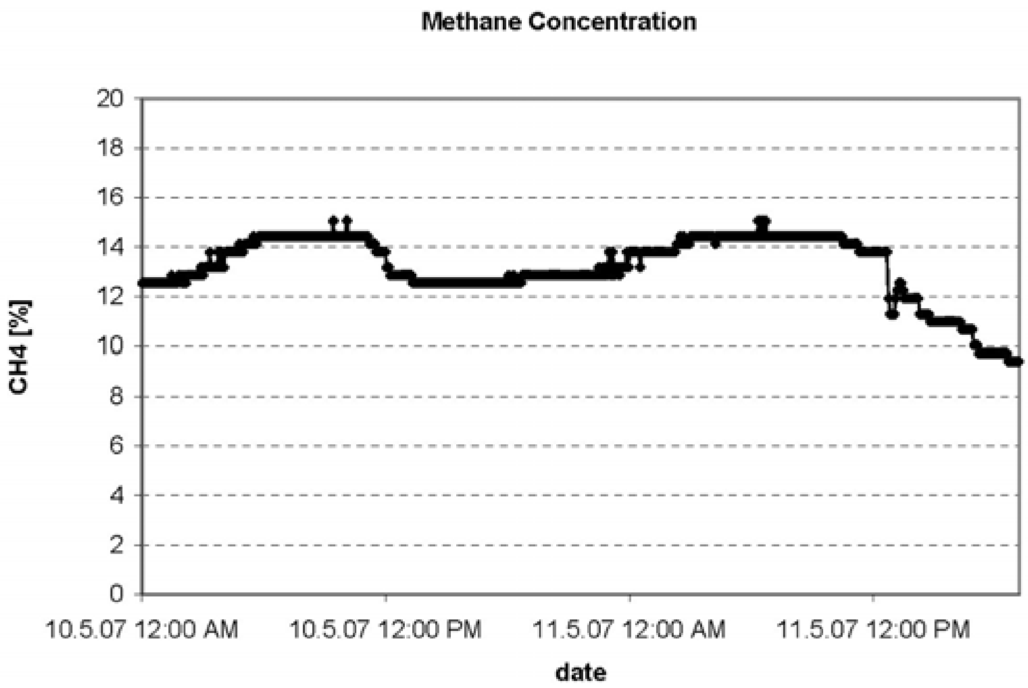
Subsequent to full factory testing, HAASE's first low calorific value flare stack was installed on a landfill site in Germany at the end of 2006. This landfill had been closed since 2003 and produces gas with a low methane content. The specific composition of this landfill gas varies, but a typical sample taken on 2nd February 2007 showed the following gas make-up:

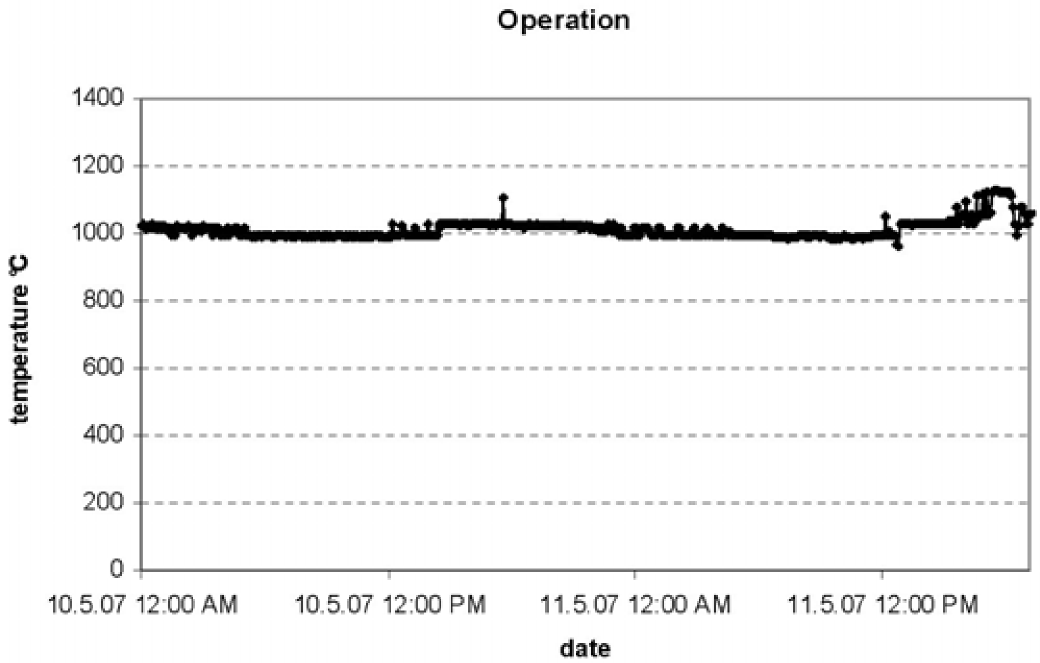
Methane CH_4	22.0%
Carbon Dioxide CO_2	20.0%
Oxygen O_2	1.1%
Nitrogen N_2 (assumed)	56.9% approx.

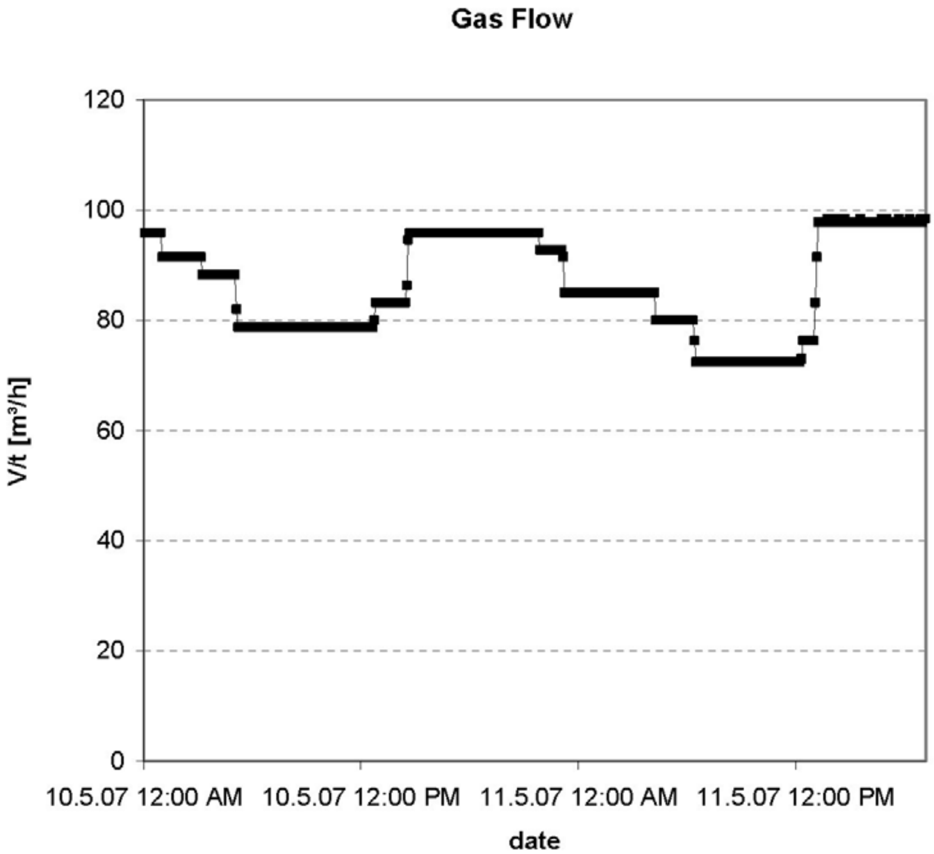


This flare is comprised of blowers for the landfill gas, air pre-heater, gas analyser for methane, carbon dioxide and oxygen, flow measurement, process visualisation and TCP/IP online system access. The data from the gas analyser is continuously monitored and saved.

The following plots show the operation of the flare. The first plot is of methane concentration and the following plots show how this impacts on the operation of the flare in terms of combustion temperature of operation and gas flow rates.







It can be seen that this flare was operating in the 10-15% methane regime and maintained the 1000°C combustion temperature as required. The gas flow plot shows how the flow rate is controlled to achieve a constant thermal load as the methane content, and hence the energy content, of the gas varies.

The ignition system for the flare requires that the combustion chamber is preheated with a propane burner, which also serves for the ignition of the landfill gas. The preheating phase lasts for about 20 minutes and consumes approximately 1m^3 of propane gas per ignition for the prototype flare. The propane can be supplied from standard camping gas bottles.

Initially this flare system was installed in conjunction with a backup system, but this was decommissioned in June 2007 as the prototype unit had proven its reliability.

5. Flare Development

The second flare is now installed at a landfill site in Dorentrup, also in Germany. This flare is designed with a thermal load of 1800kWth and has a load regulation of 3:1, giving the ability to turn down to 600kWth. The volumetric flow rate range for the landfill gas is 240-1800Nm^3/hr. This is achieved through the use of a special two-stage burner. In its initial operation this flare is designed to operate on higher calorific value gas with methane concentration of around 65% by volume. The preheating system will be installed as required at a later stage to provide the capability to operate on low calorific value gas, thus illustrating the modular nature of HAASE's flare technology.

6. Operational Costs

In general terms the ongoing costs for operation of the flares comes from three main sources:

i) electrical requirements of the flare

ii) propane 'charge' on intial start-up

iii) maintenance costs.

The electrical consumption of the prototype low calorific value flare already described is approximately 8kW; 2kW for the switchboard and additionally 2kW for each of three separate blowers.

The propane charge required for the prototype flare is approximately 1m^3 per start-up.

The recommendation for maintenance of the flare is for this to be carried out every three months. Each maintenance visit will take approximately one man-day and for a competent individual to carry this out will cost approximately

£2000 per annum. Additionally, maintenance parts will cost approximately £250 per annum. Please note that these prices are based on current exchange rates and are intended to be budgetary prices only. Maintenance costs will be confirmed and fixed upon the provision of a maintenance contract available from Clarke Energy Limited.

7. Landfill Gas Field and Flare Operation

Typically neither Clarke Energy Limited nor HAASE Energietechnik AG are involved in the infrastructure of the landfill site itself or in the gas extraction system or field balancing, so little can be said from a position of authority on these issues. The extremes of our scopes of supply would usually be the gas booster unit(s).

However, certain aspects of the landfill and its gas do inform the operation of the low calorific value flares.

i) From experience on the prototype site it has been noted that the continuous suction drawing the landfill gas out of the field creates a little under-pressure of about 10mbarg.

ii) The composition of the landfill gas itself also informs the operation of the flare, in particular with regards to providing warning signs for the gas field and hence the flare operation.

The principle criteria affecting the operation of the low calorific value flare are outlined below:

Reading	Comments	Recommended Action
CH_4:CO_2 ratio less than 1.2:1	• A CH4:CO2 ratio of 1:1 is possible due to low methane levels in general as does not necessarily indicate a hazardous operating regime.	• Reduce/close well.
O2 > 3% but < 6%	• Indicates that air is being drawn into the system. • 3% level triggers O_2 pre-alarm.	• Operator should check system for leaks and make necessary repairs. • Check for symptoms of fire.
O2 > 6%	• Indicates major air leak into the extraction system • Danger of explosive gas mixture forming in transmission pipe-work. • 6% level triggers O_2 main alarm.	• Operator should check system for leaks and make necessary repairs. • Check for symptoms of fire.
CH4+ CO2 > 100%	• Possible indicator of elevated levels of non-methane hydrocarbon interfering with the methane reading. • May be simple gas analyser malfunction.	• Operator should check meter readings using calibration gas. • Bag sample of gas should be taken and submitted for GC-MS scan to determine trace components. • Site risk assessment may need to be amended if elevated levels of trace components confirmed.
Suction > 10mbar	• Low cal flaring will require low pressure extraction. Therefore maximum suction <10mbarg. Likely suction at wellhead ≈ 2-3mbarg. • High suction may also draw leachate up the collection well and increase capillary action around the well reducing collection efficiency still further. • High suction levels are likely to draw air into the site encouraging aerobic conditions and increasing the risk of a fire.	• Suction levels should be reduced. • Extraction well should be dipped to check integrity and leachate level. • Check for symptoms of fire.

Carbon Monoxide > 100ppm Symptom of fire	• Some gas monitoring equipment records CO as standard (e.g. Geotechnical GA2000, GA2000+ and GEM2000+) • Carbon Monoxide is a product of incomplete combustion, it is not formed by any other biological or chemical reaction within the landfill. • Carbon Monoxide levels of more than 100ppm and rising **(confirmed by laboratory sample**) are a positive indicator of a deep seated fire.	• Sample should be taken for confirmatory laboratory analysis. Suction should be reduced or shut off. • If high levels are confirmed suction must be stopped (if not done already). • Fire action plan should be instigated if confirmed CO levels indicate a fire.
Temperature > 60˚C Symptom of fire	• Anaerobic bacteria rarely exist at temperatures exceeding 55˚C. Elevated temperatures are either an indicator of aerobic conditions being prevalent or of a fire within the site. • Temperatures > 75˚C are a major cause for concern • Temperatures > 90˚C are highly indicative of a fire	• Check to see if CO also present. • Shut of extraction system and instigate fire action plan.

A standard high temperature flare will also operate according to gas field criteria relating to the Nitrogen content of the landfill gas. It would be usual that if the nitrogen content of the gas is greater than 20% this would indicate the entry of air into the field which could furthermore cause concerns over the risk of fire. Due to the nature of a closed landfill site it is possible, in fact likely, that the nitrogen content of the gas will be greater than 20%, as can be seen from the gas analysis for the German prototype site. Hence, it is principally the oxygen content, carbon monoxide levels and temperature of the landfill gas which act as indicators and the alarm symptoms of fire. The borehole extraction system is running alright with a negative pressure of 1 to 2 m barg and methane and carbon dioxide in equilibrium oxygen appox 0.9% redundancy should be incorporated in the gas extraction system to ensure the flare is able to operate in a stable manner, and to ensure the longevity of the system

8. Conclusions

The HAASE lean calorific value flares are of a proven design whilst still undergoing continuous development and improvement. The units are capable of operating on a wide range of gas compositions and the modular design enables them to be modified during their and the landfill site's life-cycle in order to best treat the gas being produced.

This 'best in class' HAASE technology is paired with Clarke Energy Ltd.'s experience within the landfill gas industry and our extensive engineering and maintenance expertise. The flare can be used for water heating schemes

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Appendix 3

HOF*GAS*® *Sparky XS* – Low Calorific Gas Flare Trial

Trial Date:	18th August 2006
Conducted for:	ENnate Limited
Conducted by:	ENnate Limited Hofstetter Umwelttechnik AG CPL Laboratories
Location:	Metallic Tile Landfill Site, Stoke-on-Trent

Introductory Summary

On Friday 18th August 2006, a trial took place to monitor the performance and emissions from a modified Hofstetter **HOF***GAS*® *Sparky XS* flare, designed to combust low calorific gas whilst complying with the EA emissions standards. The trial was held at Metallic Tile Landfill Site in Stoke-on-Trent, which is owned by Cleanaway. Present to record the performance of the flare were engineers from ENnate Limited and Hofstetter Umwelttechnik AG – manufacturers of **HOF***GAS*® equipment. Representatives C Greenaway and A Taylor-Jones from CPL Laboratories, an independent company commissioned by ENnate Limited, were also in attendance to record the emissions results from the trial. Emissions from the flare were found to be below the emission standards quoted in the landfill directive document LFGN 05.

Equipment

A standard **HOF***GAS*® *Sparky XS* high temperature flare was used for the trial (due to its small size therefore being quick to set-up and easily portable). Modifications were made to the flare by replacing the standard burner with an injection type burner, a device for primary air adjustment and other associated equipment necessary to allow detailed monitoring. The modification required to operate on low calorific gas can be scaled-up for the other units in the **HOF***GAS*® range.

Testing & Monitoring Proceedure

Engineers from ENnate Limited and Hofstetter Umwelttechnik AG carried out the following tests;

- Monitoring of input gas for methane, carbon dioxide and oxygen, together with flow measurements, using suitably certified hand held equipment.
- Monitoring of exhaust emissions for CO, NOx and residual oxygen, using suitably certified Testo equipment.
- Monitoring was conducted with flow rates varying between 34 Nm^3/h and 140 Nm^3/h and with varying gas quality by making adjustment to the gas collection scheme.

CPL Laboratories conducted emissions monitoring, which comprised of recording the determinations of the following emissions from the flarestack;

- Total volatile organic compounds (VOCs)
- Non-methane volatile organic compounds (NMVOCs)
- Oxides of nitrogen (NO_x)
- Sulphur dioxide (SO_2)
- Carbon Monoxide (CO)
- Acid halides and halogens

Oxygen and moisture were also determined for concentration referencing.

Tables of Reference and Results

Table 1, 2, 3 & 4 shows results from CPL Laboratories emissions monitoring. Table entitled 260064 shows performance results of the flare.

Conclusions of Trial

The results concluded that the combustion of low calorific gas was achievable at levels as low as 13% CH_4 whilst still maintaining emissions that comply with the EA standards.

TEST REPORT

1618

CONFIDENTIAL

Report Reference: 06/262B

Report Issue Date: 21st September 2006

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Part of CPL Industries

EXECUTIVE SUMMARY

Mr. Paul Glenister, of ENnate Technology Ltd., commissioned CPL Laboratories to monitor emissions to atmosphere, from the **HOF**GAS® Sparky XS high temperature flare stack at Metallic Tile Landfill Site, Stoke -on-Trent.
The following emissions where monitored: Total volatile organic compounds (VOCs), non-methane volatile organic compounds (NMVOCs), oxides of nitrogen (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO) and acid halides and halogens

The key findings of this study, carried out on 18th August 2006, were as follows:

Emissions from the flare were found to be below the emission standards quoted in the landfill directive document LFGN 05.

1 INTRODUCTION

1.1 Mr. Paul Glenister, of ENnate Technology Ltd., commissioned CPL Laboratories to monitor emissions to atmosphere from the **HOF**GAS® Sparky XS high temperature flare stack at Metallic Tile Landfill Site, Stoke-on-Trent.

1.2 C. Greenaway and A Taylor-Jones of CPL Laboratories carried out the monitoring on the 18th August 2006. Monitoring comprised the determination of total volatile organic compounds (VOCs), non-methane volatile organic compounds (NMVOCs), oxides of nitrogen (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO) and acid halides and halogens emitted from the stack. Oxygen (O_2) and moisture were also determined for concentration referencing.

2 SAMPLING PROCEDURE

2.1 The monitoring and analytical procedures employed during this survey are presented in Table 1.

3 RESULTS

3.1 The results of the monitoring and analysis are summarised in the Table 2.

4 UNCERTAINTY

4.1 Where possible, assessment of measurement uncertainty was performed in accordance with CPL Procedure No.15 and UKAS Publication LAB12 and M3003.

5 DISCUSSION OF RESULTS

The key findings of this study, carried out on 18th August 2006, were as follows:

Emissions from the flare were found to be below the emission standards quoted in the landfill directive document LFGN 05.

Table 1 Methods Employed in Emissions Monitoring

Determinand	Reference Method	CPL Procedure No.	Summary of Procedure
Carbon Monoxide	ISO 12039	ML001	NDIR
Oxides of Nitrogen	ISO 10849	ML001	Chemiluminescence
Total VOCs	BS EN 13526	ML001	FID
Sulphur Dioxide	ISO 7935	ML001	NDIR
NMVOCs	BSEN 13649	ST13	Carbon tubes, GC/FID
Acid Halides/Halogens	EPA method 26	ST 8A	Liquid, Ion Chromatography
Oxygen	ISO 12039	ML001	Paramagnetic
Moisture	USEPA Method 4	ST2	Gravimetric
Temperature	BS9096	ST6	Thermocouple

COMMENTS

1. NMVOCs analysis carried out by AES, Newcastle-upon-Tyne

Table 2 Results of Emission Monitoring

Site: Metallic Tile
Monitoring Location: **HOF**GAS® Sparky XS high temperature flare stack
Date: 18/08/06
Time: 11:35-13:35
Process Status: **See Table 4 below**
Reference conditions: 273K, 101.3 kPa, 3 % oxygen, dry

Determinand		Test 1	Test 2	Mean	Uncertainty %
Carbon Monoxide (2 hr profile Ave)	mg/m^3	4.7		4.7	± 2
Oxides of Nitrogen (as NO_2) (2Hr)	mg/m^3	9.3		9.3	± 3
Total VOCs (as Carbon) (2Hr)	mg/m^3	1.5		1.5	± 7
Sulphur Dioxide (2Hr)	mg/m^3	< 3		< 3	± 16
NMVOCs (as Carbon)	mg/m^3	< 1.0	< 1.5	< 0.82	-
Hydrogen Fluoride	mg/m^3	< 7.8	< 1.3	< 4.5	-
Hydrogen Chloride	mg/m^3	< 7.6	10.5	< 9.1	-
Hydrogen Bromide	mg/m^3	N.D.	N.D.	-	-
Fluorine	mg/m^3	<8.1	<1.3	<4.7	-
Chlorine	mg/m^3	30	2.2	16.1	-
Bromine	mg/m^3	N.D.	N.D.	-	-
Oxygen (2Hr)	%	4.5		4.5	± 1
Moisture	%	10.3	10.0	10.15	-
Temperature	^oC	1054	1046	1050	-

< Denotes Limit of Detection of analyser . N.D. denotes non-detected.

Table 3 Flare Emission Limits

Determinand	Emission Limit (mg/m^3)
Carbon Monoxide	150
Oxides of Nitrogen	50
Total VOCs	10
NMVOCs	5

FOOTNOTE

1. Values relate to flare stacks at normal operating conditions and load and reference conditions of 273K, 101.3 kPa, 3% oxygen and dry gas

Table 4 Data provided by Site Engineer

Process Data			
Suction		-16 mbar	
Flow		90m3/hr	
Flare Temperature		1050°C	
Burner Pressure		25mbar	
Gas Quality		**Pre Testing**	**Post Testing**
Methane	%	14.1	13.3
Carbon Dioxide	%	13.4	13.1
Oxygen	%	9.4	9.6

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End of Report

260064 Results Hofstetter Low Calorific Value Flare

NO	Raw Gas Concentration (%)	Flow rate (Nm3/h)	Combustion Temperature (°C)	Fluegas file no	Combustion Quality	Comments
1	CH4 19.1 CO2 15.4 O2 8.2	34	Set at 900°C	1	Main burner stable / smooth combustion	-
2	CH4 19.1 CO2 15.4 O2 8.2	34	Set at 900°C	2	Main burner stable / smooth combustion	-
3	CH4 19.6 CO2 15.7 O2 5.9	48	Set at 1050°C	3	Main burner stable / smooth combustion	-
4	CH4 20.3 CO2 16.1 O2 5.7	95	Set at 1000°C	4	Main burner stable / smooth combustion	-
5	CH4 21.6 CO2 16.5 O2 6	95	Set at 1050°C	5	Main burner stable / smooth combustion	-
6	CH4 21.5 CO2 16.7 O2 5.7	95	Set at 1100°C	6	Main burner stable / smooth combustion	-
7	CH4 21.8 CO2 16.6 O2 5.8	120	Set at 1100°C	7	Main burner stable / smooth combustion	-
8	CH4 21.5 CO2 16.5 O2 5.9	130	Set at 1100°C	9	Main burner stable / smooth combustion	-
9	CH4 21.5 CO2 16.5 O2 5.9	130	Set at 1100°C	10	Main burner stable / smooth combustion	-
10	CH4 17.8 CO2 14.9 O2 7.8	130	Set at 1100°C	11	Main burner stable / smooth combustion	-
11	CH4 16.9 CO2 14.2 O2 8.3	140	Set at 1000°C	12	Main burner stable / smooth combustion	-

12	CH_4 15.8 CO_2 13.7 O_2 8.5	140	Set at 1000°C	13	Main burner stable / smooth combustion	-
13	CH_4 12.9 CO_2 12.5 O_2 9.1	140	Set at 1000°C	14	Main burner stable / smooth combustion	-
14	CH_4 12.3 CO_2 12.2 O_2 9.3	140	Set at 1000°C	15	Main burner stable / smooth combustion	-

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