REPORT ON

REVIEW OF LANDFILL SURFACE EMISSIONS MONITORING

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1.0 INTRODUCTION

1.1 Background to the Research

The project “Review of Landfill Surface Emissions Monitoring”, WR0604 (WRT369), was commissioned through Defra’s Waste Strategy Research Programme, which aims to produce an evidence base for the policy making process. This project is concerned with improving the methods of quantifying the emissions of methane (CH\textsubscript{4}) to atmosphere from the surface of landfill sites. Methane has a high global warming potential and is the principal component of the gas generated from the biodegradation of organic wastes in landfill. The methane in landfill gas releases are estimated to make a significant, and avoidable, contribution to the UK’s reported emissions of Greenhouse gases under the Kyoto Protocol. Landfill operators are required under their permit to quantify emissions of methane through the surface of the landfill cap.

The current Guidance issued by the Environment Agency is based on research initiated by the Department of the Environment (DoE) in 1995. It recommends the use of flux boxes to quantify the emissions from capped areas. Since the mid 1990s, meteorological, optical and other remote sensing techniques which can measure emissions from parts of the landfill, or the entire landfill, have been tested by a number of international researchers. However, the various techniques have not been standardised or independently evaluated for their suitability or practicality on UK landfill sites. This current project aims to examine these alternative technologies and their applicability for both regulatory and gas management purposes.

The general aim of the project is:

- To review the methods for estimating the pattern of fluxes of gases across the surface of a landfill and their variations with time, i.e. spatial and temporal variation in emissions

This report reviews the methods currently available to practitioners for quantitative emissions measurement. It considers techniques which have the potential for monitoring landfill emissions; to look at the various regulatory needs, and to assess each method against these regulatory requirements for their suitability, ease of use, potential problems and costs. The review has identified the most suitable techniques which have potential for use in the UK.

1.2 Potential Reasons for Measuring Methane Flux through the Surface

The amount of methane gas found near the surface of a landfill may be measured for a number of reasons. It is recognised that different techniques may be suited to different measurement needs. In assessing the potential techniques their applicability for the following circumstances will be considered.

A. Qualitative walk-over surveys for leakage
1. To qualitatively check on the emissions from extensive areas of relatively consistent capping (e.g. to find faults in the engineering or gas management system);

2. To qualitatively check on the emissions from point sources, particularly close to intrusions into capping (e.g. to identify high leakage rates around extraction wells); and

3. To identify when relatively high emissions of gas are sourced from the active tipping area (e.g. to check when the freshly buried waste has begun to emit significant amounts of gas through uncapped areas such as side slopes and faces).

B. Threshold monitoring at boundary

4. To provide boundary monitoring to give early warning that gas emissions are beginning to rise from a managed area of landfill and that off-Site levels of gas may be unacceptable (e.g. to alert staff to a developing fault in the gas management system); and

5. To aid in identifying sources of odour (e.g. by tracking the gas plume that may be perceived as unusually odorous).

C. Quantification of emissions close to particular surfaces

6. To look for quantitative changes in gas emissions from a managed area over short periods to look at effectiveness of gas control or impact of changed management (e.g. quantifying benefits or assessing potential gas that could be used).

D. Total emissions in the plume arising from sites

7. To quantify methane emissions from a site as part of an annual emissions survey (e.g. to give the sum of emissions over a year); and

8. To quantify with considerable accuracy the emissions from a representative area or site so that this value can be used as the default for emissions from other similar sites (e.g. using data from a few sites to aggregate the likely emissions from all sites).

These cover both regulatory and operational requirements for information. All are likely to be undertaken by the operator but only the quantification of a site’s annual surface emissions from capped and temporary capped surfaces is a regulatory requirement.
1.3 UK Flux Box Research

Over the past decade there have been several research projects to quantify surface methane emissions. The majority focussed on the flux box technique, and are briefly summarised as follows.

UK landfill surface emissions research started in 1995, when the DoE commissioned the research project ‘Methane Emissions from Different Landfill Categories’ (Environment Agency, 1999). At this time, the standards of landfills were varied:

- Designs were either dilute and attenuate or partially/fully engineered;
- Capping was variously soil caps, clay caps or lapped low density polyethylene (LDPE);
- Gas control ranged from no gas control through perimeter gas control (the most common) to full site gas utilisation schemes;
- There was little regulatory incentive, other than nuisance, to improve gas collection; and
- The Non-Fossil Fuel Obligation (NFFO) was the only economic driver.

Surface methane flux was measured on 26 landfill sites using flux boxes. Emissions from the surfaces of the landfill sites were found to vary according to age, depth, filling regime, waste quantity, seasonality, cap type and efficiency of the landfill gas collection system. It was this study which first proposed the surface emission threshold of $1 \times 10^{-3}$ mgCH$_4$ m$^{-2}$ s$^{-1}$, which is now part of the Environment Agency’s regulatory requirements under the Pollution Prevention Control (PPC) regulations. In 1998, the University of Nottingham funded by Biffaward followed the pattern of the Environment Agency research, with a project entitled ‘Research into Methane Emissions from Landfills’ (Johnston et al., 1999). The objectives of this project were to:

- Quantify seasonal methane fluxes from 19 landfills using flux boxes;
- Assess the factors which control the spatial and seasonal variability in methane emissions rates from landfills;
- Monitor the methane emissions from passive vents at one operational landfill; and
- Conduct a methane audit of the Site.

The results of flux box measurements from the 19 operating sites showed that like the DoE study, an engineered cap and effective gas management can reduce the methane emissions from landfills by at least three orders of magnitude. This Biffaward study showed all average flux measurements on engineered caps were indeed below the $1 \times 10^{-3}$ mgCH$_4$ m$^{-2}$ s$^{-1}$ emissions threshold now used as a regulatory limit by the Environment Agency. The results also indicated that methane emissions on operational surfaces could be much higher than from completed caps.

The study did observe some seasonable variability affecting fluxes, but failed to provide definitive conclusions on the effects of variation in atmospheric pressure, waste type, waste age and waste depth on methane fluxes from landfill surfaces. Monitoring of open gas vents showed that methane emissions from passive venting systems were significant. The
methane audit of one site showed a significant difference between the gas generated at the Site and the measured methane emissions. This difference may be attributed to some pathways that were not measured such as the tipping face and discontinuities in the cap and liner. Overall, this research report confirmed the findings of the Environment Agency (1999) Report.

In 1998, the Environment Agency NW region commissioned a second report, specifically for the NW Region entitled ‘Determination of Methane Emissions from North West Landfills’ (Meadows and Parkin, 1999). The principal aim of the project was to quantify emissions from the North West’s landfills and estimate the regional contribution to the UK’s total of landfill derived emissions. Forty sites were modelled using an early spreadsheet version of the GasSim model (www.gassim.co.uk), and flux box surveys were conducted using the same methodology as before (Environment Agency, 1999). The model overestimated surface emissions compared to the values suggested by the flux boxes, since the flux boxes were not deployed on the operational areas of the landfill.

The next significant research project, ‘Minimising Methane Emissions from MSW Landfills’ was funded by Shanks First and Biffaward with Environment Agency support (Barry et al., 2004a-c). Twenty one sites were visited on 32 occasions and surveyed using flux boxes. This report focused on:

- Establishing the scales of surface methane emissions during the early phases of landfilling by measuring surface flux on a number of UK landfills;
- Assessing when methanogenesis commences in newly deposited wastes; and
- Identifying the practical methods of controlling surface emissions during operational phases of landfilling.

Project results confirmed that gas generation and surface emissions rates were affected by a wide range of variables including physical and meteorological conditions. Results also indicated that over time, flux rates increased with a maximum flux within 20 - 24 months, with methanogenesis evident within 1 - 2 months of waste placement.

Measurements indicated that the vertical gas permeability of the waste is three to five times lower than the horizontal permeability, with higher fluxes emitted from waste side slopes and near landfill edges. Measurements also highlighted that temporary capping reduces surface emissions but not to the same extent as permanent capping (Barry et al., 2004a-c).

1.4 The Development of Alternative Techniques to Flux Boxes

A number of alternative surface emissions measurement methodologies have been devised and trialled in the UK, Europe and US.

In 1995, in a parallel study to the Waste Technical Division of the DoE, the Global Atmospheric Division of the DoE commissioned National Physics Laboratory (NPL) to provide a report entitled ‘An Estimate of Methane Emissions from UK Landfill Sites based on
Direct Flux Measurements at Representative Sites’ (NPL, 1997). In all 35 sites were studied. The projects objectives were to:

- Develop and carry out a measurement programme to quantify annual emissions of methane from representative sites in the UK and to target the study on larger, better characterised sites and to determine the effects of gas collection system;
- Comparison of modelled gas generation with measured methane emissions; and
- Provide an assessment of annual methane emissions form landfills in the UK and also to highlight any uncertainties.

The results of the site investigations confirmed that a good quality cap and the presence of full site gas control have a strong beneficial effect on controlling methane emissions.

This project delivered the first total UK emissions estimate of 887 kty\(^{-1}\) (652 kty\(^{-1}\) – 1135 kty\(^{-1}\)), and the measurements demonstrated that fluxes of methane from landfill sites which have a comprehensive gas collection and flaring or utilisation as a gas management technique were significantly lower than uncontrolled or partially controlled landfill sites, and such sites perform better than previously modelled estimates.

Eleven sites were shared with the Waste Technical Division study, and both studies compared data derived from the Siemens HAWK, the main analyser used in the surveys, with the flux box method. The HAWK data were either of equivalent or of higher emission value than the flux box data. This was primarily attributed at the time to the presence of fractures on caps, which were not observed by the flux box method.

Optical techniques for landfill emissions measurement did not proceed any further in the UK. However, in Europe, with the adoption of tracer techniques, open path measurement techniques became more commonly reported. In 2004, Sira Ltd conducted a report of ‘Recommendations for Performance Standards for Open-Path Instrumentation’ (Sira Ltd, 2004a). This report included a field trial of the different types of open path instrumentation available for measuring fugitive emissions.

In recent years, French research has looked into the methane balance using flux box techniques and optical tracer methods. Spokas et al. (2005) were able to show good correlation between the two techniques. However, this research has not led to the acceptance of new methods in France.

In the Netherlands, a series of trials have been conducted by Scharff et al. (2003) to measure methane emissions. These experiments began by trialling the mass balance and stationary plume methods, and comparing them to the mobile plume with a tuneable diode laser (TDL) at four different landfill sites in the Netherlands. The results of this experiment showed that both the mass balance and stationary plume methods provide suitable methods for measuring methane emissions (Scharff et al., 2003). As a consequence of this research a simplified version of the stationary plume method, which is more straightforward and also more cost effective, has been developed.
In Sweden, Chalmers University have developed an optical technique not too dissimilar to the mobile plume with TDL method developed in the Netherlands, but using Fourier Transform Infra Red (FTIR) technology instead. In 2001, this method was trialled at four different landfill sites in Sweden to give estimates on methane concentration as well as methane oxidation. Samuelsson et al. (2001) concluded that FTIR spectroscopy had proven to be an applicable method for measuring total methane emission measurements at landfills of a variety of different sizes.

In Finland, the Finnish Meteorological Institute has developed a micrometeorological based system. In 2005, they trialled this system against a TDL technique at the Ämmässuo municipal landfill in Finland. The campaign spanned over six months measuring both methane and carbon dioxide. Lohila et al. (2006) concluded that despite the restricting assumptions of this method, i.e. a flat landfill with homogeneous emissions, it was capable of producing continuous, area-averaged estimates of the landfill methane emissions.

In the US, Modrak et al. (2005) on behalf of the United States Environmental Protection Agency (USEPA) conducted a study to evaluate fugitive emissions of methane and volatile organic compounds (VOCs) at a former landfill site in Fort Collins, Colorado. The study used three different types of ground optical remote sensing devices: Open Path Tuneable Diode Laser (OP-TDLAS), Open Path Fourier Transform Infra Red (OP-FTIR) and Ultra Violet Differential Optical Absorption Spectra (UV-DOAS). Monitored data from each of the pieces of apparatus proved to be comparable for area emissions when a wide range of concentrations were measured.

A review of the techniques identified here has been carried out, and is reported in Section 3.

1.5 Current Regulatory Setting

1.5.1 Reporting Methane Surface Emissions

The document ‘Guidance on Monitoring Landfill Gas Surface Emissions’ (Environment Agency, 2004b) recommends the technique operators should use to monitor surface emissions from landfills in the UK. Quantifying surface emissions is a requirement of the PPC Regulations (Environment Agency, 2004a) for the majority of PPC permitted non-hazardous waste landfills.

This guidance recommends a two stage process, firstly using a Flame Ionisation Detector (FID) in a site walkover, followed by an FID flux box survey using static chambers. This staged approach is used to:

- First assess gas management qualitatively by identifying defects in the site’s gas management system, and therefore determining areas of the Site requiring remediation; and
Then to quantify emissions of methane through the cap annually, to demonstrate compliance with the emissions thresholds of $1 \times 10^{-3} \text{mgCH}_4 \text{m}^2\text{s}^{-1}$ for completed caps, and $1 \times 10^{-1} \text{mgCH}_4 \text{m}^2\text{s}^{-1}$ for temporary caps.

This flux box technique is based on that first reported in the Environment Agency (1999) report TR P233a. In the surface emissions guidance (Environment Agency, 2004b) it is not proposed for operational areas, but Barry et al. (2004a-c) showed that flux boxes are indeed suitable for measuring surface emissions from operational areas, and as a consequence, the flux box could be used for whole site surveys.

1.5.2 Pollutant Inventory Reporting

The main objectives of the Pollution Inventory (PI) are to:

- Tell the public about pollution from industrial and other sources in their local area and nationally;
- Help environmental regulators to protect the environment; and
- Help the Government to meet national and international commitments and obligations for reporting.

Landfill operators are required to provide details of emissions about each of the species in the PI on an annual basis. Emissions are compared to the relevant reporting threshold, and if exceeded, are reported. The PI can be determined by modelling or measurement. Typically, landfill operators use GasSim2 or GasSimLite1.5 to report PI statistics, but emissions measurement techniques can be used to determine actual (rather than modelled) landfill emissions.

1.5.3 Greenhouse Gas Emissions

Methane is a very important greenhouse gas. In 1998, the methane emissions inventory for the UK totalled some 2.6 million tonnes, of which approximately 29% or 0.775 million tonnes were derived from landfills (Brown et al., 1999). The 2005 estimate, based on the Intergovernmental Panel on Climate Change (IPCC) default methane oxidation rate of 10%, and a landfill gas collection efficiency of 75%, is 0.927 million tonnes (Golder Associates, 2005).

The Landfill Directive requires that measures should be taken to reduce the production of methane gas from landfills to reduce global warming. This is to be achieved through a reduction in the landfilling of biodegradable waste and requirements to introduce landfill gas control. In the UK, the greatest amount of methane emissions are currently abated by utilisation or flaring rather than by diversion of biodegradable waste to other treatment methods (Gregory et al., 2003; Golder Associates, 2005).

The Environment Agency (2004a) has stated that the benchmark for global warming should be based on achieving an annual 85% efficiency for the collection and treatment of
methane emissions. This relates to the operational period of gas recovery. It is possible that over the entire life cycle of the landfill, gas collection efficiency may be much lower than this, and modelled calculations using GasSim suggest a value of 50% may be a more appropriate life cycle estimate (ERM, 2006).

Whole site estimates of landfill gas emissions, scaled up to the UK inventory, has been the way that the UK landfill methane emissions estimates have been produced over the last decade, using the NPL (1997) measurement estimate as a calibration marker (Brown et al., 1999; Gregory et al., 2003; Golder Associates, 2005). A new technique of measuring the UK’s whole site landfill methane emissions inventory would allow the better calibration of methane emissions for inventory reporting purposes.
2.0 CONCEPTUAL MODEL OF LANDFILL EMISSIONS

A typical landfill will comprise of an operational area and a number of complete or partially complete phases or cells. Active gas management systems are installed in completed and partially completed areas of fill, and more recently there has been a drive to install gas management systems in operational areas. All active gas management systems are designed to actively collect gas generated within the landfill mass. The gas which is collected is combusted either in a flare or one or more gas engines. The gas which cannot be collected will find its way to the surface of the landfill, where it will be emitted as a fugitive emission.

Figure 1: A typical landfill site with the main sources of emissions indicated

The gas balance for a landfill site will therefore comprise the sum of the emissions from all the managed and unmanaged pathways. This can be written pseudo-mathematically as the following simple relationship:

\[
\text{Whole Site Emissions} = \text{On-Site Surface Emissions} + \text{Off-Site Surface Emissions via Lateral Migration} + \text{Combustion Emissions}
\]
2.1 Surface Emissions

Landfill gas which is not collected by a gas collection system will make its way through defects in the capping or through the surface of uncapped waste and will be lost to the atmosphere as a fugitive emission. This gas may be oxidised while passing through the cap, resulting in a reduction in the amount of methane lost through the surface compared with the source term flux.

Currently, surface, or fugitive, emissions are evaluated through means of FID and flux box survey. First a FID walkover is conducted in order to detect any faults within the capping. Large defects are identified by sight or by smell and smaller defects through the use of the FID, which measures the concentration of landfill gas in air. Once any defects identified during the walkover have been rectified, a flux box survey is then performed. This technique gives an estimation of the methane flux from the landfill i.e. the mass of methane per unit area per unit time. Such an emission rate can also be converted into tonnes per year or for those more familiar with landfill gas extraction systems, m³/hr⁻¹. Flux box measurements are made at a discrete number of evenly spaced locations over the capped zone and extrapolated to give an emission from the whole area. There are thresholds for both the temporary and permanently capped areas of a site as indicated in Table 1. The emission rate over the operational area may be comparable in magnitude to the gas generation rate.

Table 1: Emission Standards for Different Types of Capping

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<td>Temporary</td>
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<tr>
<td>Permanent</td>
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The emission rate for fugitive surface emissions from all area sources on a landfill site can be approximated by summing the emission rates measured from flux box measurements over the area of each surface type, or by integrated optical methods, which may or may not be able to disaggregate the emissions from the different surface types. Such an emission rate calculation takes into account methane oxidation in the cap.

Surface emissions (tyr⁻¹) = \(\sum\) (emission rate (mgm⁻²s⁻¹) x area (m²) x 3.1536 x 10⁻²)

2.2 Lateral Emissions

Lateral emissions are believed to be a very small contributor to methane emissions. They occur below the surface of the landfill, from the mass of waste through cracks/defects in the lateral lining system. The only way of determining whether lateral emissions are occurring is through the use of borehole measurements outside of the Site. The trigger level set by the Environment Agency for methane concentrations in boreholes is typically 1% v/v above background concentrations (normally 0% methane v/v), and for carbon dioxide concentrations is typically 1.5% above background (which can be much more variable, depending on the local geological and hydrogeological environment).
In older sites, however, the lateral emissions may be larger as the liner specification may be less rigorous than current requirements, and/or the number of defects may increase with age.

2.3 Combustion Emissions

The combustion plant, in the form of flares and gas engines is used to destroy a significant proportion of the landfill gas generated within the Site. Neither flares nor gas engines achieve 100% destruction of hydrocarbons to carbon dioxide. Typically, flares are designed to achieve close to 99% destruction efficiency. Gas engines may achieve 96 - 99% destruction efficiency. The apparent loss in efficiency compared to flares is primarily caused by the process of “bulking” of landfill gas, otherwise known as methane slippage, where the unburnt methane passes through the gas engine during the part of the engine cycle when both the inlet and exhaust valves are open at the same time.

The primary parameters which are measured in combustion plant emissions are nitrogen oxides (NO\textsubscript{x}), carbon monoxide (CO), VOCs and Non-methane Volatile Organic Compounds (NMVOCs). NMVOCs are usually a small fraction of the total VOCs, the bulk of which is methane.

Stack emissions are measured at stack temperatures along with other parameters such as stack velocity, oxygen (O\textsubscript{2}) content, moisture content and temperature, in order to derive a normalised emission concentration (in mgN\textsubscript{1}m\textsuperscript{-3}) for compliance monitoring purposes. The same information can be processed differently in order to yield an emission rate in gs\textsuperscript{-1} or ultimately tyr\textsuperscript{-1} from the sum of all combustion plant on a landfill site:

\[
\text{Combustion plant emissions (tyr}\textsuperscript{-1}) = \sum \text{(emission rate (gs}\textsuperscript{-1}) \times (100 - \text{downtime(\%)} \times 31.536)
\]
3.0 REVIEW OF TECHNIQUES FOR EMISSIONS MEASUREMENT

3.1 Flame Ionisation Detection Walkover Method

3.1.1 How it Works

Flame Ionisation Detectors (FIDs) work on the principle of maintaining a voltage between two electrodes located across a small hydrogen flame burning in the air. As gas is drawn into the instrument, the organic compounds present pass through the flame, producing an increase in the current flowing between the electrodes. The response is proportional to the amount of flammable gas present. FIDs are unsuitable for monitoring in an oxygen deficient environment as their flame requires oxygen to support combustion. Although intrinsically safe FIDs have been introduced, the flame poses a potential ignition source where flammable and explosive atmospheres are encountered.

3.1.2 What it Can Do

FIDs are portable and consequently are frequently used to measure gas concentrations close to the surface in order to detect leaks. When the sample probe is held as close to the surface as possible, it will take in air containing any localised emissions of gas through the surface. By sampling at head height, local emissions can also be determined from emissions further upwind. FIDs can provide point concentration measurements but are also used currently as part of site walkovers. The surveyor walks along predetermined lines, monitoring the gas concentration continuously. In the location of high methane concentrations, the survey should deviate to detect the likely source. Once located this area is then closely surveyed to determine the extent of the feature before the surveyor resumes the rest of the survey traversing lines of between 25 m and 50 m (Environment Agency 2004b).

3.1.3 Assessment

FIDs are portable, allowing the detection of emissions at specific locations. Problems associated with this method, however, include the effect of weather conditions and barometric pressure. Saturated ground and rising pressure can suppress emissions from the cap making them less easy to identify.

On the whole however, the walkover with FID approach is a reliable and reasonably straightforward way of obtaining emission concentrations. To aid the walkover process, there are also currently a new range of FID on the market which have a built-in Global Positioning System (GPS). The cost of a walkover survey, generally required once annually, is around £1,000 - £1,500 and would take approximately 1 day. The estimated percentage error using FIDs is approximately 10%.
Figure 2: A photograph of a FID in use

Table 2: A Summary of the FID Walkover Survey Method

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration (ppm v/v flammable gases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>15 seconds</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>1 day +</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Approximately 10 %</td>
</tr>
<tr>
<td>Further analysis of FID output</td>
<td>None required</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>The FID walkover will not give an emission rate, it is used to indicate the locations where the cap and point source defects exist. Current regulations require 1 FID survey annually.</td>
</tr>
<tr>
<td>Cost</td>
<td>£1,000 - £1,500 per survey</td>
</tr>
</tbody>
</table>

3.2 FID with Flux Box Method

Flux boxes can be used to measure the flow of methane from a surface, i.e. the rate of change in emission concentration over time. They are used to produce flux box surveys, the objective of which is to quantify the total release of methane from the surveyed area.
There are two different types of flux box available to do this, the static closed chamber and the dynamic closed chamber.

3.2.1 Static Closed Chambers

3.2.1.1 How it Works

The simplest method of measuring methane fluxes from a landfill site is to use static closed chambers. A static closed chamber is a box of approximately 0.5 m$^2$ with one open side on the bottom and two ports fitted at the top. The inlet port is used for pressure calibration and the outlet port leads to the gas monitoring equipment in which the increase in methane over time can be measured. The flux box is placed on the ground open side down with the bottom side sealed temporarily onto the ground. The concentration of methane within the box is measured at short time intervals over a period of up to an hour. Methane fluxes are directly obtained from the rate in increase in concentrations:

$$flux = \frac{V}{A} \left( \frac{\Delta C}{\Delta t} \right)$$

Where change in chamber methane concentration with time is denoted by ($\Delta C/\Delta t$), chamber volume ($V$) and the area ($A$).

3.2.1.2 What it Can Do

Flux box surveys are used in regulation to assess emissions from capped areas of a landfill site, once the main faults in a gas management system have been identified and rectified as part of a walkover survey with a FID as described above. An intact, defect free cap is assumed to produce a relatively homogeneous emission. Flux boxes may also be used on the operational area of the landfill.

Depending on the size of the landfill, a number of flux box sampling locations are identified a set distance apart (Environment Agency, 2004b). For example for a 50,000 m$^2$ landfill, 40 locations are required with an average spacing of 35 m. One flux box is positioned at a control station and is used as a reference. At this control station, variation in flux, atmospheric pressure, rainfall and wind speed are all recorded for use in calculating the overall site flux. At each of the other sampling locations, the flux boxes are temporarily sealed to the ground, the gas analysers are connected and a sampling period of approximately 30 seconds is used in order to obtain a reading. Data loggers can be set up to take ten readings over a 20 second interval and calculate the mean of these values. Initially measurements are made every minute but after the first few, this interval can be increased to 5 minutes or more, for up to a period of one or two hours. The results from the flux box survey are generally averaged to give an emission rate for each surface type, and then extrapolated to give a whole site value.
3.2.1.3 Assessment

In general, once sufficient points are measured on the landfill, closed chamber measurements are found to be in good agreement with other methods (e.g. Scharff et al., 2005, Spokas et al., 2005). They also prove to be very simple and straightforward sampling devices as well as being comparatively cheap. The nature of the method used, however, requires a lot of measurements to be taken at a lot of different locations. This makes it very time intensive as well as labour intensive due to the need for personnel to be available to measure every single flux box reading. The method may also be used to provide some spatial information about site emissions. It can be used to determine discrete fractures in the cap which arise due to poor design/engineering and maintenance, but the reliability of any spatial information is dependant upon the number of flux box measurements made.

Disadvantages of the flux box technique include problems associated with sampling times. As the methane concentration builds up within the chamber, it eventually reaches the same concentration as within the landfill, this triggers a back diffusion effect and thus limits the amount of time for a measurement to be taken. Another disadvantage is that emissions of carbon dioxide cannot be measured using a static closed chamber. The chamber itself influences assimilation-dissimilation patterns of the vegetation, but the relatively small volume differences introduced by this phenomenon are not as significant as other errors in the technique. Static chamber methods are also not particularly suitable for inhomogeneous
landfills as the total landfill emission is extrapolated from a discrete number of flux box measurements which may miss all of the ‘hot spot’ locations.

There is a large potential for error with flux box monitoring as identified by the guidance (Environment Agency, 2004b). Uncertainty can arise from a number of different issues associated with the sampling conditions and technique. Heating from solar warming or cooling by wind chill can lead to ±100% in measurement error. Similarly a waterlogged ground or high wind speeds can change the measured flux by at least an order of magnitude. The largest source of error, however, is caused by high concentrations of methane in the ambient air. If the ambient air contains a significant concentration of methane, this will reduce the sensitivity of the technique and make it particularly difficult to measure low concentrations. This can then render the measurements invalid. Human error also needs to be accounted for as a large part of this method relies on the selection of representative flux box locations and on adequate interpretation of the aggregated data. This error is likely to be greatest on sites with a number of different zones with very different characteristics and/or if the surveys are undertaken by inexperienced personnel.

In conclusion, a flux box survey provides information about the flux of methane from an area of site, i.e. the mass of methane emitted per unit area and time. Such an emission rate can also be calculated in tonnes per year. A typical flux box survey is required annually and will cost approximately £12,000 - £25,000 depending on the size of the Site and taking approximately 2 -3 weeks. Errors associated with this method can be larger than 100% if not used under the most favourable conditions. Ideally, two or more surveys per year, at £24,000 - £50,000 per year, will give a reasonable annual emissions estimate.

### Table 3: A Summary of the Static Chamber Method

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration (ppm v/v flammable gases) to derive flux in mgm⁻¹s⁻¹ methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>30 seconds per measurement recorded, up to 2 hours per flux reading determined</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>2 - 3 weeks depending on landfill size</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Can be much greater than 100%</td>
</tr>
<tr>
<td>Further analysis required</td>
<td>Some further calculation needed</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Current regulation requires one flux box survey every 2 - 5 years. Ideally 2 - 4 per year will give a reasonable annual emission estimate. The number of campaigns, and the sample frequency, are both inversely proportional to the error in the technique.</td>
</tr>
<tr>
<td>Cost</td>
<td>£12,000 - £25,000 per survey, ideally £24,000 - £50,000 per year to give a reasonable annual emissions estimate</td>
</tr>
</tbody>
</table>

#### 3.2.2 Dynamic Closed Chambers

#### 3.2.2.1 How it Works

Dynamic closed chambers resemble static closed chambers except that a continuous air-flow is maintained through the box by means of pumping an auxiliary or ‘sweep’ gas at a selected
pumping rate. This constant air flow thus avoids the build up of concentrations which affect the flux. Instead fluxes are obtained from the air flow through the chamber and the inlet and outlet concentrations. Maintaining the pressure in the chamber at comparable levels at ambient pressure is very important and inlet and outlet fans can be used to maintain the air-flow.

3.2.2.2 What it Can Do

Dynamic closed chambers are used in a very similar manner to the static closed chamber in order to perform a flux box survey. The number of sampling locations chosen is proportional to the size of the area to be monitored and measurements are made at regular intervals over the surface.

3.2.2.3 Assessment

Generally dynamic chambers have the same advantages and disadvantages as static closed flux boxes discussed above (Scharff et al., 2005). Barry et al. (2004a) conducted tests showing that dynamic flux box measurements are affected by the period of monitoring as well as the pumping speed. They showed that the greater the pumping speed of the auxiliary gas through the chamber, the greater the methane flux which is observed. Clearly this has a great effect on the accuracy of this technique as the pumping speed is selected as part of the survey and hence the method itself is affecting emission rates.

Dynamic chamber methods are frequently used to measure the flux of trace components rather than methane, and are closely related in their principles of operation to Lindval Hoods which are used for monitoring odour. The operator of a dynamic flux chamber needs to be well trained because of the complexities of the technique. This method is most suited to R&D.

The costs and timescales associated with performing a dynamic flux box survey are similar to those using a static chamber flux box.
Table 4: A Summary of the Dynamic Flux Box Method

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration (ppm v/v flammable gases) to derive flux in mg/m²s⁻¹ methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>30 seconds per measurement recorded, up to 2 hours per flux reading determined</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>2 - 3 weeks depending on landfill size</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Can be much greater than 100%</td>
</tr>
<tr>
<td>Further analysis required</td>
<td>Some further calculation needed</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Current regulation requires one flux box survey every 1 - 5 years. Ideally four per year will give a reasonable annual emission estimate. The number of campaigns, and the sample frequency, are both inversely proportional to the error in the technique.</td>
</tr>
<tr>
<td>Cost</td>
<td>£12,000 - £25,000 per survey, Ideally £24,000 - £50,000 per year to give a reasonable annual emissions estimate</td>
</tr>
</tbody>
</table>

3.3 Meteorological Based Methods

A number of methods have been developed which use local meteorological data as a large part of the process in calculating emissions. The micrometeorological method, discussed in Section 3.3.1, looks at local weather data at a very local scale and the mass balance method, discussed in Section 3.3.2, uses the wind profile.

3.3.1 Micrometeorological Method

3.3.1.1 How it Works

Micrometeorological methods are often proposed to measure emissions from larger surfaces as they provide spatially averaged, continuous measurements. The method relies on the fact that within the surface layer, typically the lowest 0 – 50 m of the atmosphere during daylight hours, gas is carried down the concentration gradient due to vertical mixing induced by turbulent eddies. Micrometeorological methods are currently used in landfill applications by the Finnish Meteorological Institute but have previously also been used by the Dutch research organisations TNO and CEH.

The micrometeorological technique described by Laurila et al. (2005) uses eddy covariance methodology. This involves the wind components in each of the three directions and a scalar, e.g. temperature or gas concentration, measured at a high frequency, typically 10 times per second.

The covariance between the vertical wind speed and the scalar, calculated over an average period of usually 30 minutes, gives the flux from an area upwind of the flux mast. The measurement height, the horizontal wind speed, atmospheric stability and the roughness of the surface determine the magnitude of the area sampled with this technique.
The vertical flux density is calculated as:

\[ F = \left( w - \langle w \rangle \right) \left( x - \langle x \rangle \right) \]

Where \( w \) and \( x \) are the instantaneous values of vertical wind speed and the scalar constituent, e.g. gas concentration or air temperature, synchronised with \( w \). The angle brackets represent the average defined by autoregressive filtering with a running meantime constant of 200 seconds. The over bar denotes arithmetic averaging (Laurila et al., 2005).

In the method described by Laurila et al. (2005), the dynamical response characteristics of the measurement systems are identified using spectral analysis. The overall system response is given in the form of a transfer function. This transfer function is determined directly from the field data based on the assumption that there is co-spectral similarity between the heat and mass fluxes. The transfer function used by Laurila et al. (2005) was:

\[ G(f) = \exp \left[ -\ln(2) \left( \frac{f}{f_0} \right)^2 \right] \]

Where \( f \) is the frequency and \( f_0 \) the half power frequency. The co-spectrum of each mass flux component was normalised to that of \( H \) for \( f < 0.1 \text{ Hz} \) and \( f_0 \) was determined by fitting \( G \) to the normalized data for \( f > 0.1 \text{ Hz} \) (Laurila et al., 2005).

### 3.3.1.2 What it Can Do

Lohila et al. (2006) conducted a continuous long term eddy covariance campaign. The campaign spanned over 6 months measuring methane and carbon dioxide from Ämmässuo Municipal Landfill in Finland. A mast was placed in the northeastern part of the landfill. To the west of the landfill lay slightly undulating land and to the East a slope of around 7° inclination. The northern direction had to be excluded from analysis as a cabin 30 m away from the mast was expected to disturb the flow. Under neutral conditions, it was estimated by Rinne et al. (2005) that 90% of fluxes measured by eddy covariance methods originate from within an area 150 m away from the mast which corresponds to an area of around 7 Hectares (Ha).

The methane flux instrumentation included a three-axis ultra-sonic anemometer and a FID in a gas chromatograph chassis for fast response total hydrocarbon concentration measurements. Dried air samples were fed directly into the FID, from which the column had been removed. Simultaneously with the FID measurements, the methane flux was measured with a tuneable diode laser (TDL).

In the campaign, friction velocity (\( U_* \))-observations of lower than 0.1 ms\(^{-1} \) were omitted from the results. The reason for this is that turbulent flow is less well developed under nearly calm
periods or when the temperature stratification is very stable. This leads to the eddy covariance method underestimating surface fluxes.

The results were compared against results from a simultaneous flux box campaign. The fluxes measured by the two methods agreed reasonably well although this result has limited value as the flux box survey was limited in the number of measurement locations used.

Figure 4: A photograph of the micrometeorological mast and equipment used by Laurila et al. (2005)

3.3.1.3 Assessment

The main assumption of micrometeorological techniques is that the surrounding landfill site is flat and that emissions from the landfill occur in a homogeneous manner. In reality this ideology is somewhat flawed. No landfill sites are completely flat and the sloping areas of such sites are major emission sources (Scharff et al., 2000). Likewise landfills are typically characterised by a large spatial heterogeneity in surface fluxes. Problems with eddy covariance methods in heterogeneous environments thus arise in the dependence of the measurement on the wind direction. For example day-to-day variation in emissions is difficult to measure with constantly changing wind directions. One possible solution to this problem is having more than one mast at the same landfill but in turn this increases cost.

Another key problem is that the gas analyser used must be able to resolve concentration variations at sufficiently high frequencies, up to 10 Hz. Laurila et al. (2005) showed that a fast response FID detector performed to a similar standard as a TDL based reference system. The result of this finding is thus to show that the method can be relatively simple and cost effective in field conditions and thus suitable for emission monitoring purposes.
The area integrating characteristics and the continuity of the measurements are of vital importance in this case.

A further disadvantage of this technique is that it does not work well under low wind velocities. Under nearly calm periods or when the temperature stratification is very stable, turbulent flow is not well developed. In these conditions, eddy correlation methods tend to underestimate the surface fluxes (Lohila et al., 2006).

One advantage of this method though is that compared to the tracer method, this micrometeorological method also provides the carbon dioxide flux, which makes it possible to estimate the generation and surface cover oxidation of methane. Another advantage of the eddy covariance technique is that it causes no disturbance to the surface under examination, a problem which is very difficult to avoid with the chamber technique.

The trial of Lohila et al. (2006) comparing micrometeorological methods with flux box techniques showed good comparison between the two sets of results and that even though the micrometeorological eddy covariance method is subject to some restricting assumptions, it is capable of producing continuous, area-averaged estimates of the landfill methane emissions. The main issues however relate to the applicability of the technique and its suitability to different sizes and morphology of landfill sites.

For the micrometeorological method, a four week survey is sufficient to quantify emissions from a site which would cost in the region of £8,000. The accuracy of this method was assessed by Lohila et al. (2006) as giving approximately 20% uncertainty.

### Table 5: A Summary of the Micrometeorological Method

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration ($\mu g m^{-3}$) and then a derived Flux ($mg m^{-2} s^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>30 minutes</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>Approximately 4 weeks depending on landfill size</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Approximately 20%</td>
</tr>
<tr>
<td>Analysis required</td>
<td>Detailed further analysis required</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Estimated twice yearly to account for seasonal variation. The number of campaigns is inversely proportional to the error in the technique.</td>
</tr>
<tr>
<td>Cost</td>
<td>£8,000 per survey, £16,000 per year to account for seasonal variation</td>
</tr>
</tbody>
</table>

### 3.3.2 Mass Balance Method

#### 3.3.2.1 How it Works

In the mass balance method, methane and carbon dioxide emissions are obtained from an interpretation of wind velocity and the methane concentration at different heights over the landfill surface. In this method, a vertical mast is erected in the middle of the Site at which measurements of the wind velocity and methane concentration can be obtained at different height intervals. At each of these levels, the product of concentration and wind velocity
provides the horizontal flux and is subsequently related to the landfill area upwind of the sampling points. If the measurements are performed to a sufficient height over the landfill, the whole methane plume is sampled and the emission flux is obtained with results for the very top of the mast indicating the background concentration. At varying wind directions, emissions from all parts of the landfill are sampled and therefore this method provides some spatial information about high and low area of emissions (Scharff et al., 2000).

3.3.2.2 What it Can Do

In 2003, Scharff et al. conducted an assessment of the mass balance method measuring vertical methane and carbon dioxide concentration profiles along with a wind velocity profile, using sampling points on a mast up to 10, 15 or 25 metres high. Both methane and carbon dioxide concentration profiles were measured using an opto-acoustical gas monitor. Profiles were then interpreted and emissions from the region up stream were calculated using:

\[
J = \frac{\int_{z=0}^{z=1} u z (c_z - c_1) dz}{x}
\]

- Where \( J \) is the methane flux through the landfill surface (\( \text{L m}^2\text{s}^{-1} \));
- \( u_z \) is the wind velocity at height \( z \) (\( \text{m}^2\text{s}^{-1} \));
- \( c_z \) is the concentration at height \( z \) (\( \text{L m}^3 \), vol % or methane ppm);
- \( c_1 \) is the concentration at height \( l \) (\( \text{L m}^3 \), vol % or methane ppm);
- \( l \) is the height of the mast (m); and
- \( x \) is the upstream distance from the mast to the landfill slopes otherwise referred to as the fetch (m).

This method has been used in the Netherlands on a number of occasions. Oonk and Boom (2000) report that the method is easily automated and emissions can be obtained for long periods of time. Based on information collated by Oonk and Boom (2000) approximately three weeks sampling is required to obtain consistent average emissions although carbon dioxide emissions measurements are not as accurate as methane measurements. They also highlighted that limitations to the measurement method include the applicability of using a 10 m high mast to situations where the distance to the landfill boundary is less than 150 m. Therefore the results in terms of the emission estimates depend on assumptions on distribution over the surface.

3.3.2.3 Assessment

The mass balance method was trialled against the Tuneable Diode Laser (TDL) method by Scharff et al. (2003). The results of this experiment correlated well but there are other factors to consider in the evaluation of this technique. One disadvantage is the practicality of using this method at large landfill sites. In order to sample the whole plume, upper sample points...
may need to be located in excess of 25 m high and erecting a mast of suitable height may pose somewhat of a problem. Likewise, at larger landfills, emissions originating from slopes may disperse to greater heights and consequently the methane plume from the landfill is higher than the mast causing underestimation.

Another disadvantage of the mass balance technique is that larger point sources further away from the mast may result in disruption of the concentration profile causing increased concentrations in the middle or at the high end of the mast.

In the method described by Scharff et al. (2003) such concentration profiles are neglected and larger point sources remain undetected in the current set up. Emission estimates downwind of the mast will also be missed as the mast only provides information for the area of landfill upwind from it at that particular time. Other problems arise in the form of trees and buildings which can disturb the dispersion pattern and result in non ideal concentration profiles and consequently unrealistic estimates of emissions.

An advantage of the system, however, is that it allows representative emission levels to be obtained for large parts of the landfill. For example it is possible to use the method to determine emission levels from just one particular cell. The method can also be used to provide temporal patterns of the landfill emissions. Other benefits include the ease and simplicity of the method. Only one measurement location is needed and once the mast has been erected, automated, continuous measurements over a long period of time are possible. Also, the data which are obtained from this method are then straightforward to interpret.

A further advantage of the mass balance method is that it can also be used to obtain carbon dioxide emissions upon provision of suitable monitoring equipment.

In conclusion, the mass balance method can be used to provide a quantification of the methane flux from a landfill site. The costs of this method are estimated as approximately £7,000 - £8,500 per four week sampling campaign and with the assumption that eight measurements are required per five year period. The error of this method is estimated as around 25% (Scharff et al., 2003).

Table 6: A Summary of the Mass Balance Method

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration (µgm⁻³) and then a derived Flux (mg/m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>Approximately 4 weeks</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>Approximately 4 weeks</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Approximately 25%</td>
</tr>
<tr>
<td>Analysis required</td>
<td>Detailed further analysis required</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Estimated twice yearly to account for seasonal variation. The number of campaigns is inversely proportional to the error in the technique.</td>
</tr>
<tr>
<td>Cost</td>
<td>£7,000 - £8,500 per survey, £14,000 - £17,000 per year to account for seasonal variation.</td>
</tr>
</tbody>
</table>
3.4 Stationary Plume Methods

A number of the methods developed use information about the plume in order to determine emissions. They use the prevailing wind direction to sample concentrations at a number of stationary points downwind of the Site.

3.4.1 Stationary Plume Measurement

3.4.1.1 How it Works

The stationary plume method uses a sampling system to measure the concentration of methane observed downwind of the landfill site. A number of gas bag sampling stations are located evenly around the landfill site. For a particular sampling period, the air samples collected within the gas bags downwind of the Site are selected and analysed along with the gas bags directly upwind so as to provide background concentration data. The contents of each gas bag are evaluated in conjunction with meteorological data to measure the concentration over time at the location of the estimate and the modelled time series are averaged over the sampling time. Dispersion models are then used to calculate the expected concentrations at the receptors. Comparison of the modelled and monitored concentration levels provides estimates for the strength of the source which caused the plume.

3.4.1.2 What it Can Do

Scharff et al. (2003) used the stationary plume method during a field trial comparing various methods of measuring surface emissions. The stationary plume method site was set up with four fixed gas bag sampling stations spread evenly to give one in each quarter of the landfill. The meteorological conditions were monitored on the landfill site by an automatic weather station connected to a computer. From this data, the methane concentrations at each of the four sampling stations were then calculated. The computer was set up with a set threshold level so that once the estimated concentration at any of the stations surpassed that given level, the computer activated the particular receptor station by telemetry. As a result, a battery operated electronic unit at the station was activated to sample air in a gas bag for a 30 minute period. The central station triggers both an upwind and a downwind station so as to provide both upwind and downwind concentrations.

In general there were two daily sampling events and each station could hold seven bags. At the end of each week the full gas bags were replaced with empty bags. The samples were then analysed using a Gas Chromatography Flame Ionisation Detector (GC-FID). After the samples had been analysed, Scharff et al. (2003) used a Gaussian model to calculate the expected concentrations level at each receptor station using a set of point sources across the landfill. At each point source, a Gaussian plume was calculated; the reflection of the ground level was taken into account.
The distance between the source and the receptor was not more than 2000 m as at this distance the effects of an inversion layer only occur at night under stable condition. Therefore no correction was deemed necessary for reflection at the inversion layer. For each source receptor combination the receptor concentration was obtained from:

$$Concentration(x, y, z) = \frac{Q}{2\pi \nu \sigma_y \sigma_z} \cdot e^{-\frac{y^2}{(2\sigma_y)^2}} \cdot \left( e^{-\frac{(z+H)^2}{(2\sigma_z)^2}} + e^{-\frac{(z-H)^2}{(2\sigma_z)^2}} \right)$$

With $$\sigma_y = Ax^b \cdot Z_0^{0.2} \cdot T^{0.35} \cdot \sigma_z + Cx^D (10z_0)^{0.5E}$$ and $$E = x^{-0.22}$$.

Where x, y and z are the distance along the plume axis, the axis perpendicular to the plume axis and the height above ground level respectively. Q is the source length, u the wind speed measured on top of the landfill and H is the height of the emission (top of the landfill). Sigma y and z, $$\sigma_y$$ and $$\sigma_z$$, are dispersion parameters that depend on distance to the source, the degree of turbulence of the atmosphere, the roughness length of the surface ($$z_o$$), and on the timescale used for averaging. The various atmospheric stability classes are defined by the letters A, B, C and D. T is the averaging time, which equals the sampling time of 0.5 hour.

The final model concentrations of Scharff et al. (2003) are obtained by adding together each of the contributions from the various different sources. The sources on the different parts of the landfills are then scaled to get a total Q(model)=1 gCH4s⁻¹ and the emission in gCH4s⁻¹ is then calculated using:

$$Q \ (\text{Landfill}) = Q \ (\text{model}) \times (\text{Conc(plume)}-\text{Conc(background)})/ \text{Conc(\text{model})}$$

Scharff et al. (2003) also conducted sensitivity runs to determine the optimum sampling time. Their results show that over longer sampling periods, e.g. a couple of hours, the plume may well have moved away from the receptor, due to changes in wind conditions. For shorter sampling periods though, the exact position of the station in the plume is important.

Meteorological data is used within the model and stored and processed at the central computer and the model is run at wind direction +5° and -5°. When the three model concentrations are close together the sample is taken in the middle of the plume and therefore the uncertainty in the emission is smaller.

In general, sensitivity analysis for the method shows that the effect of the wrong assumption of the main emitting area on the landfill led to a ± 10% estimation of emission from a single station. However, as stations are situated in different wind directions, underestimation of the emissions at one site will automatically mean an over estimation at the Site in the opposite wind direction. Once enough data points are obtained the effect of the average emission should be lower than 10%.
3.4.1.3 **Assessment**

Scharff *et al.* (2003) found that the stationary plume method is a good practical solution for measuring emissions across the landfill. It works particularly well for larger landfills but less so for the smaller sites. The shorter distance between the source and receptors makes the method much more susceptible to disturbance of the plume and sensitive to the exact location of the source. Scharff *et al.* (2003) suggested that the distance to the landfill, for those of less than 20 ha, should be approximately 300 m so as to allow the stationary plume receptors to be within the plume for a significant period each month.

One disadvantage of the method is that it provides too small a dataset to give temporal information about the plume. Other problems lie in locating the sampling stations in suitable areas i.e. out of reach from other sources of methane e.g. cows. The stations must also not be located too close to the source and issues of vandalism and theft must be taken into consideration when equipment is placed off-Site. One final problem with this method is that it is considered unreliable in the measurement of emissions calculated from the edge of the plume.

Scharff *et al.* (2003) estimated the cost associated with the stationary plume method to be approximately £10,000 - £12,000 per sampling campaign. Scharff *et al.* also suggested a total of eight measurements deemed necessary over a period of five years. The corresponding error associated with this method was estimated at around 25% (Scharff *et al.*, 2003).

**Table 7: A Summary of the Stationary Plume Method**

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration (µgm⁻³) and then a derived Flux (mgm⁻²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>30 minutes</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>1 - 2 days</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Approximately 25%</td>
</tr>
<tr>
<td>Analysis Required</td>
<td>Detailed further analysis required</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Estimated twice yearly to account for seasonal variation. The number of campaigns is inversely proportional to the error in the technique.</td>
</tr>
<tr>
<td>Cost</td>
<td>£10,000 - £12,000 per survey, £20,000 - £24,000 per year</td>
</tr>
</tbody>
</table>

3.4.2 **Simplified Stationary Plume Method**

3.4.2.1 **How it Works**

Jacobs *et al* (2006) have developed a simplified version of the stationary plume technique aimed at reducing the costs of the method and increasing practicality whilst still retaining results of a high level of accuracy. The method is simplified by omitting the computer commanded sampling along with the meteorological measurements and modelling to become a manually operated sampling system. Instead of the sets of sampling stations, a set of approximately twelve evacuated gas canisters containing capillary tubes are placed downwind of the Site, with one placed upwind to indicate background concentration levels. At the end
of the day the gas canisters are taken away to a laboratory for analysis. The methane release of the landfill can be determined by comparison with the recovery of a known release of tracer gas which is released at the beginning of the sampling period.

### 3.4.2.2 What it Can Do

In January 2006 a comparison experiment was carried out by Jacobs et al. using the simplified stationary plume method to quantify methane emissions from a landfill. Ten gas canisters were positioned between 500 m and 1,500 m downwind of a landfill which would sample air over a 6 - 8 hour period.

At the beginning of the sampling period, nitrous oxide was released from the landfill as a tracer in order to quantify the emissions measurements. Simultaneously, dynamic plume measurements were carried out with a quantum cascade laser (QCL) mounted in a truck. At the end of the day the contents of the canisters were analysed three times with the QCL.

Jacobs et al. (2006) perceived that the meteorological data used in the ordinary stationary plume method lead to better understanding of the plume shape observed with the canisters. If used with this method it could provide an important quality control for the methane emission estimate and it only increases the cost by 6%.

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**Figures 5A (left) and B (right):** A schematic of how the gas canisters are placed around a landfill site in the simplified stationary plume method (Jacobs et al., 2006) and a photograph of one of the gas canisters used for tracer release (Jacobs et al., 2006)

### 3.4.2.3 Assessment

The main advantages of this method are that it is particularly cheap and straightforward, not requiring a skilled personnel presence throughout the sampling period. The equipment used is all very simple and easy to obtain and costs could be further decreased by use of a GC- FID.
rather than a QCL as was used in the experiment detailed above. The results obtained from the Jacobs et al. campaign showed a good correlation with the dynamic plume method.

The main disadvantages of this technique are that it is still in the early stages of its development and aspects such as suitability and accuracy of this technique could still be better explored at a wider variety of landfills. Accuracy can be improved by increasing the number of gas canisters used along the transect on which the tracer plume is found, although in turn this will lead to an increase in the cost of the method.

This method also has some implications on global warming as nitrous oxide has a high global warming potential (GWP) of 296. Jacobs et al., however, have been looking into the option of substituting nitrous oxide (N₂O) for propane as it has a much lower GWP of 10 as well as enabling the use of GC-MS analysers.

Other problems with this method are related to instrumental damage. The capillary tubes within the gas canisters are easily damaged by dust and rain although this problem can be helped through valves/angling of the capillaries. The gas canisters themselves are highly susceptible to theft and vandalism however as they are generally located off-Site as well as being easy to carry, and (in the UK at least) would have a perceived monetary value.

In summary, the simplified stationary plume method is a cheap and simple way of quantifying methane concentrations downwind of a landfill. The costs of using this method are approximately £1,700 per sampling campaign once an initial capital cost of approximately £6,000 is spent on the necessary equipment. Ten campaigns per annum are necessary to maintain an error within 20% (Jacobs et al., 2006).

Table 8: A Summary of the Simplified Stationary Plume Method

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration (µgm⁻³) and then a derived Flux (mgm⁻²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>6 - 8 hours</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>1 - 2 days</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Approximately 20%</td>
</tr>
<tr>
<td>Analysis required</td>
<td>Lab analysis of samples required</td>
</tr>
<tr>
<td>Number of surveys required per year to</td>
<td>The number of campaigns is inversely proportional to the</td>
</tr>
<tr>
<td>obtain an accurate annual emission</td>
<td>error in the technique. Ten campaigns will give 20% error</td>
</tr>
<tr>
<td>estimate</td>
<td>(estimated), fewer campaigns, greater error.</td>
</tr>
<tr>
<td>Cost</td>
<td>£6,000 capital cost; £1,700 per survey, £23,000 for first year, £17,000 thereafter.</td>
</tr>
</tbody>
</table>

3.5 Mobile Plume Methods

Mobile plume methods are used to obtain time resolved concentration measurements of methane in the downwind plume of the landfill.

Optical methods are used to trace the plume downwind of the landfill. An optical path is established between a laser source on one side and the reflector on the other. Absorption of
the light emitted from the laser occurs in an astigmatic multi-pass cell. By sending the laser through the optical path to the reflector and back again, a signal, which varies according to the amount of gas in the path is generated. The system is built into a unit and located in a van. The van is driven along roads located downwind of the Site and ambient air is sampled from the roof of the van and lead through the cell. Each plume transect takes approximately 5 - 7 minutes. The methods are coupled to an actual emission by means of a tracer gas.

3.5.1 Mobile Plume Method with TDL

3.5.1.1 How it Works

One way of applying the mobile plume technique is using a Tuneable Diode Laser (TDL) to measure the methane concentration downwind of the landfill in a transect through the plume.

Unlike most optical sensing techniques, TDLs have line widths of only a few MHz, and are therefore suited to high resolution spectroscopy, making it possible to measure absorption from single absorption lines so passage through the cell takes only a few seconds. The laser source is tuned in wavelength by temperature and current to the wavelength corresponding to an absorption line for the gas one wants to measure. The 1270 and 1271 cm\(^{-1}\) absorption lines are used for methane and nitrous oxide respectively.

3.5.1.2 What it Can Do

The TDL system used by Scharff et al. (2003) has a 10ppb resolution for methane and 20 ppb for nitrous oxide and can measure at frequencies up to 20 Hz. (The 1 Hz data set was generally used). Standards were used to calibrate the equipment prior to and after a transect measurement and calibration was carried out while in motion. GPS was used to provide the position of the van. Two meteorological stations were set up, one on top of the landfill and one on top of the van.

In the assessments by Scharff et al. (2003), the measured concentration in the plume transect was compared with the output of multiple Gaussian plume models described under the stationary plume method (Section 3.4). The emission strength of the landfill is equal to the source strength needed in the model to get an agreement between the integral of the concentration along the measurement transect for the modelled and measured plume. The meteorological data that was needed for the model calculations (wind speed, wind direction and turbulence) was obtained either from the measurements on top of the landfill or from measurements at the van. These measurements indicate the Pasquill stability class. Nitrous oxide was released from a gas flask on top of the landfill and the TDL measured the nitrous oxide plume while also measuring the methane plume. The model calculation for the plume was used as a check of the parameters that determine the dispersion and also used to calibrate the emission rate if necessary.
3.5.1.3 **Assessment**

The mobile plume method is an established method and is therefore available for use at landfill sites. It has also been shown to work well for landfills of different sizes (Scharff et al., 2003). The spatial information it provides can also be used in identifying hot spot locations and hence determine spatial variation in emissions. The TDL devices are also known to have long life and consequently instruments based on this technique can be thought of as highly reliable and with subsequently long service intervals.

One potential problem with this method is that it requires established roads at least 100 - 1000 m at one side of the landfill. In addition to this, sampling has to be carried out when the wind is in the right direction (making the available roads downwind of the Site); there are no significant pressure changes; no major disturbances at the landfill and personnel are available. The accuracy of this method is affected by changes in wind direction as well as instrumentation noise, drift of the laser and uncertainty in background concentrations.

Scharff *et al.* (2003) estimate that each sampling campaign costs approximately £5,500 per landfill/day with approximately two days expected to measure the emissions from a site and four - six campaigns required per annum. The error associated with this method is estimated as 10 - 25% depending on location.

**Table 9: A Summary of the Mobile Plume Method with TDL**

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration (µg m⁻³) and then a derived Flux (mg m⁻³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>5 - 7 minutes per sample</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>Approximately 2 days</td>
</tr>
<tr>
<td>Percentage error</td>
<td>10 - 25% depending on location</td>
</tr>
<tr>
<td>Analysis Required</td>
<td>None for a simple emission profile, however, more detailed analysis is required to determine contributions from specific site areas.</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Estimated at four - six per year to account for seasonal variation. The number of campaigns is inversely proportional to the error in the technique.</td>
</tr>
<tr>
<td>Cost</td>
<td>~£11,000 per survey, £44,000 - £66,000 per year to account for seasonal variation.</td>
</tr>
</tbody>
</table>

3.5.2 **Mobile Plume Method with FTIR**

3.5.2.1 **How it Works**

Fourier Transform Infrared Spectroscopy (FTIR) is used to obtain time resolved concentration measurements of methane in the downwind plume of the landfill. This optical technique allows a wide spectral range to be recorded simultaneously. Infrared light is transmitted over a long path in the gas under study, and an absorption spectrum is recorded allowing a number of gases including CO₂, CH₄, N₂O, CO, H₂O and hydrocarbons to be analysed. The long
optical path is used to provide low detection limits down to a few ppb. The optical system is generally accompanied by a system for making meteorological measurements.

3.5.2.2 What it Can Do

Samuelsson et al. (2001) conducted trials on four sites in Sweden and used a medium resolution FTIR spectrometer connected to an optical multiple-reflection gas cell with an adjustable path length, ranging from 9 to 107 m. A path length of 96 m was normally used to optimise optical throughput and absorption levels. The system was built into a unit and located in a van. The recorded spectra were analysed by multiple regression techniques. Methane was analysed in the wave number region around 2950 cm\(^{-1}\) and nitrous oxide around 2200 cm\(^{-1}\). The FTIR was calibrated and the detection limits determined for all gases analysed.

The meteorological data used in this method was collected from two different systems. A stationary system located at the top of the landfill and a mobile system located in the van. The data collected included wind speed and wind direction, measured from a 5 m tripod mast, as well as air temperature, relative humidity and soil temperature which were all averaged over 1 minute and recorded on a battery powered logger. A telescopic 10 m mast was mounted on the van with a gas inlet located on top of the mast so as to sample air from within the wind plume and beside the measurement location for wind speed and direction. The sampled airflow was then channelled through inert Teflon tubing to the gas cell. Air temperature, relative humidity and barometric pressure were also measured in the optical cell. All measurements were synchronised with the spectrum collection and stored with the spectra. The system was powered by either the vans engine or a generator depending on the location of the measurements being taken.

The Time Correlation Tracer method can be used to couple the concentration measurements to actual emission. In this case nitrous oxide was used as the tracer gas. It was released in a controlled manner from the point sources of methane emissions in the area. This was conducted to allow the tracer to mix with the methane in the landfill plume and by time resolved analysis of the methane and tracer concentrations far enough downwind of the landfill, the emission was derived. The part of the time series where the concentrations correlate is assumed to be where the tracer was released and can be quantified using the known tracer flux in:

\[
Q_{CH_4} = Q_{\text{Tracer}} \frac{C_{CH_4} M_{CH_4}}{C_{\text{Tracer}} M_{\text{Tracer}}}
\]

Where C is the mixing ratio and M is the molecular weight (Samuelsson et al., 2001).
As the wind plume sweeps in and out over the measurement location it is possible to determine how all the tracer release simulates the methane emission by looking both at the concentration correlation and the wind direction and whether the total emission or only a fraction of it is simulated.

Samuelsson et al. (2001) recommend that approximately 2 - 6 tracer point sources should be used although this depends on the size of the landfill. Each source releases a maximum of 2.8 kg h$^{-1}$ of nitrous oxide. The released amount of tracer can be controlled by rotameters and integrating gas flow meters, and by weighing gas tubes. Distances to the measurement location are selected depending on the size of the landfill and typical distances range between 600 m and 2400 m.

Figure 6: A photograph of the FTIR instrumentation located in a van used by Samuelsson et al. (2006)
Figure 7: A sample of some of the results from trials by Samuelsson et al. (2006), showing different profiles of emission rates associated with different parts of the landfill

3.5.2.3 Assessment

One of the main advantages of the mobile plume with FTIR method is that the whole plume can be measured instantaneously, regardless of landfill topography and management. This means it is possible to judge in real time if measurements have been successful and enables a second test to be conducted whilst still on-site. The instrumentation also allows online information on the plume location and development. As most of the equipment is located within a van it is also suitable for use in all seasons.

Unlike the stationary plume method, the mobile plume with FTIR method also facilitates the study of the edges of the plume, providing information of the quality of the source simulation by the tracer release. Figure 7 also shows how the results of a sampling campaign can be analysed in order to ascertain the contribution to the overall site emissions from different areas, for example different cells.

The constraints on the method include: the need for roads within 500 - 2500 m on one side of the landfill for the van to drive along so that the plume can be traversed; ideally wind speeds over 2 ms⁻¹; and winds blowing in the direction of the accessible roads. It may take time to wait for a favourable wind direction to occur but upon observing the desired wind direction, approximately only 2 - 4 days are required to obtain an emission provided skilled personnel are available. A final main disadvantage is that the tracer release does contribute to global warming, this problem could theoretically be minimised through the use of a less harmful pollutant however, in a similar way to that discussed for the mobile plume with TDL.
The mobile plume with FTIR method has been estimated as giving between 15% and 30% error depending on meteorological conditions (Galle et al., 2001). The technique takes approximately 2 - 4 days, to provide an emissions estimate for a whole site and costs approximately £8,000 - £10,000. To obtain an annual estimate, approximately 6 - 8 measurements are required over a recommended three year period.

Table 10: A Summary of the Mobile Plume Method with FTIR

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Concentration (µgm⁻³) and then a derived Flux (mgm⁻²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>1 minute per sample</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>Approximately 2 – 4 days</td>
</tr>
<tr>
<td>Percentage error</td>
<td>15 - 30% depending on meteorological conditions</td>
</tr>
<tr>
<td>Analysis Required</td>
<td>None for a simple emission profile, however, more detailed analysis will be required to determine contributions from specific site areas.</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Estimated at three per year to account for seasonal variation. The number of campaigns is inversely proportional to the error in the technique.</td>
</tr>
<tr>
<td>Cost</td>
<td>£8,000 - £10,000 per survey, £24,000 - £30,000 to account for seasonal variation.</td>
</tr>
</tbody>
</table>

3.6 Ground Optical Remote Sensing Techniques

Ground optical remote sensing techniques were designed to characterise the emissions of fugitive gases from area sources and provide detailed spatial information from the use of iterative algorithms. As with the mobile plume methods, the remote sensing can be conducted using a variety of methods, in particular Open Path Tuneable Diode Laser (OP-TDLAS) and Open Path Fourier Transform Infra Red (OP-FTIR). All the techniques are based on sound spectroscopic principles: light of an appropriate wavelength or wavelengths is transmitted and the concentrations of target gases are calculated based on the light received back into the detector at the other end of the measurement path. Such is the variety of methods available that the incident radiation may vary from the mid-infrared region through to the ultraviolet.

The main difference between open path techniques compared with those mentioned previously is that they sample over a line rather than a point source. This offers a variety of advantages including that within the area surveyed, there is an improved chance of detecting small or concentrated leaks in a non-uniform or poorly-mixed environment.

The quantitative analysis, which is conducted as a part of this technique, uses the assumption that the concentrations of species being measured are related to the data from the measurement technique used. For the spectroscopic methods used in ground optical remote sensing techniques, the Beer-Lambert law defines a simple linear relationship between measurement and composition:

\[ A = abc \]
Where $A$ is absorbance, $\varepsilon$ is wavelength, $b$ is path length and $c$ is the concentration of the species of interest. (Sira Ltd, 2004a).

**Figure 8: An example of an open path system**

The Beer-Lambert law is a limiting law and is only strictly obeyed for monochromatic radiation. No spectrometer is capable for measuring at infinitely high resolution, however, the Beer-Lambert law is generally obeyed because the true absorbance value $A(v)$ is expected to vary linearly with the concentration of each component in the sample and also, the measured or apparent absorbance is generally found to vary linearly with true absorbance.

Further assumptions of the Beer-Lambert law are that it assumes no scattering, that the beam is strictly collimated and that pressure broadening effects are negligible. In ground optical remote sensing techniques this is generally but not necessarily true.

### 3.6.1 Ground Optical Remote Sensing Techniques Using IR and UVDOAS

#### 3.6.1.1 How it Works

Open path gas detection technology has been developed to include the Differential Optical Absorption Spectroscopy (DOAS). This technology analyzes at least two wavelengths within each spectral band, one in a region where the hazardous gas absorbs and one where it does not absorb. The ratio between these absorption lines when compared to background spectral absorption lines can provide accurate information with regards to gas concentration and the location or migration of a cloud (Sira Ltd, 2004a).

#### 3.6.1.2 What it Can Do

The Open Path Gas Detection system consists of two modules: A unique light source (totally different from surrounding radiation sources) that can be activated at various different frequencies and emit a wide spectral band; and a detector which consists of several sensors with unique filters for sensing and analysing.
The light source and the detector are mounted and aligned at a fixed length with the monitored optical path being the direct line of sight between them. Since the distance between the light source and the detector varies from one installation to another, the gas concentration is not measured in absolute units of ppm but in ppm x metre.

The average gas concentration over the optical path (in ppm) is obtained by dividing the measured concentration in units of ppm x metre by the distance between the light source and the detector (in metres).

The Siemens-HAWK is an example of an IR-DOAS system. It has previously been used by NPL to assess methane emissions (NPL, 1997).

For the purposes of this study, measurements were taken alternately along a path at ground level and along a path towards the top of a mast so as to obtain background concentrations. The excess concentration in the plume was then calculated by subtracting the background measurement from that at ground level. The corresponding flux through the measurement plane was calculated using measured values for the wind speed and direction. The measured flux was then converted into an area emission rate by calculating the area of the Site upwind of the measurement plane.

3.6.1.3 Assessment

The most obvious example of potential measurement error in ground remote optical sensing techniques is partial or complete obscuration of the beam. This can be caused by meteorological conditions (rain, snow, fog etc) or by objects such as foliage, vehicles or people. Commercial instrument manufacturers are aware of such issues and their instruments are designed to cope with beam blockage.

Most ground optical remote sensing technique measurements are recorded over a transect and consequently are unable to give a profile of the spatial variation in concentration over the transect. This means that they are of little use in identifying leaks or large point sources because the line averaged concentrations may still be below threshold levels. Additionally if the landfill is graded at a steep gradient and a point source on the top of the landfill is emitting methane there is potential for the majority of the gas to pass above the laser transect.

Open path techniques have an advantage over point source detectors in that the sampled volume is so much greater than the effect of non uniformity of mixing within it that this effect is mitigated and a more representative value of the concentration of the compound is obtained. Under field conditions, the degree of mixing is affected by the local environment – primarily wind and thermal gradients. Where concentration gradients exist and mixing is limited there may be considerable variability in the concentrations detected according to the positioning of the instrument. Equally, the acquisition time and measurement intervals used may affect the values obtained.
Finally the issue of cross sensitivity must be addressed. The environment measured by open-path instruments is unconstrained and as a result it is possible that a variety of species may be present in the atmosphere being sampled.

In summary, the IR and UV DOAS systems are ground optical remote sensing devices for measuring the average concentration over the path length. The cost of a piece of apparatus such as this is estimated as approximately £30,000 but once installed, the instrument is able to provide automated measurements as frequently as needed. The error associated with the technique is reported to be between 3.8% and 13% (i.e. 5 - 15% practically) for methane (USEPA technical specifications).

Table 11: A Summary of IR and UV DOAS Methods

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Continuous measurement of concentration averaged over distance (ppm x m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>Near instantaneous</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>Fixed systems are set up in semi-permanent fashion for continuous monitoring. The NPL (1997) technique used a mobile system</td>
</tr>
<tr>
<td>Percentage error</td>
<td>5 - 15%</td>
</tr>
<tr>
<td>Analysis Required</td>
<td>None</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Fixed systems will not deliver an annual emissions estimate. Mobile systems, like all other techniques, will require 2 - 4 surveys per year.</td>
</tr>
<tr>
<td>Cost</td>
<td>Approximately £30,000 per installation</td>
</tr>
</tbody>
</table>

3.6.2 Ground Optical Remote Sensing Techniques using OP-TDLAS

3.6.2.1 How it Works

The Open Path Tuneable Diode Laser (OP-TDLAS) system is a relatively fast and interference free technique that is capable of measuring continuous concentrations of many gases including CH₄, CO, CO₂, and NH₃ in the range of tens of parts per billion over an open path up to 1 km. The laser emits radiation at a particular wavelength when an electrical current is passed through it. The light wavelength emitted depends on the current passing through and hence allows scanning over an absorption feature and the analysis of the target gas concentration using Beer’s Law. The OP-TDLAS uses a small telescope which directs the laser beam to a mirror. The laser beam is returned by the mirror to the telescope, which is connected with fibre optics to a control box containing the laser and a multiple channel detection device. The signal produced varies according to the amount of gas in the path.

3.6.2.2 What it Can Do

An advantage of OP-TDLAS compared to some of the other open path remote sensing techniques is that it measures over a single absorption line. However, the specific absorption line must be carefully chosen to ensure that absorption lines from other gases are not present. It is possible to automatically compensate any variation of the absorption line width caused
by the presence of other gases although, as a result of applying this method, the instrument becomes completely insensitive to other gases but to the extent where it only measures free molecule concentrations of the specific gas and hence becomes insensitive to molecules which are bound in other complexes or dissolved (Sira Ltd, 2004a). The measured gas concentration is thus proportional to the absorption line amplitude.

An OP-TDLAS system has been installed at Calvert Landfill Site in the UK (Figure 8). This particular unit is a NEO (Norsk Electro Optikk) OP-TDLAS. It is set up on a 120 m transect with a multi-lensed receiver panel. The equipment was initially developed to look at exhaust emissions but has now been developed to incorporate specific emissions monitoring. The unit requires a stationary stable base and as such the laser unit in this instance is constructed onto the side of a brick built building. The receiver lens is situated on a metal pole set in a concrete base to prevent movement. The lens unit records methane concentrations in ppm x m and automatically stores the results to a data logger before transmitting the results to the data processor along with the necessary meteorological data collection from a weather station.

3.6.2.3 **Assessment**

As mentioned previously, an advantage of OP-TDLAS is that it measures over a single absorption line. This makes results quicker to obtain.

The reliability of the instrumentation is very much related to the quality of the laser diode used and the detection limit depends upon the actual absorption strength of the particular molecule. The TDL is capable of measuring low levels of specific gases in a very complex gas mixes where traditional spectroscopic techniques will suffer from cross interference. The extreme selectivity in this case is a very important feature, but it may in other cases be a disadvantage if you want to quantify mixes of gases e.g. NOx.

At Calvert Landfill Site, the main issue has been found to be the lack of portability of the equipment. Although theoretically it could all be moved and relocated elsewhere to monitor a different set of emissions, a suitable location needs to be found for the equipment which is steady and unsusceptible to heavy vehicles causing vibrations on the ground which would lead to recurrent breaks in the laser receiver path. Once a suitable location has been found, the path length must again be measured and the instruments realigned. It was also found that the casing units are susceptible to frosting although a small heating unit can be installed to prevent this occurring. The unit and equipment is not affected by fog although heavy moisture spray has been known to affect it through steaming up of the lenses.

Due to the maximum length available for the pathway the method would be ideal for a small landfill site boundary <250 m. Such limitations could be overcome by a series of units placed at specific spacing.
Like most ground optical remote sensing techniques, measurements are recorded over a transect using OP-TDLAS and consequently are unable to give a profile of the variation in concentration over the transect. This means that it is of little use in identifying leaks or large point sources because the line averaged concentrations may still be below threshold levels. Additionally if the landfill is graded at a steep gradient and a point source on the top of the landfill is emitting methane there is potential for the majority of the gas to pass above the laser transect.

In conclusion, the OP-TDLAS system provides a ground optical remote sensing device which measures the concentration of methane averaged over its path length. The unit and the software can be installed at the Site for about £25,000, the unit has the ability to self calibrate although potentially there is a requirement to realign the laser if there is any ground vibration resulting in movement. In terms of accuracy, the equipment is estimated as having an error range of within 10% (Modrak et al., 2005).

Table 12: A Summary of the OP-TDLAS Method

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Continuous measurement of concentration averaged over distance (ppm x m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>Near instantaneous</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>Systems are set up in semi-permanent fashion for continuous monitoring</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Approximately 10%</td>
</tr>
<tr>
<td>Analysis Required</td>
<td>None</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>The technique will not deliver an annual emissions estimate.</td>
</tr>
<tr>
<td>Cost</td>
<td>Approximately £25,000 per installation</td>
</tr>
</tbody>
</table>

3.6.3 Ground Optical Remote Sensing Techniques using OP-FTIR

3.6.3.1 How it Works

The Michelson interferometer is the main component of an Open Path Fourier Transform Infra Red (OP-FTIR) device. It is an amplitude splitting interferometer which uses a simple configuration of mirrors and beamsplitters. It accepts the beam of infra red light emitted by the source and divides it equally into reflected and transmitted beams.

The reflected beams are transmitted to a mirror of a fixed pathlength and the transmitted beams to one of variable path length, before returning to the beam splitter where they are once again divided into reflected and transmitted beams and directed towards the detector. Due to the two different path lengths of the mirrors, a path difference between the two beams is created so that when they recombine at the detector, an interference pattern is created. By analysing the interference pattern with a good knowledge of the laser wavelength, a spectral frequency calibration is obtained. The FTIR then processes the IR detector signal, performing a Fourier transform to give the intensity varying with spectral frequency.
By analysing different absorption bands, the Beer-Lambert Law, described above, can then be used to calculate the species concentrations (Sira Ltd, 2004a).

3.6.3.2 What it Can Do

The OP-FTIR has high wavenumber frequency, high-energy throughput and high resolving power. This high energy throughput means that there is a large input to the FTIR spectrometer and consequently a good signal-to-noise ratio. The throughput passes all frequencies to the detector where they are measured simultaneously.

The noise level can be further improved by taking multiple scans, co-adding and averaging to remove random noise from the spectra. The consequence of obtaining these high quality, low noise, well spectrally resolved IR spectra, however, is that it can take a significant time to collect them (approximately 10 seconds). In the open air, cross wind and weather are likely to mix inhomogeneously distributed atmospheric pollutants along the absorption path in timescales which can be short compared to the FTIR spectral collection time.

3.6.3.3 Assessment

OP-FTIR techniques suffer from many of the same problems as the ground optical remote sensing techniques mentioned earlier. It also records over a transect and consequently is unable to give a profile of the variation in concentration over that transect. This means that it is of little use in identifying leaks or large point sources because the line averaged concentrations may still be below threshold levels. Additionally if the landfill is graded at a steep gradient and a point source on the top of the landfill is emitting methane there is potential for the majority of the gas to pass above the laser transect.

Like the OP-TDLAS method and UV DOAS methods described previously, OP-FTIR also suffers from problems associated with finding a suitable location which is stable and unsusceptible to ground vibrations breaking the laser beams. Again it also suffers from obscuration of the beam due to meteorological effects, people or trees.

One advantage of using OP-FTIR, however, is that the concentration of a multitude of infrared absorbing gaseous chemicals can be detected and measured simultaneously, with high temporal resolution as opposed to methods using TDL where only one absorption line can be sampled at a time.

A disadvantage of the FTIR is that when extracting the results for the desired gas, greater error is incurred than with the TDL as a greater number of spectral frequencies need to be subtracted.

In summary, the OP-FTIR is a ground optical remote sensing system which provides gas concentrations averaged over its path length. The percentage error associated with this
method has been estimated to be less than 5% under a high resolution with a unit price of approximately £30,000.

Table 13: A Summary of the OP-FTIR Method

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Continuous measurement of concentration averaged over distance (ppm x m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>Near instantaneous</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>Systems are set up in semi-permanent fashion for continuous monitoring</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Less than 5%</td>
</tr>
<tr>
<td>Analysis Required</td>
<td>None</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>The technique will not deliver an annual emissions estimate.</td>
</tr>
<tr>
<td>Cost</td>
<td>Approximately £30,000 per installation</td>
</tr>
</tbody>
</table>

3.6.4 Ground Optical Remote Sensing Techniques Using OP-FTUV

3.6.4.1 How it Works

Fourier Transform Ultra Violet (FTUV) spectroscopy is complementary to FTIR in that some gases do not exhibit suitable absorbencies in the IR part of the spectrum, but show features in the UV region which can be used to assess their concentration. FTUV is of particular interest for measuring aromatic hydrocarbons and oxides of nitrogen and sulphur.

3.6.4.2 What it Can Do

Measurement of FTIR spectra is usually based on the Michelson interferometer, a disadvantage of which is that its moving parts limit its robustness. The need for moving parts and precise tolerances in FTIR spectroscopy can limit the robustness of spectrometers. With the FTUV there is the option of a design with no moving parts based on Wollaston prisms.

Wollaston prisms are basically two right angle prisms with perpendicular optical axes. When a beam of light enters the prism it diverges into two rays at the interface. The angle of divergence can be altered by changing the wedge angle of prisms. By using a pair of prisms between crossed polarisers mounted, the beams can be recombined to form an interference pattern in the spatial domain (rather than the time domain as with the Michelson interferometer). This interference pattern can be recorded using a detector array and subsequently processed to give the spectrum.

3.6.4.3 Assessment

The FTUV suffers from many of the same problems as the FTIR. It does have one or two advantages however, it is able to measure concentrations of gas which have suitable absorbencies in the UV spectrum but not the IR spectrum which the FTIR is not able to do.
Another advantage of this method is that it can use the Wollaston prism based spectrometer rather than the Michelson Interferometer. The net consequence of this is that the FTUV becomes more robust and more suitable for use on heavy industrial plants.

Costs and accuracy associated with this equipment are similar to those for the OP-FTIR system.

**Table 14: A Summary of the FTUV Method**

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>Continuous measurement of concentration averaged over distance (ppm x m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>Near instantaneous</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>Systems are set up in semi-permanent fashion for continuous monitoring</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Less than 5%</td>
</tr>
<tr>
<td>Analysis Required</td>
<td>None</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>The technique will not deliver an annual emissions estimate.</td>
</tr>
<tr>
<td>Cost</td>
<td>Approximately £30,000 per installation</td>
</tr>
</tbody>
</table>

Any of the ground optical remote sensing devices discussed above, can also be used for the purpose of hyperspectral scanning as illustrated in Figure 9. This involves using a number of sensors rather than just one and locating them vertically on a mast. The remote sensing device can then be rotated so that it measures concentrations through different transects of the plume. This method can then be used to generate some spatial information about the plume but concentrations for each transect are still line averaged and hence only a limited amount of spatial information is gained by following this procedure.
Figure 9: A schematic example of hyperspectral scanning taken from USEPA

3.7 LIDAR

LIDAR (LIght Detection And Ranging) is a light based range finding system similar to radar. This method is laser based and used for measuring and mapping concentrations and mass emissions of various molecules in the lower atmosphere. It is non-invasive and gives 2D concentration profiles and mass emissions (kg/hr) of various species in the area being surveyed. There are several different types of LIDAR available.

3.7.1 Raman LIDAR

3.7.1.1 How it Works

Gases are able to reflect some light, these reflections are from the individual molecules within the gas. Most light which undergoes a reflection in this manner is unchanged, however a small proportion experiences a change in wavelength. Such a change arises due to the gas molecule absorbing some of the photon energy. The amount of energy absorbed by different molecules varies and is in fact a fundamental property of each particular gas. This type of wavelength shifted scatter is known as ‘Raman Scattering’ and hence the Raman Lidar works by this principle.
3.7.1.2 What it Can Do

The Raman LIDAR operates in the UV part of the spectrum and is capable of measuring species including: CO₂, CH₄, SO₂, NO, NO₂, CO, H₂O and N₂. The instrument is capable of monitoring more than one species at a time and can be used to provide both 2D and 3D concentration profiles. The equipment is compact and has a range extending to 10 km as well as able to function without personnel attendance.

3.7.1.3 Assessment

There are many advantages to the Raman LIDAR system, it is compact and a single instrument can simultaneously provide data for several gases. A main disadvantage of the Raman LIDAR system, however, is that it does not work as well for lower concentrations of gases. Raman Scattering is typically thought to be as much as 1000 times weaker than the effect of Rayleigh Scattering. The consequence of this is that the Raman LIDAR is generally unsuitable for measuring very low concentrations of gases.

The Raman LIDAR quantifies gas concentration and is able to provide both 2D and 3D concentration profiles. It has been estimated as having around a 10% accuracy for concentrations within 3 km and using a 10 minute averaging period. The cost of such an instrument is in the region of £50,000 - £100,000 depending on the specifications required.

Table 15: A Summary of the Raman LIDAR Method

<table>
<thead>
<tr>
<th>Quantity Measured</th>
<th>Concentration (µgm⁻³) and then a derived Flux (mgm⁻²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>2 - 3 days</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Less than 5%</td>
</tr>
<tr>
<td>Analysis required</td>
<td>None</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Approximately 4 to account for seasonal variation</td>
</tr>
<tr>
<td>Cost</td>
<td>£50,000 - £100,000 per instrument</td>
</tr>
</tbody>
</table>

3.7.2 DIAL LIDAR

3.7.2.1 How it Works

DIAL (Differential Absorption LIDAR) is a development of LIDAR (Light Detection and Ranging). In the DIAL-LIDAR method, a laser beam is sent out into the atmosphere and small proportions of the light are backscattered by particles along the beam path to a sensitive detector. In this sense, dust and aerosols are being used as reflectors. The laser light is emitted in short pulses and by resolving the backscattered light over time (along with the speed of light) the range resolution can be obtained, as in a simple LIDAR. This is an important advance of the more conventional monitoring systems, in which a mirror is used to return the laser beam to the detector and needs to be repositioned after each measurement.
3.7.2.2 What it Can Do

The concentrations can be converted into mass emissions by making a series of scans with DIAL along different lines within a plume and combining these with meteorological data. These measurements are then used to produce a mass emission profile for a whole site.

LIDAR can be improved by use of a tuneable diode laser, giving it an additional spectroscopic capability as the source laser can alternately be tuned both on and off an absorption feature in the known ‘spectral fingerprint’ of a specific gas. The use of two wavelengths with different absorptions for the target gas simplifies the measurement process compared with a standard LIDAR measurement (Sira Ltd, 2004a).

3.7.2.3 Assessment

DIAL validation is difficult as there are no other measurement techniques which can measure range resolved concentrations along a line, 2D concentration profiles or mass emissions.

The main advantage of the DIAL technique is that it produces range resolved as well as time resolved concentration profiles. The net result of this is that unlike all of the other ground optical remote sensing techniques mentioned above, it is a technique which can be used to locate cracks or fissures in the cap as rather than a line averaged measurement of the concentrations from an area of the Site, a 2D picture is obtained.

DIAL can also help to overcome one of the main disadvantages of ground remote optical sensing techniques, finding a suitable and stable location for the instrument. This has proved problematical in previous experiments and frequently significant amounts of money have been spent installing these instruments in appropriate locations (Sira Ltd, 2004a). One solution is to develop a series of 2D concentration profiles for the area to be measured and use these to assist in the location of ground remote optical sensing techniques. These profiles can either be produced by modelling or by measuring with a DIAL system that can produce such profiles in a few minutes.

The major disadvantage associated with DIAL LIDAR is the cost. The unit itself costs around £1 million although it was approximated by NPL that the cost of surveying a landfill with a pre-owned LIDAR would cost approximately £10,000 - £15,000 and take approximately two days. The availability is also an issue as there are only two DIAL systems in existence in the UK, both of which are owned by NPL. The accuracy associated with this method is estimated as less than 15% (Sira Ltd, 2004b).

NPL have discussed the possibility of developing a type of mini-LIDAR. This would be a simpler version that would be more suited for landfill sites. The current LIDAR is very
expensive as it is very technologically advanced. The uses of LIDAR which are relevant to landfill gas emissions only cover a fraction of its capabilities. The mini-LIDAR would be less technically complex and consequently not include a number of the capabilities which increase its cost but are irrelevant to landfill site use. Unfortunately such a technique would need approximately 2 - 3 years product development.

In conclusion, the LIDAR-DIAL system provides a method for calculating gas concentrations and can even provide a 2D profile of concentrations. The unit itself can be purchased for around £1 million or a site scan can be provided for the cost of around £10,000 - £15,000 with an estimated accuracy of around 15%. Approximately 4 scans a year are estimated as being appropriate to account for seasonal variation.

Table 16: A Summary of the DIAL-LIDAR Method

<table>
<thead>
<tr>
<th>Quantity Measured</th>
<th>Concentration (µgm$^{-3}$) and then a derived Flux (mgm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaging period required</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Time required for a survey</td>
<td>2 - 3 days</td>
</tr>
<tr>
<td>Percentage error</td>
<td>Less than 15%</td>
</tr>
<tr>
<td>Analysis required</td>
<td>None</td>
</tr>
<tr>
<td>Number of surveys required per year to obtain an accurate annual emission estimate</td>
<td>Approximately 4 to account for seasonal variation</td>
</tr>
<tr>
<td>Cost</td>
<td>£1 million per instrument, £10,000 - £15,000 per survey</td>
</tr>
</tbody>
</table>

3.8 Other Remote Sensing Approaches

3.8.1 Aerial Techniques

Aerial techniques allow for large areas of a landfill to be screened in a single operation using an optical scanning technique. The equipment is attached to an aircraft, which overflies the landfill of interest. Hyperspectral scanning responds specifically to methane/carbon dioxide and can be used to indicate the principal areas of methane and carbon dioxide gas emission activity and the scale of this activity.

This method is particularly suitable for very large sites as scanning can be achieved comparatively quickly and simply without the use of extra instruments or measurement locations. This method does only provide qualitative data, however, which means that it needs to be calibrated for quantitative assessment. This technique is also very expensive and is not very widely available at present. In previous trials, it has also been found that this method works best under clear skies and favourable weather conditions which in the UK are unpredictable and often unlikely.
3.8.2 Fixed Point Mobile Monitoring Facility Methodologies

Golder Associates Ltd (Golder) conducted a study at Roxby Landfill Site in the UK in 2006. Ambient air quality was monitored at three on-Site locations by mobile measurement facilities (MMFs) over an 8 month period. The MMFs were carefully aligned in the prevailing wind direction.

The MMFs all used chemiluminescence analysers for the measurement of NO and NO\textsubscript{x}. The chemiluminescence method for gas analysis of NO\textsubscript{x} relies on the measurement of light produced by the gas-phase titration of NO and ozone (O\textsubscript{3}) - O\textsubscript{2} is produced as a by product. The number of photons of light in the reaction chamber is proportional to the concentration of NO in the gas sample. CO and O\textsubscript{3} were measured by gas filter correlation and UV absorption, respectively. Both methods are based on the Beer-Lambert Law. A Flame Ionisation Detector (FID) was used for measuring hydrocarbon concentrations, this included THC, NMHC and CH\textsubscript{4}.

By automated monitoring over a long period of time, this method can be used to look at the diurnal variation in surface emissions as well as the variation over longer periods of time. The advantages of this method are that it is automated and once set up, little effort is required in terms of maintenance and calibration as the equipment was all connected to software in a laboratory for collection and checking so as to alert of any problems associated with it. This method may give plenty of temporal resolution however it gives little by way of spatial resolution. By simply sampling at a point it is not possible to determine any of the ‘hot-spots’ on the landfill Site and similarly it only tells of emissions at that particular point. Even if the MMFs are located in the prevailing wind direction and close to the predicted highest long term/averaged short term concentration, the wind direction and strength will fluctuate quite significantly over the time period and consequently the location of the areas with highest concentrations will change.

As a result, this particular method is of limited use in determining boundary emissions as the value at one particular point may not necessarily be representative of the whole site and will not necessarily represent a worst case scenario either.

3.8.3 Imaging Systems

The development of Imaging Systems is currently a fast evolving technology. Although currently unable to give any information on actual concentration levels, these methods can be used to scan and map the Site itself using thermal imaging. There are a variety of infra red imaging cameras on the market which are designed specifically for use in harsh industrial environments. These cameras operate in the mid-wave infrared part of the spectrum. They detect hydrocarbon gases based on their transmission and absorption characteristics utilizing an optimized narrow band-pass cold filter and have been specifically designed to detect gases such as methane. The instrument can be handheld or mounted onto an aerial
platform such as a helicopter for rapid surveillance and monitoring. It gives video playback and images of the area recorded with leaks or emissions appearing as black smoke.

The drawbacks of this system are that it is not capable of quantifying the amount of emissions. Likewise, it is also not able to differentiate between the different compounds and the camera is only sensitive to gases in the mid-wave IR spectrum. Several different methods are available to avoid these problems, however. One way is by combining the camera with the use of an FTIR. This would then help to identify the leaking gas and if placed in an appropriate location it would also be of use in determining the concentration. Similarly there is potential for calibrating emissions using a FID.

Another problem is that these cameras only show emissions at the second the film is taken, under different meteorological conditions, the emission profile of a site will change. The use of these systems for long term monitoring is expensive however as the cost of the unit itself is approximately £40,000.
### Table 17: A Summary of the Different Methods Available for Monitoring Methane Emissions from a Landfill Site

<table>
<thead>
<tr>
<th>Technique</th>
<th>Main Advantages and Disadvantages</th>
<th>Measured Quantity</th>
<th>Appropriate Applications</th>
<th>Estimated Percentage of Error</th>
<th>Time and Frequency for a Representative Sampling Campaign</th>
<th>Approximate Cost per Sampling Campaign (and sampling year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FID</td>
<td>Portable and easy to use. Does not give emission rate.</td>
<td>Concentration</td>
<td>Walkover, identifying cap defects and point sources.</td>
<td>10%</td>
<td>1 day+ Regular surveys possible</td>
<td>£1,000 - £1,500</td>
</tr>
<tr>
<td>Flux Box</td>
<td>Simple to understand and easy to use but labour intensive. Errors &gt;100%</td>
<td>Flux</td>
<td>Emissions from whole site, temporary or permanently capped, or operational areas.</td>
<td>&gt;100%</td>
<td>2-3 weeks 2-4 campaigns/year ideal</td>
<td>£12,000 - £25,000 (or £24,000 - £50,000/y)</td>
</tr>
<tr>
<td>Micrometeorological Method</td>
<td>May be automated. Suitable for relatively flat landfills and whole site emissions only.</td>
<td>Flux</td>
<td>Whole Site estimate of emissions.</td>
<td>20%</td>
<td>4 weeks 2 campaigns/year ideal</td>
<td>Approximately £8,000 (approx £16,000/y)</td>
</tr>
<tr>
<td>Mass Balance Method</td>
<td>May be automated. Suitable for whole site emissions only.</td>
<td>Flux</td>
<td>Whole Site estimate of emissions.</td>
<td>25%</td>
<td>4 weeks 2 campaigns/year Ideally over 5 years</td>
<td>£7,000 - £8,500 (or £14,000 - £17,000/y)</td>
</tr>
<tr>
<td>Stationary Plume Methods</td>
<td>Relatively inexpensive and simple but data is not obtained until after lab analysis.</td>
<td>Flux</td>
<td>Emissions from whole site, temporary or permanently capped, or operational areas.</td>
<td>20%</td>
<td>1 - 2 days 2 campaigns/year – 10 campaigns/year (simplified method).</td>
<td>Main method: £10,000 - £12,000 (£20,000 - £24,000/y). Simplified method: £6,000 for capital equipment. £1,700 per survey (£17,000/y)</td>
</tr>
<tr>
<td>Mobile Plume Methods</td>
<td>Relatively quick method which provides data at the time of measurement. May detect defects.</td>
<td>Flux</td>
<td>Emissions from whole site, temporary or permanently capped, or operational areas.</td>
<td>TDL: 10-25% FTIR: 15-30%</td>
<td>TDL: 2 days 4 - 6 campaigns/year ideal FTIR: 2 - 4 days 3 campaigns/year ideal</td>
<td>TDL: £11,000 (£44,000 - £66,000) FTIR: £8,000 - £10,000 (£24,000 - £30,000)</td>
</tr>
<tr>
<td>Open Path Remote Sensing Techniques</td>
<td>Provide automated continuous monitoring but provides a line averaged estimate rather than a point estimate.</td>
<td>Line averaged concentration</td>
<td>Boundary emission monitoring.</td>
<td>5 - 15% depending on location and instrument</td>
<td>Continuous</td>
<td>£25,000 - £30,000 equipment investment</td>
</tr>
<tr>
<td>Technique</td>
<td>Main Advantages and Disadvantages</td>
<td>Measured Quantity</td>
<td>Appropriate Applications</td>
<td>Estimated Percentage of Error</td>
<td>Time and Frequency for a Representative Sampling Campaign</td>
<td>Approximate Cost per Sampling Campaign (and sampling year)</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
<td>-------------------</td>
<td>------------------------------------------------------------------------------------------</td>
<td>--------------------------------</td>
<td>----------------------------------------------------------</td>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Very technically complex and not widely available.</td>
<td>Flux</td>
<td>Emissions from whole site, temporary or permanently capped, or operational areas. May detect defects.</td>
<td>&lt;5 - &lt;15%</td>
<td>2 - 3 days</td>
<td>£10,000 - £15,000</td>
</tr>
<tr>
<td>Aerial Techniques</td>
<td>Requires the use of aircraft and only works under clear skies and favourable weather conditions. May detect defects.</td>
<td>Qualitative (quantitative if calibrated) flux</td>
<td>Emissions from whole site, temporary or permanently capped, or operational areas.</td>
<td>Unknown</td>
<td>2 days</td>
<td>Very expensive</td>
</tr>
<tr>
<td>Fixed Point Mobile</td>
<td>Automated Mobile Monitoring facilities (MMFs) are in routine use. Only works when the wind is in the appropriate direction.</td>
<td>Concentration</td>
<td>May assist in boundary air quality emissions monitoring.</td>
<td>Low</td>
<td>Continuous</td>
<td>Variable</td>
</tr>
<tr>
<td>Monitoring Facility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methodologies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imaging Techniques</td>
<td>Portable and easy to use. Does not give emission rate. Provides no information on concentrations although could be estimated with a FID.</td>
<td>Qualitative indication of concentration</td>
<td>Walkover, identifying cap defects and point sources.</td>
<td>Unknown</td>
<td>1 - 2 days</td>
<td>Approximately £40,000 instrumentation cost</td>
</tr>
</tbody>
</table>
4.0 COMPARATIVE FIELD TRIALS

Over the past decade, a number of comparative field trials have been conducted by different research groups and organisations using a selection of the methods mentioned in the previous sections. It is through these field trials that problems with these methods have been discovered both in terms of applicability and accuracy. Through gaining knowledge about the limitations of each of the different methods their accuracy and applicability has been improved or their range of use limited to more appropriate applications. This report details the findings of previous studies.

4.1 Trials in France, 1997

In 1997, Savanne et al. conducted ‘A Comparison of Different Methods for Measuring Landfill Methane Emissions’. The project used the mass balance, micrometeorological, tracer and both closed static and dynamic flux box techniques to compare methane emissions on a landfill site in France. Flux box measurements were made at 480 points over a 20 m x 20 m grid across the landfill using a FID. These were compared with the mass balance and micrometeorological method results obtained using a mast in the middle of the Site. Tracer methods were also used for comparison. A known concentration of gas was released at the areas of main emission and their concentrations analysed against the methane concentration using gas phase chromatography or an open path FTIR.

Overall, the tracer and flux box methods showed good agreement and produced results of the same order of magnitude. Other methods proved slightly more problematical. For example, the micrometeorological and mass balance methods were hindered by the prevailing westerly and west-south-westerly winds which meant measurements could only be made from the sectors delimited by the mast and the angles between 192°N and 275°N (Savanne et al., 1997). Unfortunately the area around the mast also gave quite low emissions in comparison to the rest of the Site, as was identified during the flux box surveys. This led to low fluxes observed by the micrometeorological method. Savanne et al. (1997) concluded that the most successful way of obtaining whole site emission data is through using chamber techniques or tracer methods as the mass balance and micrometeorological methods are heavily dependent on meteorological conditions.

4.2 Trials in the Netherlands, 2003

In 2003, Scharff et al. conducted a comprehensive trial of three different methods for measuring landfill surface emissions. The stationary plume method, the mass balance method and the mobile plume method using a tuneable diode laser (TDL). The trial took place at four different landfill sites around the Netherlands. The aim of the project was the development of a measurement method to enable a reliable measurement of average annual methane emissions from an entire landfill at reasonable costs. The starting points in this development were both the mass balance and plume methods.
The mass balance method was undertaken using a 26 m high mast so as to sample from the whole of the landfill without missing any of the plume. It was also adjusted to use a carbon dioxide NDIR to provide a more accurate carbon dioxide concentration. The stationary plume method was set up using a four fixed gas bag sampling system with a computer system monitoring the meteorological conditions. The system uses these data to calculate the concentrations from the four receptor stations. The sampling system is automated by computer. Whenever the predicted concentrations at a sampling system surpass a given threshold level, the corresponding receptor station is activated by phone. At each station, a battery operated sampling system samples the air in a gas bag for a 30 minute period.

In general, two events are sampled per day. The mobile plume method with TDL was used to validate the results as it is internationally recognised as giving a good estimate of the total emission from a landfill.

The first landfill site used for the tests was Nauerna, which lies west of Amsterdam and is of approximately 1200 m x 800 m in size. In the eight weeks that the mass balance method was operational, sufficient data was obtained for some of the sectors but the meteorological conditions were not overly favourable for others. The occurrence of easterly winds was scarce and consequently limited observations from some sectors. The stationary plume method achieved on average 2 - 3 samples each day with a total of 100 obtained and 30 complete events observed with both upwind and downwind data. For validation of the mass balance and stationary plume measurements, three TDL measurement sessions were performed at different wind directions. The results showed that the two methods both agreed with the TDL within their confidence limits.

Overall, the mass balance method proved to be well applicable and no problems were observed with maintaining a power supply to the mast and the methane emission estimates were in agreement with the TDL with time series emissions correlating with air pressure. The stationary plume method also worked well, despite inexperience using this method on landfill sites. During the trial however, an incidental emission occurred in an area of the landfill. The mass balance method depends on wind direction, and as the area concerned was not up wind of the mast at the time, the effects were not registered until a few days later when the wind direction had changed. The TDL system did register the emission event but only a proportion of the elevation in emissions could be attributed to it. Scharff et al. (2003) report that a single TDL campaign during an emission event will overestimate average emissions, consequently it is important that more than one sampling period is used. The stationary plume method was able to observe such events as it samples from the whole landfill and consequently emission estimates in any part of the landfill are observed.

The second landfill to be used in the tests was Braambergen, a 10 ha site located near Almere. At this site, the stationary plume and TDL methods performed well. The mass balance method, however, generally gave a relatively low emission compared to the other two methods. The likely reasoning for this difference was thought to be a line of poplar trees separating two areas of the site which consequently affected the plume. Consequently 80-90% of profiles were unused in some sectors. Scharff et al. (2003) concluded that the
mass balance method is limited by large point sources of methane and objects that disturb dispersion.

The third landfill site to be used in the tests was Merwedehaven, a 35 ha site near Dordrecht. The mass balance method proved to be in good agreement with the TDL technique at this site. There was good correlation between the time series and pressure changes. The stationary plume method, however, gave relatively high concentrations compared to the other methods and some unexplained peaks not observed by other instruments.

The fourth landfill to be used in the tests was Wieringmeer, an 18 ha site which lies northwest of North-Holland province. The mass balance and stationary plume methods proved to be in fair agreement with the TDL data at this site. The TDL and stationary plume methods, however, showed up emissions from a composting plant and a biowaste storage nearby which the mass balance method did not pick up.

In conclusion, all three methods generally showed good correlation and proved to be practically applicable. The erection of a 25 m mast for the mass balance method did not prove a problem. Most of the problems with operational reliability were due to inexperience and infrequent use of the equipment. The only real issues identified were those associated with the use of the mass balance method near high point sources of methane or near tall buildings or trees as these act to disturb the dispersion of the plume to be observed. In terms of the stationary plume method, sensitivity analysis showed that the effect of a wrong assumption of the main emitting areas of the landfill will lead to an over/under estimation of around 10% at a single station but as sites lie in different wind directions, an overestimation at one site leads to underestimation at the Site upwind of it. Likewise, whenever the stationary plume stations measure a plume that is on the edge/shoulder of the plume that comes from the landfill, the uncertainty in the emission estimate increases. Therefore smaller landfills are more difficult to measure than larger ones.

4.3 Trials in France, 2003

In 2003, Morcet et al. conducted comparative field trials using tracer method and dynamic chamber methods. The tracer methods used SF$_6$ and the flux box measurements used a dynamic chamber with external recirculation on a 20 m x 20 m grid. The measurements took place on three different sites across France over a period of one to two weeks. During the trial, a leachate well located in the centre of one of the cells became severed. It then turned into a localised source of methane emissions for the tracer method, artificially biasing its results, although the release was not picked up by the flux boxes.

Overall, there was generally quite good agreement between the results from the three methods. In 2005 analysis of these results was expanded on by Spokas et al. Although good correlation was found between the tracer and chamber methods, it was noted that greater disagreement occurred when the measurement area was less than 1 Ha. Spokas et al. (2005) concluded that the reason for this is the associated problems of determining the footprint from
which the measured flux originates from as it is dependent on terrain and upon meteorological conditions.

4.4 EU Study, 2004

In 2004, Sira Ltd conducted a review of the different open path optical remote sensing techniques available. As part of this review, a comparative field study was conducted in a controlled laboratory with the aim of simulating as far as possible, field measurement conditions but under circumstances which permit much greater control of releases and meteorological conditions. A tunnel was used to channel the released gases of carbon dioxide, propane and toluene. The instruments tested were the Open Path Fourier Transform Infra Red (OP-FTIR), Open Path Tuneable Diode Laser (OP-TDLAS), Ultra Violet Differential Optical Absorption Spectra (UV DOAS) and Infra Red Differential Absorption Spectra (IR DOAS).

The open path instruments were inter-compared for each of the different gases, plotted against each other to see how they correlated. They were also correlated against the theoretical concentration of each gas. The correlation between the instruments was good, particularly when measuring propane and carbon dioxide. On one day during the field trial however, tests were conducted to evaluate how the instruments respond to sharp changes in concentrations by emitting pulsed releases of 10 seconds over a 1 minute duration. The correlation between the theoretical and measured concentrations over this period dropped significantly and consequently illustrated the instruments’ poor performance in responding to sharp fluctuations in the concentration of the source gas.

The overall results of this study showed a good agreement between the different instruments used although it is important to remember that the distribution of gases was simulated under laboratory conditions and hence meteorological effects were not evaluated.

4.5 Trials in the US, 2005

In 2005, Modrak et al. conducted a field study comparing open path instruments on a landfill site in America. The instruments trialled were OP-FTIR and OP-TDLAS. The aim of the experiment was to identify major emissions hot spots at the landfill and to demonstrate the operation and function of the various technologies. The OP-TDLAS and OP-FTIR instruments were both used to measure methane concentrations. Correlation between measurements of the two instruments was shown to be very good. Analysis of the data also showed that the standard deviation of OP-TDLAS data is higher than for the OP-FTIR indicating that the OP-FTIR has better precision; on closer inspection it was shown that the OP-TDLAS suffers under lower ambient background concentrations. Overall however, both instruments proved comparable for measurements over a wide range of concentrations.
4.6 Trials in Finland, 2006

Lohila et al. (2006) conducted a trial of the micrometeorological method against flux box technique measuring methane and carbon dioxide emissions at the Ämmässuo Landfill in Finland. The Micrometeorological method used a three-axis ultra-sonic anemometer and a FID in a gas chromatograph chassis for fast response total hydrocarbon concentration measurements. Closed flux chamber measurements were measured four times and over 4 - 7 minute intervals. Comparison of the two methods showed reasonable agreement although the number of flux boxes used was very small.

4.7 Summary

Each of the comparative field studies mentioned above builds on earlier ones either through the inclusion of new technology or simply by learning from its predecessors’ mistakes. Additional trials in Denmark, featuring Finnish, Swedish and Dutch researchers, will report at the Sardinia Conference in October 2007. It is important to maintain contact with these researchers to ensure that lessons from these trials are also learnt.

In the event of future field trials it is important to build further on the issues with each method developed previously.
5.0 APPROPRIATE TECHNIQUES

5.1 Identifying Defects

The purpose of site walkovers is to establish the pattern of near-surface gas concentrations in the relevant zones. According to Environment Agency Guidance (2004b): ‘It must identify features where the emissions are unusually high and mark on the ground where the main failures in the gas management system are located.’

A number of the methods described above are capable of fulfilling this requirement. For example, walkovers are currently made using an FID which is used both at a very close proximity to the ground and at head height in order to differentiate between the local contribution and the contribution from upwind sources. By walking over the landfill surface in paths 25 - 50 m apart depending on the nature of the cap and taking regular measurements with the FID, the location of cracks and fissures in the cap can be deduced.

Theoretically, the mobile plume methods could have some use in locating areas of particularly high emissions as they are able to provide spatial information across the plume transect. The technique does not provide a straightforward answer, however. It will only provide information on the general location of the hot spot with reference to the Site and further work will still be needed in order to determine the precise location.

In terms of the stationary plume techniques, although they do give some spatial variation, they rely on the tracers being located in areas where the highest emissions are expected. Consequently the locations of hot spots and fissures should ideally be made prior to the use of this method rather than as a result of it.

The meteorological based methods have limited value in this respect also. Both use a mast to determine a vertical profile of the emission plume but the emission plume which is analysed is dependant on the location of the wind direction. Consequently, results from these techniques will always miss events downwind of the measurement mast.

From the ground optical remote sensing techniques, the most appropriate method for locating cracks and fissures is the DIAL-LIDAR method. This is because it gives a 2D concentration profile rather than a line averaged emission value. It is quite an expensive method, however and although it is reasonably automated, a lot of effort is required to set up the instrument in a suitable location and to calibrate it.

Imaging techniques, using infra red cameras, are becoming popular with landfill operators because they are as quick, or quicker than, FID methods. They can be qualitatively calibrated against FID measurements to give a pseudo-FID measurement result. Walkover surveys are
only required annually but may be done more frequently. They remain the most cost-effective tool for quantitative measurement purposes against a regulatory target.

In conclusion, the walkover FID method in the Environment Agency’s Guidance (2004b) is therefore still the most cost effective quantitative method for identifying defects, but imaging techniques may also be used in a qualitative fashion.

5.2 Combustion Emissions

The monitoring of combustion emissions covers the emissions from both the flare and engines located within the gas plant. It is necessary in order to quantify the amount of unburnt methane which is released to the environment as well as the contribution from other greenhouse gases in the exhaust to global warming.

The stationary plume methods could theoretically be used to quantify the emissions from the combustion plant if located in the appropriate area downwind of the Site with the background concentration representing emissions from all areas of the Site upwind.

The meteorological based methods could also be used to monitor combustion emissions. Although gas plants need frequent access, they are generally secure fenced off areas and hence an ideal location for the mast. The mast would also potentially provide site specific meteorological data, at the location of the source, to support any air dispersion modelling. The only issue with this method for monitoring engine and flare emissions would be waiting for appropriate wind directions.

The mobile plume methods could also be used although the location of roads becomes increasingly important in this instance as they will need to be at a sufficient distance from the landfill site for the combustion plume to have grounded.

The use of ground optical remote sensing devices is also possible to quantify combustion emissions. Although, as mentioned previously, gas plants need frequent access, they are generally not susceptible to vibrations from heavy plant traffic. Also, as the compounds are generally secure areas, the instruments, which are quite expensive, are less susceptible to vandalism and theft.

The costs associated with quantifying combustion area emissions vary quite dramatically between £2,000 for use of the simplified stationary plume technique to as much as £25,000 for the ground optical remote sensing equipment.

Current regulatory requirements for mobile laboratories to sample combustion plant emissions for NOx, CO, VOCs and NMVOCs are for annual reporting. It would be possible to use this annual emissions value to calculate a yearly emission rate for combustion plant emissions.
This method would have to take into account the variation in emissions over time (such variance could be estimated based on research at Godmanchester and Roxby landfill sites carried out by Golder Associates), and the downtime of the individual gas engines and flares comprising the active gas management components at the landfill Site. Downtime for gas engines can be determined by the record of operation maintained for purposes of the sale of electricity produced. Downtime for flares is not currently reported but could be easily estimated for landfill sites where the flare only operates when the gas engine is non-operational.

Measurement of combustion emissions as a source on their own is best determined using current methods. The various methods described above which have been developed to measure whole site emissions, or parts of whole site emissions, may be able to measure methane in the combustion plume. Since the UK has the greatest installed capacity of landfill gas utilisation plant in Europe, due to the higher percentage of waste which was historically landfilled, the research trials performed in Europe using the techniques described above, have not explicitly attempted to measure the combustion plume. This could be the subject of UK specific research to ascertain whether these techniques are suitable for quantifying combustion plant methane emissions in the UK.

5.3 Fugitive Emissions

The monitoring of surface emissions covers a wide variety of different landfill areas. It can look at emissions from the active phase, from temporary capped areas, permanently capped areas and the total emissions over the whole site, although the Environment Agency only require assessment on temporary and permanent caps. Different techniques are appropriate for different areas of the landfill.

5.3.1 Operational Area

Measurement of surface emissions from operational areas is not a common requirement, however most of the techniques used for whole site assessment could be employed in the operational area. The most significant difference with operational areas is that plant traffic has to be considered. The assembly of a mast in the middle of this area for either of the meteorological based methods is extremely unpractical. Likewise, the use of any of the open path techniques is also not appropriate as the heavy plant traffic is likely to cause vibration of the ground and hence interruption of the beam. Due to the nature of flux box methods, which involve placing the instrument on the site surface, this is perhaps another method which is not ideally suitable for operational areas as it is likely to interfere with site operations.

The stationary plume methods could theoretically be used if the canister/sampling station used to determine background concentration was placed upwind and on the landfill itself so as to differentiate the active phase from the rest of the landfill emissions.
The mobile plume methods could also be used although it may take some modelling work to distinguish which parts of the plume come from each of the different areas of the landfill. This has been partly demonstrated by Samuelsson et al. (2001) but would need explicit demonstration.

The costs associated with obtaining emission data from the operational area by means of the simplified stationary plume method may be marginally reduced from those stated previously in this report for a whole site survey. In comparison the cost of a mobile plume transect is less likely to be reduced as a similar size survey will still need to be conducted. Consequently the most cost effective and appropriate method of measuring methane emissions from active areas of sites is the simplified stationary plume method.

### 5.3.2 Temporary and Permanently Capped Areas

Permanently capped areas do not suffer from the same problems as operational areas with regards to plant traffic, consequently restrictions on access and problems with unstable ground do not exist. Emissions should be low from permanently capped areas and the flux box method is very good at resolving low fluxes. The main problem with measuring emissions from permanently or temporary capped areas using other techniques is differentiating the emissions from these areas from those of the active phase.

One of the best methods for achieving a separate emission value for permanently or temporary capped areas are the mobile plume methods as these are used to transect the plume and consequently modelling can be used to identify the emissions from different areas of the Site. These are perhaps more accurate than the flux box method as the results are obtained from the same transect and hence for the same point in time and thus the same meteorological conditions apply.

The stationary plume methods are also suitable for identifying emissions from temporary or permanently capped areas. If the background sampling station is placed in or downwind of the active phase and upwind of the permanently capped area, the contribution from the operational area can be removed from the concentrations measured at the remainder of the sampling stations to provide just the emissions from the capped areas.

The meteorological based methods are perhaps not as suitable as some of the other methods for measuring emissions from just one section of a site. They could theoretically still be used, but it would become important that the masts used in these techniques were located at a sufficient distance from the active phase so that the plume from that area of the landfill does not affect the measured plume from the capped area.

The ground optical remote sensing techniques could also be used to determine emissions from permanently capped areas of sites. If they were located near the site boundary and at a
sufficient distance from the active phase they could be used to determine an average area emission. At Calvert Landfill site in Buckinghamshire, a system like this is already in operation and is used to evaluate boundary emissions from the Site. The LIDAR equipment is also suitable for this purpose as the series of horizontal and vertical scans provide 3D concentration profiles for the whole area.

Although the flux box technique has been proven a good method for resolving low fluxes which arise from temporary and permanently capped areas, the cost of a zonal flux box survey is likely to be in the region of £12,000. In comparison, some of the other methods such as the mobile plume methods have a high resolution and good accuracy as well as being less labour intensive and costing in the region of £10,000 - £15,000 or the stationary plume method which costs less than £2,000 and still provides data with approximately less than 20% error.

5.4 Whole Site Emissions

The measurement of whole site emissions serves a number of purposes. It is undertaken with a view to determining contribution of landfills to total UK greenhouse emissions as well as for the purposes of PI and PPC reporting. If repeated at varying times of the year and different atmospheric conditions on the same site, it is possible to gauge how this contribution may vary.

Monitoring of whole site emissions is not a common requirement, but could be undertaken using the flux box technique along with an FID. Flux box measurements would be taken at regular intervals across the whole of the Site to monitor surface emissions. At Roxby landfill Site, Golder Associates conducted continuous monitoring of combustion emissions from the whole Site. Unburnt methane emissions were measured by use of an FID which was left to continually monitor emissions. A number of the methods described above could also fulfil this purpose.

The mass balance and micrometeorological methods are designed for obtaining whole site emissions. Scharff et al. (2003) showed they prove an accurate technique for this purpose although ideally they are better suited to smaller landfill sites. The only problems which are associated with using these methods for whole site monitoring relate to the location of the mast which would need to be sufficiently close to the gas plant so as to also sample its plume.

The stationary plume methods are also designed to measure whole site emissions and were similarly shown by Scharff et al. (2003), along with Jacobs et al. (2006), to be a reliable method for this purpose although these methods ideally work better for larger landfill sites.

The mobile plume methods can also be used to determine whole site emissions. As the sensor is driven along roads downwind and adjacent to the landfill site it takes a transect across the plume emitted from the whole site and consequently is able to map the emissions from the
whole Site. In order to monitor the combustion emissions, however, it is important that the adjacent roads are at a sufficient distance from the Site so that the plume from the combustion plant has grounded.

The open path optical methods could also be used, if a sufficiently long path length is used. These methods would be able to tell the concentration over the particular line sample which could be extrapolated to give a whole site emission or alternatively used at a sufficient distance from the Site to give the concentration of the plume at that distance. The problem with this however is that these methods will only give a line averaged concentration. In reality the emissions will not be homogeneous over the whole landfill and even if the whole site emissions determined by this method fall below reporting thresholds they may still exceed it in some places but fall sufficiently low in others so as to reduce the potential magnitude of the emission in a particular part of the transect.

The LIDAR does not suffer from this problem and is capable of providing a 3D profile of the methane emitted from a landfill site by means of performing both a horizontal and a vertical scan.

A whole site estimate using a flux box approach could cost in the order of £12,000 - £25,000 per sampling campaign, £24,000 - £50,000 per year to account for seasonal variations, with a high error of >100%. In the case of the simplified stationary plume method, the equivalent cost could be £6,000 capital costs plus £1,700 per sampling campaign, or £17,000 for ten sampling campaigns per year with the simplified method, achieving an estimated error of just 20%. For the mass balance method, this is £7,000 - £8,500 per sampling campaign, or £14,000 - £17,000 per year, to achieve an estimated percentage error of 25%. For the mobile plume methods, this is £8,000 - £11,000 per sampling campaign and £24,000 - £66,000 per year to achieve an estimated percentage error of between 10% – 30%. The sampling campaigns for both the TDL and FTIR approaches are of comparable cost. The researcher’s estimates of how many surveys are needed per year give rise to the large variance in annual costs observed.

Depending on the level of accuracy required, either the stationary plume, or meteorological based methods would provide a comparably cost effective method of obtaining whole site emissions. From these methods, the more robust is the stationary plume method, which is applicable on a wider range of shape and sized sites under a variety of different meteorological conditions. Depending on the accuracy required, the stationary plume methods offer approximately 20% error for around £20,000, whereas the mobile plume methods can yield a percentage error of 10% - 15%, but for a higher cost, in the region of £8,000 - £11,000 per survey, and £24,000 - £66,000 per year, depending on the number of surveys performed.
6.0 CONCLUSIONS AND SUGGESTIONS

6.1 Conclusions

The measurement of fluxes from landfill sites can be conducted to fulfil a number of different requirements. It is a suitable method for local air quality monitoring, for Pollutant Inventory reporting, for PPC permit regulating, as well as for determining the contribution from the landfill to greenhouse gas emissions. The current regulatory setting predominantly requires the monitoring of methane emissions, but it is possible to extend monitoring to a multitude of different gases emitted from landfill sites.

Currently monitoring of landfill surface emissions is performed by means of an FID walkover and a flux box survey. These methods are fairly labour intensive and hence this review has looked at the variety of other methods which are presently available for this purpose. Such methods include meteorological based techniques (micro and mass balance), stationary and mobile plume sampling approaches, and optical techniques including both open path and point source methods. Each of these methods is most suited for different tasks, and for use in different types of situations.

The micrometeorological method uses eddy covariance methods to determine the fluxes emitted from a site including methane and carbon dioxide. The covariance between vertical wind speed and gas concentration are averaged over 30 minute periods and analysed to give the flux from an area upwind of the flux mast. The main problem with this method is that it relies upon the assumption that landfill sites are flat and emissions occur in a homogeneous manner - a situation which is seldom true. Further problems include the need of a sufficiently sensitive sampling device that can measure frequencies of up to 10 Hz and issues with constantly changing wind directions or calm periods. This method is mostly suitable for the measurement of whole site emissions and a four week sampling period is likely to cost in the region of £8,000 with an associated error of approximately 19%.

The mass balance method uses a mast which is erected in the centre of the landfill site and takes measurements of the concentration and wind at intervals throughout the height of the plume with the very top measurement relating to the background concentration. From this information, the concentrations of methane are determined for the area of site which is upwind of the mast. The main problems with this method are related to dependence on the appropriate wind direction to measure either the area of site you wish to monitor, or the need to wait for sufficient wind directions to represent the whole site. Similarly the practicalities of locating a mast in the middle of a landfill site may have issues in uncapped or temporary capped areas, particularly as the height of the mast may need to be in excess of 15 m for larger sites. Like the Micrometeorological method, this technique is most appropriate for monitoring whole site emissions and a site survey can cost in the region of £7,000 - £8,500 per campaign, or £14,000 - £17,000 per year, with estimated error of approximately 25%.
The stationary plume methods use prevailing wind directions with the aid of tracer release to sample plume concentrations at a number of different locations downwind of the Site. The contents of each sample are analysed along with meteorological data to give a time averaged concentration at the location of the sampling station. This method is best suited for larger landfill sites as problems can arise for smaller landfills due to the sampling systems being located closer to the Site and hence becoming more reliant on the accurate location of tracer releases near the points of greatest emissions. It is incapable of providing temporal variation of emissions but Jacobs et al. (2006) have shown that it can be used as a simple and cost effective way of obtaining emission data with spatial information. This method is most suitable for the monitoring of total emissions, either from the Site as a whole or from specific areas. A survey would cost between £2,000 and £12,000 depending on the complexity of the method used. The simplified method requires up to ten surveys per year, at a cost of £17,000 overall, to give the error estimated by Jacobs et al. (2006) as approximately 20%.

The mobile plume methods use optical techniques to trace the plume downwind of landfill sites. The optical equipment uses a multiple pass cell to determine a path between a laser and reflector. This system is located in a van which is driven along roads adjacent and downwind of the landfill. Problems with these methods include finding appropriate roads or tracks which can be used to transect the plume and the initial capital cost of the equipment used, although as the equipment is not a permanent installation it could be used to measure more than one site which in effect reduces cost. This method is most suitable for monitoring whole site emissions although it could easily be used to monitor specific cells or phases. The cost of a typical sampling campaign is approximately £8,000 - £11,000 depending on the size of the landfill, with three to six surveys per year, costing between £30,000 - £66,000, to achieve a percentage error of 10 - 30% depending on location (Scharff et al., 2003).

The ground optical remote sensing methods use open path optical instrumentation. The optical devices used are installed along a path usually at site boundaries and monitor the path averaged flux of landfill gases over the line. The main problem with this method is that the equipment needs to be located on stable ground and away from site traffic which may cause disturbance to the beam. On temporary and uncapped areas in particular, this may pose somewhat of a problem. Likewise, the equipment is only able to provide temporal information and not spatial information. Consequently, the plume could exceed threshold levels at some points along the line but may not affect the line average sufficiently to indicate a problem. The exception to this rule is the LIDAR equipment. This technique allows both vertical and horizontal scanning of the Site to give a 3D concentration profile which is extremely useful. Unfortunately however, this equipment is very expensive and there are currently very few in existence. These methods are most suitable for monitoring site boundary level concentrations with the exception of the LIDAR which could be used to fulfil almost any of the requirements of landfill emission monitoring. The cost of a survey using these methods would typically involve purchasing the apparatus and hence the initial capital
costs would fall in the range of £10,000 to £1,000,000 but with subsequent measurements costing little extra.

There are also a series of other techniques available which although have some use on a landfill site, are quite limited in terms of their range of use or perhaps their applicability. These methods include aerial techniques where optical equipment is attached to a helicopter or aeroplane and used to scan a site or a transect; laboratory methodologies, where a series of instruments, such as FID, are left to monitor a site over a substantial period of time; and imaging techniques which use advanced infra red technology to detect the emissions of gases. Problems with these methods are that the aerial techniques are very expensive and work best under clear skies which are very unpredictable, especially in the UK. The laboratory methodologies provide temporal information but no spatial information and are reliant upon a prevailing wind direction in their favour. The imaging techniques are of great use in locating the main emission areas but are unable to provide any information on the concentrations of gases. Consequently, of these techniques, the laboratory methodologies are perhaps best for monitoring boundary emissions with the aerial techniques best suited to monitoring whole site emissions and the imaging techniques most appropriate for detecting the areas of main emissions or defects in the cap.

In conclusion, there are a variety of methods available for modelling emissions from landfill sites with a variety of different functionalities. Some methods are fairly straightforward both to understand and to apply, such as the flux box techniques and the mass balance method, whereas others are far less straightforward and require a large amount of scientific modelling to output the results, such as the micrometeorological method. Likewise, some methods provide temporal data on emissions and others spatial. Very few are able to provide both. There are also a wide variety of costs associated with both the equipment involved and with the cost of an average sampling campaign. For example, flux boxes are a relatively inexpensive piece of equipment compared to some of the optical techniques, but whereas in a sampling campaign, a flux box survey requires a large amount of effort and man power which increases costs, many of the optical systems are automated and can produce results with little effort or additional cost. Similarly, a flux box survey may take weeks whereas an optical survey would be measured in days thus eliminating temporal effects.

Another factor affecting applicability is the robustness of the instrumentation and its applicability on all parts of the Site. Some of the instruments discussed are more suitable for use on capped areas of land, such as the meteorological based methods. They are not appropriate for active areas, either as they would interfere with site work or site work would interfere with monitoring processes. The final issue is availability. Although some of the techniques may fulfil a number of the purposes described above, they are not necessarily all available in a sufficient quantity for use nationwide. For example there are only 2 LIDAR in existence in the UK. Similarly, the mobile plume methods developed by Scharff et al. (2003) and Samuelsson et al. (2001) were developed by research groups and consequently
reproducing this equipment would take time and effort. The techniques however, are relatively straightforward to use following training. On the other hand, methods such as the stationary plume method (Jacobs et al., 2006) are very easy to reproduce and require no skilled personnel etc to set up the trial, merely the use of a laboratory for analysis of the collected samples.

In terms of the applicability of the methods to different techniques and for different purposes dictated by UK legislation, the methods most suitable to a variety of different applications are the stationary and mobile plume methods. Both of these are appropriate for measuring emissions from active areas as well as providing spatial information for the Site as a whole.

6.2 Suggestions

Progress in optical and other above ground techniques means that these methods are more reliable and more cost effective than they were ten years ago, or even five years ago. It is therefore appropriate that these techniques are assessed on a typically engineered landfill site under typical climate conditions and with typical methane emissions from typical landfilled wastes in the UK.

The landfill site selected should have the following key characteristics to make the trial practical:

- A site in various stages of landfilling, with both operational and restored areas, is required. Any areas of temporary capped landfill would need to be identified;
- There should be a weather station on-Site to provide accurate meteorological data;
- There should be a well maintained and sparsely vegetated cap on fully restored areas;
- The surrounding environment should be free of tall buildings and medium to tall trees;
- Road access should be available on all sides of the Site within 100 – 2500 m of the operational area; and
- Ideally (although not essential) the Site would be located in the Midlands or the southeast, and be free of extreme topography.

The techniques which Golder believes are suitable for practical use in the UK are as follows:

- FID and FID/Static Closed Chamber Flux Box Technique. This technique is suitable for walkover surveys, and is the default surface emissions technique for temporary caps, final caps, and is also suitable for operational areas. Consequently, this technique could be used for whole site emissions calculations for PI or greenhouse gas inventory purposes;
- Stationary Plume Method. This technique, pioneered by Afvalzorg Deponie BV, uses what is in effect a sophisticated sampling container set out along a traverse downwind of the landfill. It can detect the plume from a completed surface or an operational area, but because of sample spacing, is most likely to be applicable for whole site emissions measurements. It is relatively inexpensive;
Mobile Plume Method, using TDL. This technique, used by ECN, is able to resolve methane along a traverse, and so is not limited by the number of sample points as in the stationary plume method. It can detect the plume from a completed landfill surface or an operational area. It is limited to one analyte (i.e. methane) and so is a dedicated instrument. It is relatively inexpensive; and

Mobile Plume Method, using FTIR. This technique, used by Chalmers University, is the most sophisticated technique we believe is practicable at the current state of development. It too, like the TDL method, is able to resolve methane along a traverse, and so is not limited by the number of sample points as in the stationary plume method. It can detect the plume from a completed landfill surface or an operational area. Unlike the TDL, FTIR are whole spectra instruments, which make the analyser potentially suitable for detecting many different types of emissions. This flexibility means that the FTIR, while initially more expensive, could be used by a testing laboratory, for various purposes. It is the most expensive technique of those identified for comparative trialling, but is still a practical consideration.
7.0 REFERENCES


30) USEPA Technical Guidance on Spectrex SafEye 227 Infra-Red Open Path Monitor, USEPA.