

REPORT

An Estimate of Methane Emissions from UK Landfill Sites Based on Direct Flux Measurements at Representative Sites

**Final Report to
Department of the Environment
Global Atmosphere Division**

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at Representative Sites**

**Commissioned by
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Global Atmosphere Division
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Approved on behalf of Chief Executive, NPL,
by D H Nettleton, Head of the Centre for Optical and Environmental Metrology

EXECUTIVE SUMMARY

Methane is the second most important of the greenhouse gases (after carbon dioxide), and contributes approximately 12% of the global warming potential of all man-made gases emitted by the UK at present. The anaerobic decay of organic waste in landfill sites is a major national source of methane, but a lack of detailed information on emissions has resulted in large uncertainties in current estimates. In view of the importance of methane emissions from landfill to total UK greenhouse gas emissions, this study was commissioned to establish an improved estimate based on direct flux measurements.

Measurements of the flux of methane have been carried out at 35 representative sites using three complementary techniques: optical integrated-path, flux survey and flux enclosure methods. The sites were chosen to be representative of UK conditions, and included, *inter alia*, large modern sites incorporating the latest gas-control systems, older sites that have had gas-control systems fitted after completion and sites that have not received waste or maintenance for more than 15 years.

The results show that the principal factors that influence the total emissions of methane to atmosphere from a landfill site are: the depth of waste in place and the presence of a comprehensive gas extraction system (together with a low permeability capping layer). A statistical stratification of the flux measurements was used to divide the sites into four categories. The mean for each category was then scaled to calculate total annual emissions from the UK using information about the number and size of sites in each category.

Total methane emissions from landfill are estimated to have been 887 kt y⁻¹ in 1995, with a 90% confidence interval between 652 kt y⁻¹ and 1135 kt y⁻¹. The measurements have demonstrated that fluxes of methane from landfill sites that have comprehensive gas extraction systems (and low permeability caps) are significantly lower than estimated in previous studies which relied solely on model calculations.

Taking into account known and anticipated changes in the mass of waste being sent to each category of landfill, annual UK emissions of methane from landfill are estimated to have been 1039 kt y⁻¹ in 1990, and are estimated to fall to 699 kt y⁻¹ by 2000 and 349 kt y⁻¹ by 2010.

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1 INTRODUCTION

This report describes the results of a research project commissioned by the Global Atmosphere Division of the Department of the Environment under contract EPG/1/1/10. The aim of the project was to improve the UK's estimate of methane emissions from landfill sites. Methane is the second most important anthropogenic greenhouse gas (after carbon dioxide), and the anaerobic decomposition of waste in landfills is estimated to be the UK's most important source of anthropogenic methane.

1.1 Objectives

The objectives of the project were:

- to develop and carry out a measurement programme to quantify annual emissions of methane from representative landfill sites in the UK.

- to target the study on larger, better-characterised sites and the influence of gas-collection systems.

- to compare the result with methane emission estimates based on modelling of the landfill process, to highlight and reduce uncertainties in individual key parameters and to recommend appropriate revisions.

- to produce a revised assessment of current total annual methane emissions from UK landfill sites including an analysis of the specific uncertainties involved.

1.2 Structure of Report

The report begins with a review of the international requirements (Section 2) which led to the commissioning of this project. Section 3 reviews the results of the measurements carried out and describes how they were analyzed statistically to determine the most important factors influencing methane emissions at each site. Section 4 shows how the average methane potential of UK waste and the average emission reduction due to the use of a gas extraction system were calculated from the measured data set. Possible sources of data about the characteristics of UK landfill sites are reviewed in Section 5 and combined with the results of Section 3 to calculate the final result for UK emissions which are presented in Section 6. In Section 7, a "risk analysis" type calculation is used to estimate the uncertainty in the final result. The project is summarised in Section 7 where the conclusions are also presented.

The major innovative feature of this work has been that an estimate of total methane emissions from UK landfill sites has been made which is based on direct measurements of methane fluxes. A description of the measurement techniques used is given in Annex A and the complete set of measured data is summarised in Annex

B. An analysis of a set of measurements carried out in order to quantify the spatial and temporal variability of emissions at a single site is given in Annex C. Annex D presents a detailed mathematical description of the operation of a particular design of flux enclosure which has been developed to explain some of the results observed during this project.

2 IPCC REQUIREMENTS AND RELATED WORK

2.1 UK Requirements for Reporting to the FCCC

The Framework Convention on Climate Change (FCCC) requires countries to report national annual emissions of all greenhouse gases (except those covered by the Montreal Protocol). A default methodology for carrying out these calculations is recommended in the Intergovernmental Panel on Climate Change (IPCC) Guidelines [1]. This method is described in the next section.

The convention also commits developed countries to adopt policies and measures that will have the effect of reducing emissions in 2000 to the level of 1990, and in future the FCCC is likely to adopt emissions targets beyond 2000.

Therefore, the principal objective of this project has been to provide representative data based on direct emission measurements of landfill methane which will help the UK Government to respond to existing and future commitments under the FCCC.

2.2 IPCC Default Method

The default method recommended by the IPCC in 1995 is based on the work of Bingemar and Crutzen [2]. It uses an empirical approach which estimates the fraction of degradable organic carbon (DOC) in waste and then assumes that during anaerobic degradation 50% of this is emitted as methane (and the remainder as carbon dioxide). It leads to an expression for the methane generated per tonne of municipal solid waste (MSW) landfilled as:

$$\begin{aligned} \text{Methane emitted [per t(MSW)]} = & \\ & \text{Fraction DOC in MSW} \\ & * \text{Fraction DOC dissimilated} \\ & * 0.5 \quad [\text{g}(\text{CH}_4) \text{ per g}(\text{C}) \text{ dissimilated}] \\ & * 16/12 \quad [\text{RMM}(\text{CH}_4)/\text{RMM}(\text{C})] \end{aligned}$$

where the factor 16/12 is used to convert the relative molecular mass (RMM) of carbon to the RMM of methane. The fraction DOC dissimilated refers to the proportion of carbon in DOC that is converted into landfill gas. Using the default values recommended for OECD countries, this method leads to a value of 98 kg(CH₄)/t(MSW). This value of the specific methane potential of MSW is multiplied by the total mass of MSW sent to landfill and then the amount of methane recovered is subtracted to calculate the total amount of methane emitted to the atmosphere.

This published methodology has been modified slightly by the IPCC in 1996 in a revised version of their reference manual that is due for publication in 1997 [3]. The modifications include the introduction of a factor to the above equation to allow for

the influence of the oxidation of methane to carbon dioxide by bacterial action in the upper layers of the site. Although this factor was introduced, the IPCC expert panel recognise that there is no international agreement on what the factor should be and have therefore given it a default value of zero (corresponding to no oxidation).

2.3 Previous Work on the Estimation of Methane Emissions from UK Landfills

In successive projects carried out by the National Physical Laboratory (NPL) and AEA Technology, the UK has developed an approach that is consistent with IPCC reporting guidelines and is significantly more sophisticated than the IPCC default method [4,5]. The work of Bellingham *et al* [4] included a breakdown of the composition of municipal solid waste in the UK. This enables the amount of carbon placed in landfill and the extent to which it is degradable to be calculated. It resulted in an estimate for methane emissions from landfill in 1994 of 1.9 Mty^{-1} (with upper and lower bounds of 4.2 and 0.6 Mty^{-1}). Subsequently, the work of Aitchison *et al* [5] extended this work to allow for the time decay of methane emissions by using an exponential model. This resulted in an estimate for methane emissions from landfill in 1994 of 1.8 Mty^{-1} with an estimated 90% confidence interval of 1.1 to 2.2 Mty^{-1} .

2.4 Advantages of a Measurement-based Approach

The major innovation introduced in the work presented here is the use of direct measurements of methane emissions from representative landfill sites as the basis for estimating the UK total. This approach reduces the need for assumptions about waste composition and the decay process which are required to perform an estimate based on modelling the methane emission process. Although such models can use the best available information, they are limited to using a significantly simplified model of the very large number of processes involved in the generation of methane from landfill sites. Many of the parameters required to characterise these processes are only based on laboratory simulations or empirical arguments, so they cannot be relied upon to be genuinely representative of real landfill conditions.

The measurement-based approach introduces a requirement for a robust methodology for calculating the national total from measurements carried out at a small number of representative sites. In this study, this has been done by establishing a statistical stratification that groups sites into categories according to certain key characteristics that determine the amount of methane they emit. In order to provide some comparison between different methods that can be used to do this, four different stratifications have been tested in this work and one of them has been selected as the basis for the final calculation.

This study was carried out in collaboration with work carried out by W.S. Atkins (funded by the Environment Agency and Surrey County Council) [6]. This other study had the aim of assessing methane emissions from different categories of landfill sites, and was based on measurements of surface fluxes.

3.3 Landfill Characteristics Used in Data Analysis

At the simplest level, the amount of methane emitted into the atmosphere from a landfill site is determined by the amount of methane generated within the site, the amount of gas extracted from the site (in a controlled way) and the amount of methane oxidised within the site. The balance between these processes is given by:

$$\text{Total CH}_4 \text{ emitted} = \text{CH}_4 \text{ generated} - \text{CH}_4 \text{ extracted} - \text{CH}_4 \text{ oxidised}$$

The following sections outline how each of these terms has been analysed in this work.

3.3.1 Methane Emission Measurements

This work is based on a set of measurements of methane emissions carried out at 35 UK landfill sites. The measurement data have all been reported as average surface emission rates calculated according to:

$$\text{Average surface emission rate} = \frac{\text{Total CH}_4 \text{ emitted}}{\text{Total site area}}$$

The measured value of the total site emission of methane includes emissions to the atmosphere through the surface as well as from all other sources. These might include leaks from the extraction system, from around the edges of the cap or by any other route. This report is based on measurements made with techniques that are able to measure the total emissions from the site (regardless of their origin). The measurement data are shown in Annex B. These measurements of average surface emission rates will not always be the same as surface emission rates measured directly over small areas of the site using flux enclosures. The extent of this difference at one particular site is discussed in Annex C.

3.3.2 Methane Generation

Although there are many factors that control the rate at which methane is generated (such as moisture, temperature and leachate circulation), these do not have first-order effects on the total quantity of methane generated over the entire period of decay. The two factors that most directly determine the total quantity of gas generated within a site are the amount of waste and the type of waste. During this study it was found that information collected from site operators was insufficient to quantify the variations in the type of waste in the measured sites (although it was possible to exclude sites principally accepting inert waste). However, the depth of waste can be estimated and is used in this study as one of the principal site characteristics incorporated into the stratification schemes.

3.3.3 Methane Extraction and Oxidation

There is an increasing trend for sites to be fitted with gas extraction systems in order

3 ANALYSIS OF THE MEASUREMENT RESULTS

3.1 Measurement Methods and Data Sets

Emissions of landfill gas can be measured by a number of different methods. The objectives of this study require the use of methods that measure the total flux from the site. Two such methods have been used:

an optical integrated-path technique, which uses measurements of integrated-path concentration made with an optical monitor,

a gas flux survey method based on the use of a portable methane monitor.

Both of these methods are described in detail in Annex A. These total flux measurements were augmented by a limited number of surface flux measurements made with a flux enclosure. These were used to quantify the extent of spatial and temporal variations in emissions on a landfill site, and are described in Annex C. The flux enclosure measurements reported here were also used as the basis for a comparison with the results of other workers using the same technique [6].

The emission measurements are summarised in Annex B. At the request of the majority of site operators who allowed access for these measurements, the identities of the sites measured in this study are not disclosed.

3.2 Measurement Strategy and Basic Landfill Properties

Many attempts have been made to quantify the influence of different processes and operating conditions on the decay of organic material within a landfill [4,5,6]. The objectives of this work require a statistical analysis of the behaviour of emissions and not a detailed process or biochemical model. A statistical analysis enables sites to be grouped in categories according to various characteristics. Although these categories are intended to bring together sites with similar methane emission characteristics, there may not be a direct link to a fundamental description of the processes involved. The rationale for the categorisations (or stratifications) studied in this work is described in the following sections.

The wide variation in measured emissions at different sites presents a significant challenge for the design of a representative programme of measurements. Since the range in measured emissions is much larger than the uncertainty in any of the measurement techniques, the strategy developed has been to carry out as many measurements as possible in order to sample the variation as representatively as possible. This has been done by using the gas flux survey technique (described in Annex A) to measure sites quickly and reproducibly. The accuracy of these measurements was then assured by comparing the results with measurements made with the optical integrated-path technique which is more accurate, but significantly slower. The flux enclosure technique was then used to quantify the extent of spatial and temporal variations in landfill emissions in order to establish a basis for calculating long-term emission rates on a finite set of measurements.

to control lateral gas migration, odour and emissions to the atmosphere. Such extraction systems can also provide fuel for electricity generation or other energy schemes. These are almost always accompanied by a low permeability cap. For sites with an extraction system, the amount of methane extracted is clearly determined by the design and the efficiency of the system. This will depend on the fraction of the site that it covers, the depth and number of wells, as well as the effectiveness with which the site is sealed by a low permeability cap on the top, and other measures around the sides and base.

The most important mechanism that destroys methane within a landfill is oxidation by bacteria in the upper layers of the site and the cap. During this study, it has not been possible to distinguish between the influence of gas extraction systems in removing methane and of oxidation within the cap and surface layers of the site, since they both have the same result of reducing methane emissions. It would be possible to quantify the extent of these two processes if similar sites were available with comprehensive gas extraction systems and without low permeability caps and *vice versa*. However, this is a combination of conditions that is not often found because sites with comprehensive gas extraction systems usually have low permeability caps. The small number of sites that do not follow this trend are generally older and are therefore more difficult to compare directly. Consequently, in this analysis a single "emission reduction factor" (section 4.2) has been evaluated that does not distinguish explicitly between oxidation and extraction*.

Hence, the first two key site characteristics that are used to establish the stratification schemes used in this study are the average depth of the waste and the presence of a comprehensive gas extraction system (together with a low permeability cap).

3.3.4 Site Age and the Temporal Decay of Emissions

The rate at which decaying waste emits methane follows a characteristic time variation which starts with a rapid rise to a level which subsequently decreases to zero. It is usually assumed that this decrease follows an exponential function [5]. Previous models used to estimate methane emissions from landfill have avoided the requirement to describe this time dependence quantitatively by adopting a steady-state or equilibrium basis. This assumes that if the mass of waste sent to landfill each year has remained relatively constant for many years, then the amount of gas emitted each year will be the equilibrium value which is equal to the amount liberated by the total decay of the waste placed in landfill that year [4].

The model used by Aitchison *et al* [5] incorporated an explicit exponential time-dependence for the emitted methane. This is possible when modelling emissions on a national scale, because an appropriate exponential factor can be applied to the emissions from all of the waste sent to landfill in each year. However, in the measurement-based approach used here it is not possible, because the measured emissions in any particular year are a sum of emissions from the waste placed in the site during all previous years. Since the masses sent to landfill in each of these years are generally not known with good accuracy, it is not possible to use a single

* A more sophisticated set of measurements including the quality and quantity of gas extracted could resolve this issue. Such an experiment is beyond the scope of this work, but would yield a great deal of insight into the processes leading to methane emission.

numerical factor to characterise the time dependence.

Consequently, we have introduced a third key characteristic to the stratification schemes which refers to the age of the site. This is done by labelling sites "old" if the rate at which methane is emitted is dominated by their age rather than by other factors. The quantitative definition used in this study is that "the site has not received waste for at least 15 years". (A rationale for this definition is given in Section 5.4).

Hence, the three key characteristics which have been used in this study are: the average depth of waste, the presence of a comprehensive gas extraction system (plus a low permeability cap) and the age of the site. The stratification schemes described below combine these in various ways in order to group the different landfills measured for this project into categories.

3.4 Statistical Analysis of Stratification Schemes

Before the details of the four stratification schemes are proposed, it is appropriate to discuss how they can be compared. In this study it is done by applying the statistical technique of Analysis of Variance (ANOVA) [7] by which the total variation in a set of data may be reduced to components associated with possible sources of variation whose relative importance is to be quantified. This is done by stratifying the data for the average surface emission rate for each of the sites into four or five categories. Each stratification scheme is then analysed by ANOVA to determine the extent to which the measured variability is explained by the proposed site categories. This is measured by Fischer's F parameter which measures the ratio of variance between and within categories (after taking account of the number of degrees of freedom involved). The higher the value of F, the better that the model (with its stratification) fits the data. (Strictly, a null hypothesis should be tested using a critical value of F for a specified confidence level. In this work we use F as a more general indicator of "quality of fit" and use it to compare the effectiveness of the different approaches.)

3.4.1 Stratification Scheme No 1

The first stratification scheme divides all of the measured sites into the four categories defined in Table 1.

The allocation of the measured sites to these categories is shown in Table 2. The results of an ANOVA analysis applied to the data using this stratification are summarised in Table 3. The ANOVA method considers the total variance of all of the measured data, and calculates how much of it can be explained by a model that attributes it to variation within and between the specified categories. It provides a quantitative method of comparing this stratification classification with other stratifications applied to the same data. The results include a mean for each category, together with the standard deviation of this estimate. In this study, the standard deviation is used as a measure of the range of emission rates that are included within a category.

**Table 2 - Allocation of Sites to Categories
for Stratifications 1, 3 and 4**

Site	Stratification No		
	1 and 2	3	4
1	None	deep/unp	deep/unp
2	Old	s/old	s/old
3	Active	Active	Active
5	Comp	deep/p	deep/p
6	Comp	s/old	s/old
7	Comp	shallow	shallow
8	Ltd	deep/p	deep/lt p
9	None	deep/unp	deep/unp
10	Old	s/old	s/old
11	Ltd	deep/p	deep/lt p
12	Old	s/old	s/old
13	Old	s/old	s/old
14 a	Comp	deep/p	deep/p
14 b	Ltd	deep/p	deep/lt p
15	Comp	deep/p	deep/p
16	Ltd	deep/p	deep/lt p
17	Comp	deep/p	deep/p
18	Comp	deep/p	deep/p
19 a	None	shallow	shallow
19 b	Comp	shallow	shallow
19 c	Comp	shallow	shallow
20 b	Active	Active	Active
20 a	Comp	deep/p	deep/p
21 a	Comp	deep/p	deep/p
21 b	Comp	deep/p	deep/p
21 c	Active	Active	Active
22	Old	s/old	s/old
23	Old	s/old	s/old
24 a	Ltd	deep/p	deep/lt p
24 b	None	deep/unp	deep/unp
24 c	Active	Active	Active
25	Comp	deep/p	deep/p
26	Ltd	shallow	shallow
27	Comp	deep/p	deep/p
28	Old	s/old	s/old

Active	- measurements made on an active site area.
Comp	- site with comprehensive gas extraction (including a low permeability cap).
Ltd	- site with limited gas extraction system.
None	- site with no gas extraction system.
Old	- old site that has not received waste for more than 15 years.
Deep/unp	- site > 20m deep without gas extraction
Deep/p	- site > 20m deep with gas extraction
s/old	- old, shallow site.
shallow	- shallow (but not old) site.

Table 1 - Four Categories of Site used for Stratification No 1

Site Category	Definition
None	Sites with no gas extraction system.
Comp	Sites with a comprehensive gas extraction system and a low permeability cap.
Limited	Sites with a limited gas extraction system and/or partial coverage by a low permeability cap.
Old	Sites that have not received waste for more than 15 years. These sites may have some form of gas extraction (often designed to prevent lateral migration or odour).

Table 3 - Results of the ANOVA Analysis
Stratification No 1

Site Category	Mean Emission Rate [mg m ⁻² s ⁻¹]	Standard Deviation [mg m ⁻² s ⁻¹]	σ/Mean
None	1.01	0.50	50%
Limited	0.19	0.12	63%
Comp	0.080	0.057	71%
Old	0.028	0.019	69%

The analysis had 34 degrees of freedom, with an F-coefficient of 34.

Figure 1 shows the spread of measurements within each of these categories.

3.4.2 Stratification Scheme No 2 - Introducing Depth Explicitly

The second stratification scheme extends the first one by introducing the average depth of waste explicitly into the calculation. This is done in the most straightforward way possible, by dividing the average surface emission rate of each site by the average depth of waste in order to calculate the average emission rate per unit volume of waste:

$$\begin{aligned} & \text{Average emission rate per unit volume of waste} \\ &= \frac{\text{Total CH}_4 \text{ emitted}}{\text{Total site area} * \text{Average Depth}} \end{aligned}$$

The four categories of site remain the same as in Stratification No 1. The use of the depth in this way as a proportional factor presumes that emissions from any unit

Figure 1 - Average Surface Emission Rate
in Categories for Stratification No.1

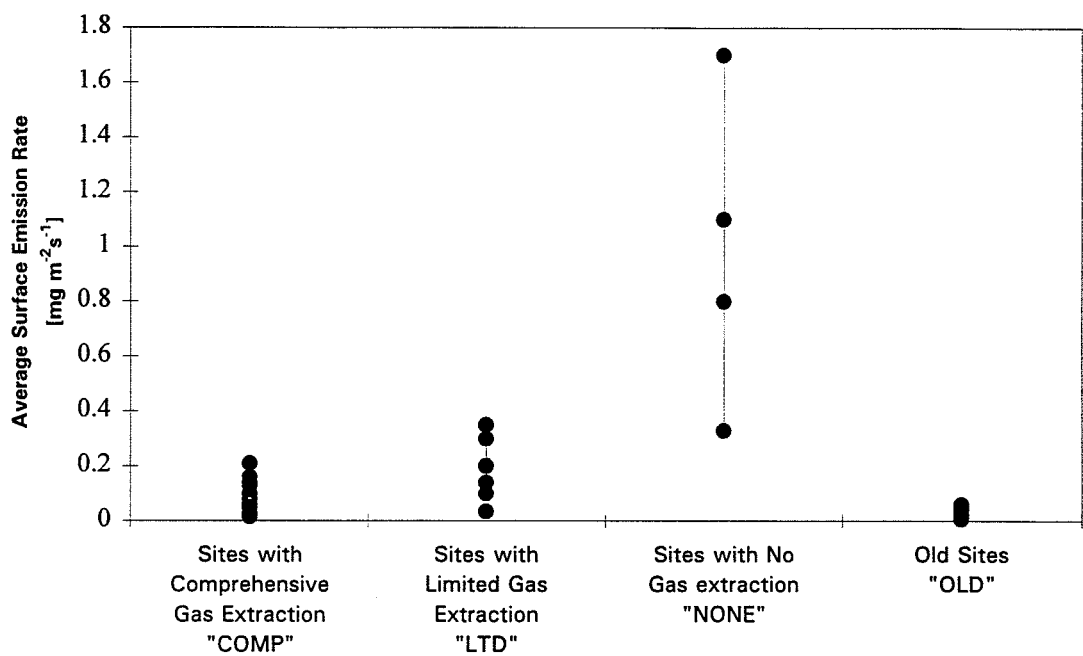
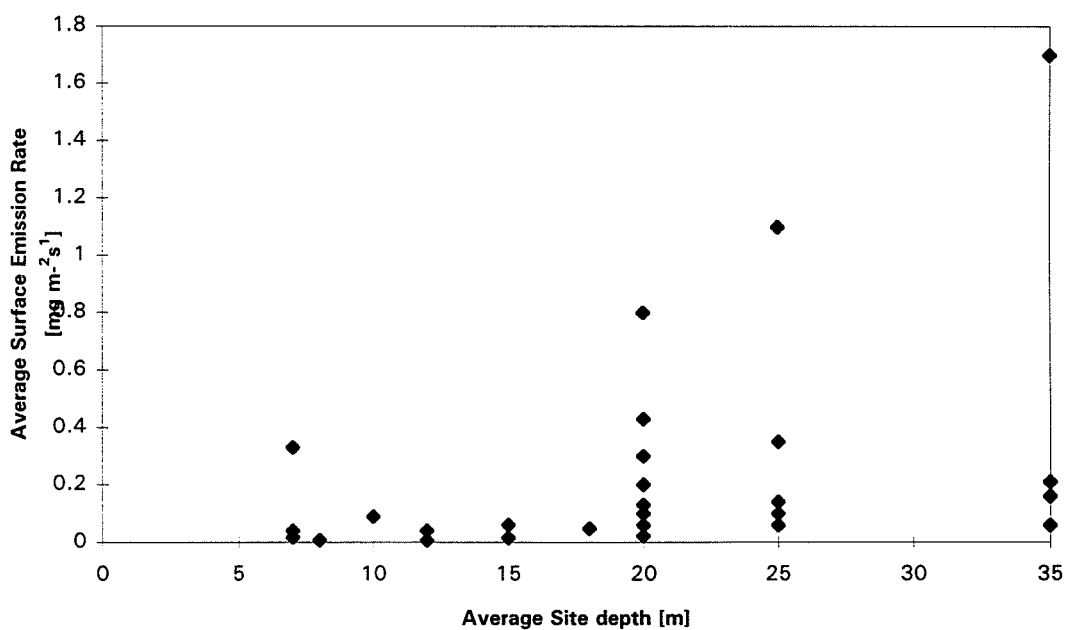


Figure 2 - Average Surface Emission Rate
at Different Sites versus Site depth



volume of waste are the same regardless of the depth of the waste within the site. This assumption is equivalent to the assumption that the extent of oxidation within the waste mass itself is small (although there may be significant oxidation in the cap). Figure 2 shows the average surface emission rate at all of the sites versus the average depth of the site. The data points are well spread but indicate a general trend towards deeper sites having higher average surface emission rates.

Since an estimate of the average depth of waste is available for every site for which the surface emission flux has been measured, the average emission rate per unit volume of waste has been calculated in this way for each of the measured sites and used as the input variable for the ANOVA analysis.

The validity of this step in the analysis is substantiated by the fact that it leads to a justifiable separation of the measured data into the stated categories. Table 4 summarises the results of the ANOVA analysis of Stratification No 2.

**Table 4 - Results of the ANOVA Analysis
Stratification No 2**

Site Category	Mean Emission Rate [mg m ⁻³ s ⁻¹]	Standard Deviation [mg m ⁻³ s ⁻¹]	σ/Mean
None	0.045	0.003	7%
Limited	0.009	0.005	56%
Comp	0.0034	0.002	59%
Old	0.0020	0.0011	55%

The analysis had 34 degrees of freedom, with an F-coefficient of 297.

The range of values within each site category is shown graphically in Figure 3. The ratio of the standard deviation to the mean for the results within each category gives a measure of the spread of results within a category. For the sites with no extraction system this ratio is 7%. However, for each of the other categories of site it is greater than 50%. A comparison with Table 3 shows that the category "None" is much more tightly grouped under Stratification No 2 than in Stratification No 1, but the other categories are broadly similar.

Figure 4 shows the average surface emission rate versus the depth for all sites in the category with comprehensive gas extraction systems. The trend towards the deeper sites having higher emissions is strong. A possible explanation for this is that it is a consequence of the wide variations in the scope and effectiveness of the gas extraction systems that are in place. For the purposes of this study, we assume that the spread of these results reflects the real spread in emissions at sites within this category.

In this analysis, the site category "old" has been used to group together sites whose emissions are most obviously dominated by their age rather than by other factors. It does not account explicitly for the range of possible ages within the category. Figure 5 shows the average surface emission for each of these sites versus their average

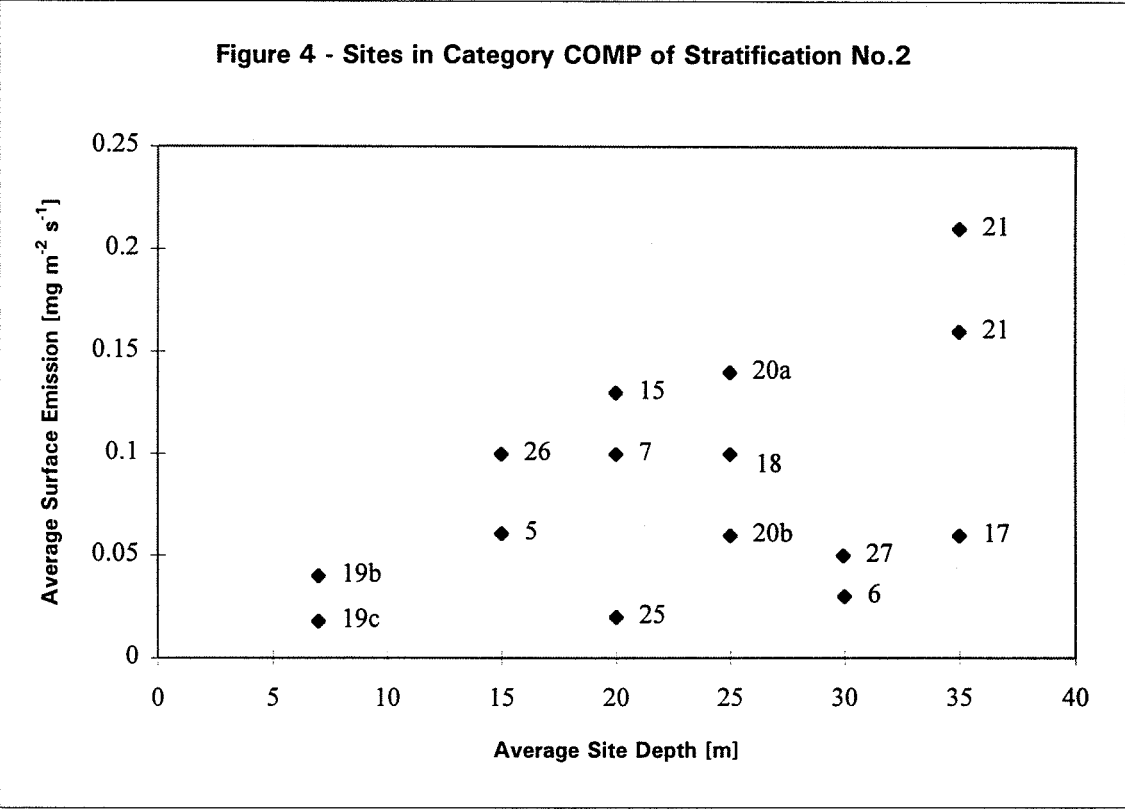
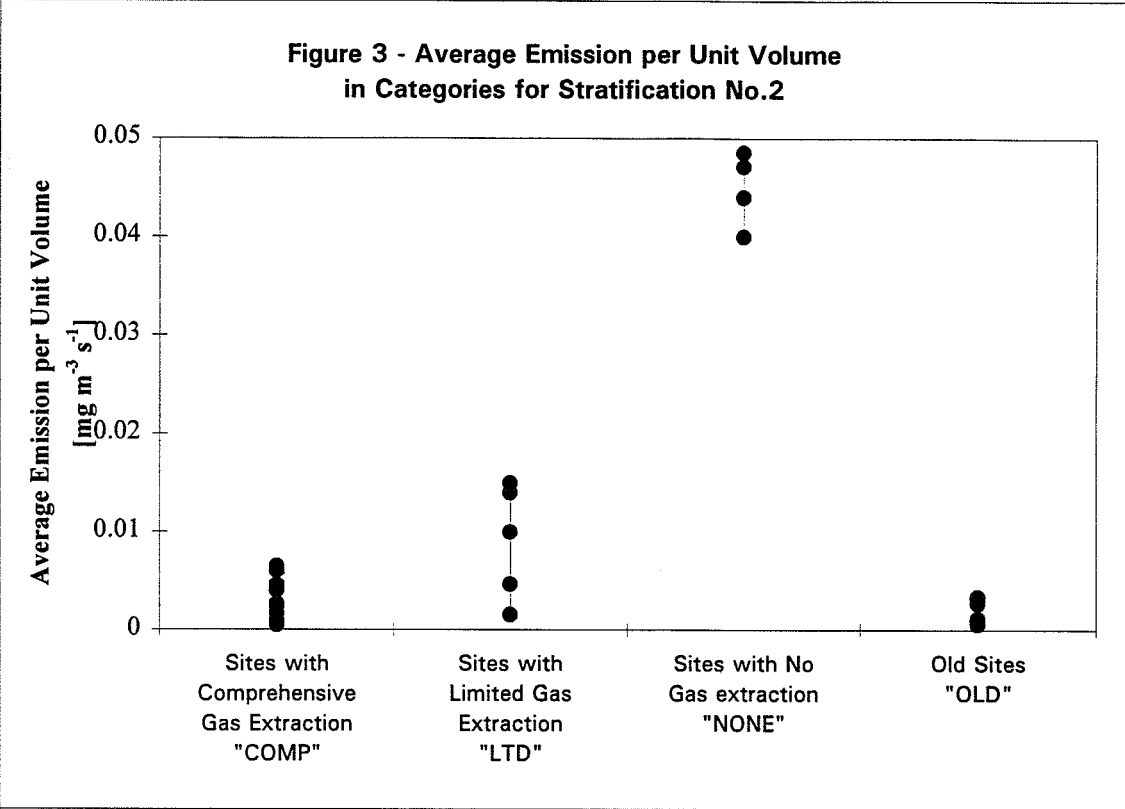


Figure 5 - Average Surface Emission versus Depth for OLD Sites in Stratification No.2

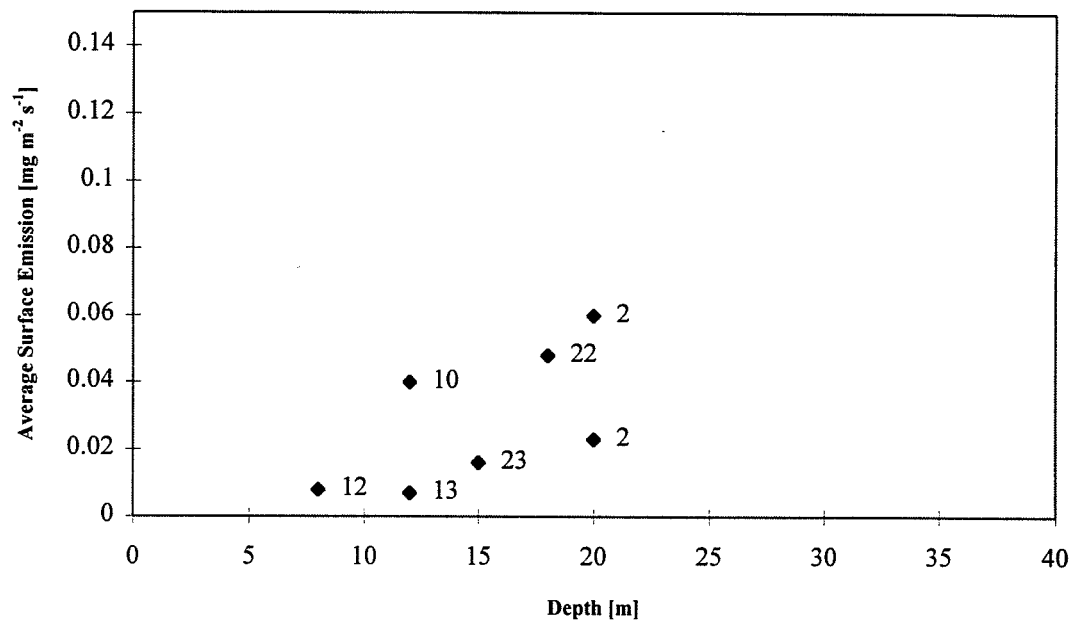
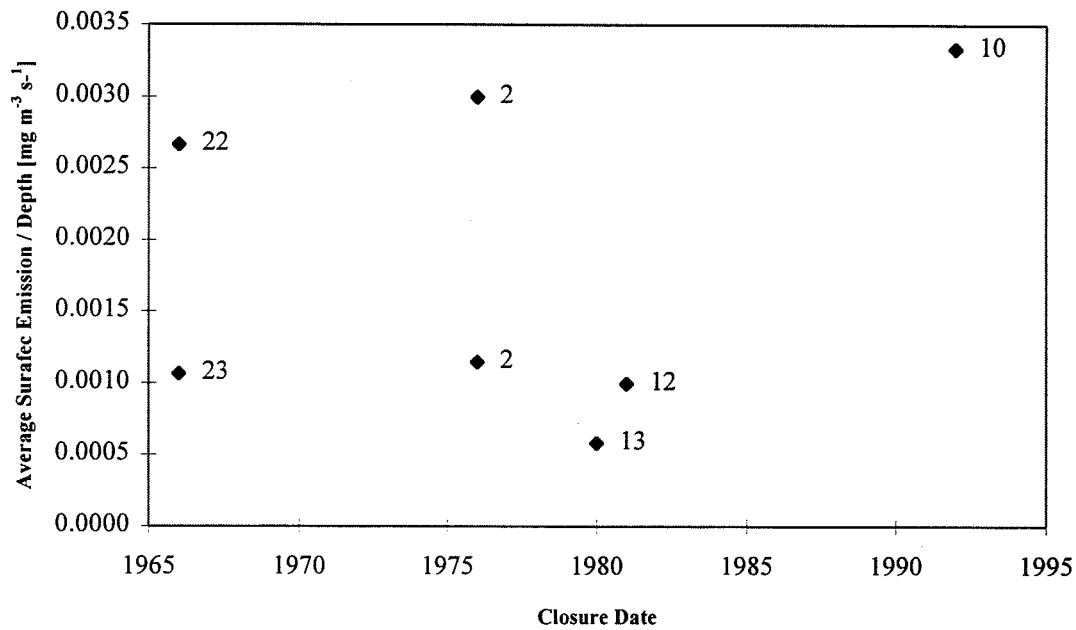


Figure 6 - Average Surface Emission / Depth versus Closure Date



depth. Figure 6 shows the average surface emission per unit volume of waste for the seven measurements made at sites that were placed in the "Old" category. All of these sites received waste for between 10 and 25 years. These data do not contain sufficient information to fit a model or to determine a decay lifetime with any confidence.

3.4.3 Stratification Scheme No 3

The third stratification scheme differs from the second by the use of the average waste depth to stratify all of the sites into two categories as either deep or shallow. This eliminates the quantitative dependence of the results on the estimated waste depth used in Stratification Number 2, since it only requires an estimate of whether the waste is more or less than 20 metres deep. The stratification is then extended by dividing the deep sites into those that have comprehensive extraction systems and those that do not. Since it is found that the category of shallow sites contains more older sites than the category of deep sites, it is subdivided into "shallow" and "shallow old".

The definitions of the four categories are shown in Table 5 and the allocation of the sites to the categories are shown in Table 2. The results of the analysis are shown in Table 6 and Figure 7.

Table 5 - Four Categories of Site used for Stratification No 3

Site Category	Definition
Deep/p	Sites with an average waste depth greater than 20 m and a comprehensive gas extraction system (and a low permeability cap).
Deep/unp	Sites with an average waste depth greater than 20 m, but without a comprehensive gas extraction system.
Shallow/old	Sites with an average waste depth less than 20 m that have not received waste for at least 15 years.
Shallow	All other sites with an average waste depth less than 20m that have received waste in the last 15 years.

Table 6 - Results of the ANOVA Analysis
Stratification No 3

Site Category	Mean Emission Rate [mg m ⁻² s ⁻¹]	Standard Deviation [mg m ⁻² s ⁻¹]	σ/Mean
Deep/p	0.127	0.099	78%
Deep/unp	1.175	0.38	32%
Shallow/old	0.034	0.023	68%
Shallow	0.12	0.12	100%
The analysis had 34 degrees of freedom, with an F-coefficient of 68.			

Figure 7 - Average Surface Emission Rate
in Categories for Stratification No.3

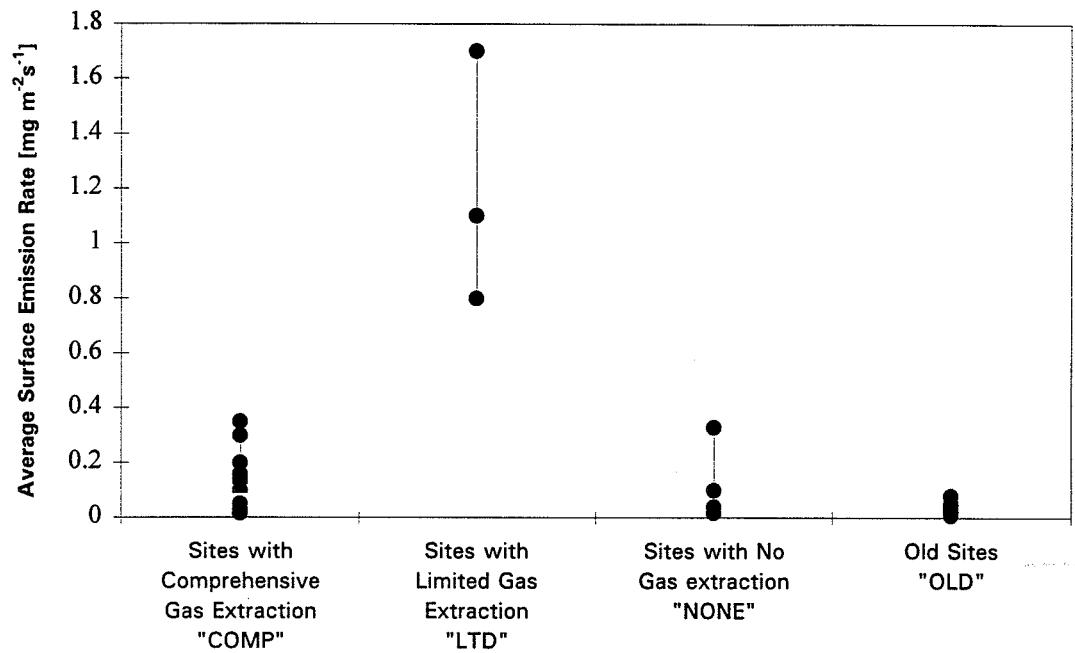
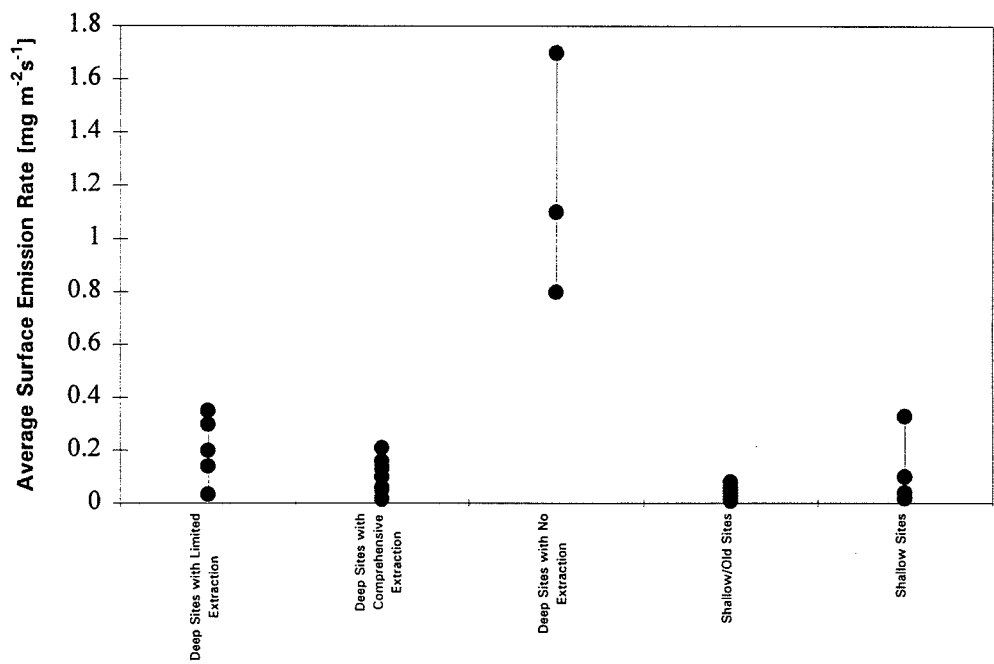


Figure 8 - Average Surface Emission Rate
in Categories for Stratification No.4



3.4.4 Stratification Scheme No 4

The fourth scheme uses the same categories as the third, with the further distinction that the category of deep sites with extraction ("Deep/p") is further sub-divided into those with comprehensive pumping and those with limited pumping. The results of the ANOVA analysis are shown in Table 7.

Table 7 - Results of the ANOVA Analysis
Stratification No 4

Site Category	Mean Emission Rate [mg m ⁻² s ⁻¹]	Standard Deviation [mg m ⁻² s ⁻¹]	σ/Mean
Deep/p	0.091	0.056	63%
Deep/lt p	0.21	0.12	60%
Deep/unp	1.18	0.38	32%
Shallow/old	0.034	0.023	68%
Shallow	0.12	0.12	100%

The analysis had 34 degrees of freedom, with an F-coefficient of 53.

These results are plotted in Figure 8.

3.5 Conclusions from the ANOVA Results

Table 8 summarises the results of the ANOVA analysis of the four stratifications.

Table 9 - Results of the ANOVA Analysis
Four Stratifications

Stratification No	No of Categories	F
1	4	34
2	4	297
3	4	67
4	5	53

The analysis carried out with 5 categories has a lower "critical" value for F than the others.

The ANOVA analysis leads to a reasonably clear conclusion that Stratification Number 2 provides the best basis for subsequent analysis. Hence the results in Table 4 are used in the following sections to estimate the total amount of methane emitted

by all UK landfill sites.

4 QUANTITIES DERIVED FROM THE MEASUREMENT RESULTS

Before proceeding to calculate total UK methane emissions from the results of Section 3, it is useful to make some comparisons between these results and the results of other work.

4.1 Specific Methane Potential of Waste

The average value for the emission per unit volume from the sites with no extraction system resulting from the ANOVA analysis of Stratification No 2 is $0.045 \text{ mg m}^{-3} \text{ s}^{-1}$. In principle, this value should be directly comparable to the estimates of the specific methane potential of waste (L). In order to make such a comparison, we multiply by an estimate for the mean density of waste (800 kg t^{-1}) to yield the specific methane emission rate. In this case it is $1.14 \text{ kg(CH}_4\text{) tonne(MSW)}^{-1} \text{ year}^{-1}$.

If we assume that this emission rate remains constant throughout the lifetime of the waste, then this value can be multiplied by an estimate of the decay lifetime of waste to give the specific methane potential. For the case of lifetimes of 20 and 30 years;

$$L = 34 \text{ kg t}^{-1} \text{ (over 30 years) or } 23 \text{ kg t}^{-1} \text{ (over 20 years).}$$

These values are consistent within the range expected from theoretical estimates of the specific methane potential (data from [4] re-worked in Figure A of [5]).

4.2 Emission Reduction Due to Gas Extraction Systems

Although the category of sites in Stratification No 2 with comprehensive gas extraction systems is a very varied group with a relatively wide spread of results, the mean of this group can be compared with the mean of the group with no extraction systems to calculate the average reduction in emissions due to the use of an extraction system. This can be quantified by reference to the Emissions Reduction Factor (η_r) defined as

$$\eta_r = 1 - \frac{\text{Average emission with extraction}}{\text{Average emission without extraction}}$$

$$\eta_r = 1 - 0.0034 / 0.045 = 92\%$$

This value is consistent with industry estimates of the extent of emission reductions resulting from the use of a gas extraction system.

4.3 Comparison with the Results of Aitchison (1996)

Aitchison *et al* [5] developed a classification of all UK sites into two categories defined as:

Type I - sites where the majority of completed areas have a well-engineered low-permeability cap and an extraction system that sends gas to a flare or energy recovery scheme. (Assumed extraction efficiency = 70% followed by an oxidation efficiency of 40%).

Type II - all other sites. (Assumed oxidation of 20% of all methane generated).

This definition of Type I encompasses every site categorised as "Comp" in Stratification No 2 as well as some sites in the "Limited" category. As such, the set of categories used here represents an extension of the two Types used by Aitchison *et al.*

The value used by Aitchison *et al* for the extraction efficiency of a Type I site is 70%, together with a reduction in emissions of 40% due to oxidation. Hence the net emission implied in their calculation is $(1-0.7)*(1-0.4) = 0.18$ or 18% which corresponds to an emission reduction factor (η_r) of 82%. This value corresponds reasonably with the value of 91% calculated in the previous section.

5 BASIS FOR SCALING THE RESULTS OBTAINED IN THIS STUDY

In order to use any of the statistical stratifications identified in Section 3 to calculate the total mass of methane emitted from all UK landfill sites, it is necessary to identify the total mass of waste contained within the particular sites that were measured as a fraction of the total mass of waste in all UK landfill sites.

5.1 The Landfill GIS Database

The Landfill GIS database [8] is the most comprehensive database covering the properties of landfill sites in the UK. At the time when the database was used for this work (November 1996 to January 97) it contained information on 11,290 landfill sites with a calculated mass of waste in place of 1084 Mt. (The calculated mass takes into account the stated mass of waste where it is available, or the equivalent mass of waste in sites that only report data for the volume of waste.) The information recorded varies considerably from site to site according to the extent of information collected from the records of Waste Regulation Authorities. The entries are most often incomplete for older sites which accepted waste before the current waste regulations were introduced.

In order to reduce any bias that gaps in the database might introduce, this study has made use of a subset of the database consisting of 6615 sites for which the information recorded is reasonably complete. These are identified in the database because they are not flagged as having "Limited Data". These sites contain a calculated mass of 909 Mt of waste. All of the values quoted in this section refer to this subset of 6615 sites. The final calculation of methane emitted uses a factor of $1084/909=1.19$ to allow for the sites that have been excluded for this reason.

Although the Landfill GIS will eventually include all available information on landfill sites in England, at the time of this work, its coverage was not complete. The calculation required to correct for this is described in Section 5.3. All of the data presented in this Section refer to the raw data before any corrections have been made

for coverage. Considerable attention was paid to establishing the best combination of database fields to describe the categories of site established from the measurement results. Many different combinations of field were studied on an experimental basis. This report only records the details of the preferred approach.

5.2 Data in the Landfill GIS Database

The data held in the database about the extent of gas control at sites is shown in Tables 10 and 11. Table 10 shows how the date at which sites were closed is related to the response to the database question "Are there landfill gas control systems in place". This illustrates the strong bias of the set of 6615 sites away from sites that were closed before 1980.

Table 10 - Number of Sites with Gas Control Subdivided by Age

Site Age	Gas Control	
	Yes	No
All ages	617 sites 262 Mt	5994 sites 648 Mt
Age	Not Closed	585 sites
	Before 1980	258 Mt
	Closed	607 sites
	Before 1980	31 Mt
Only includes sites with Limited Data=No Does not include 4 sites with no recorded waste mass.		

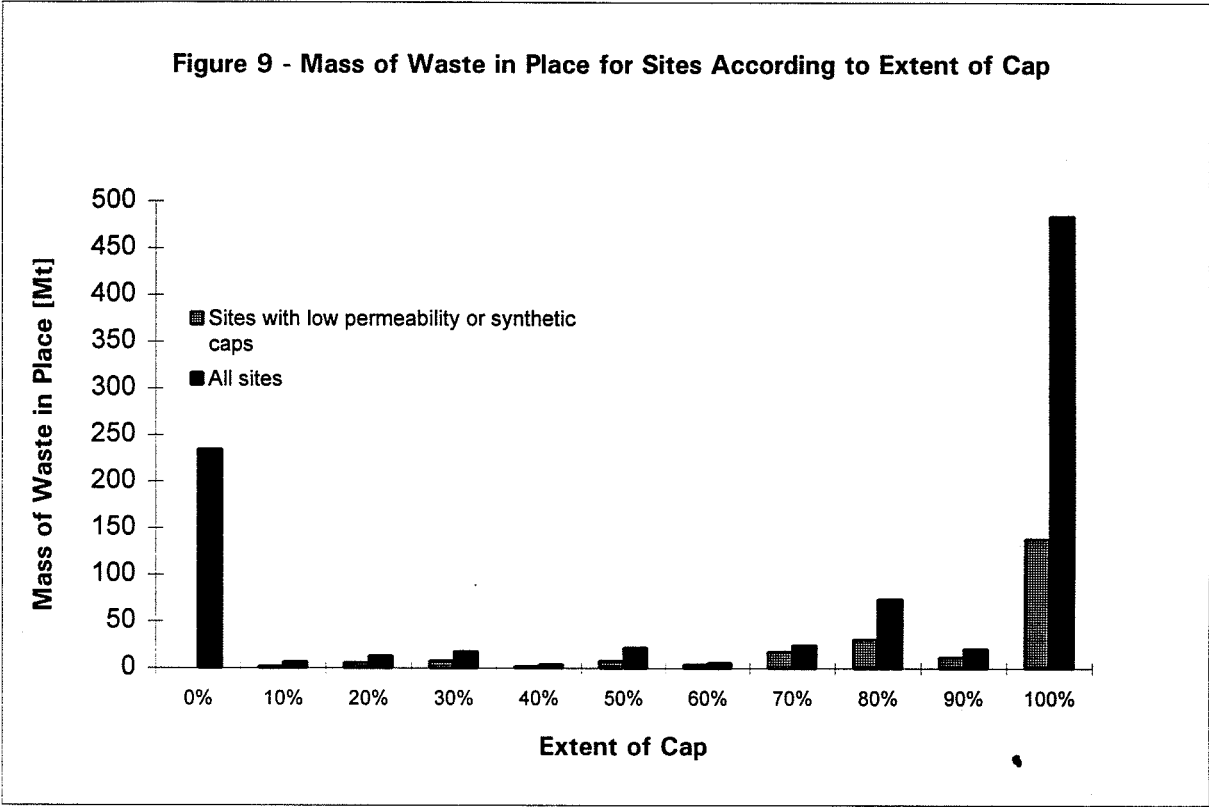
The database field [Gas Control] does not provide specific information about the extent of the system or its effectiveness. This can best be established by combining information about the extent of the cap with the type of cap material used. Table 11 shows the number of sites and calculated mass of waste according to the type of cap used.

Table 11 - Number of Sites with Different Types of Cap

Cap Type	No of Sites and Calculated Waste Mass
Permeable Cap	4626 sites / 531 Mt
Low-Permeability Cap	685 sites / 224 Mt
Synthetic Material	29 sites / 11 Mt
Only includes sites with Limited Data=No Does not include sites with no cap.	

In order to relate the data on cap types to the effectiveness of gas control at these sites, we also require some data on the extent of the cap. Figure 9 shows the

Figure 9 - Mass of Waste in Place for Sites According to Extent of Cap



distribution of sites according to the extent of their cap. This distribution is substantially skewed towards the extremes of 0% and 100% cap. Since the category of sites with "Comprehensive gas control" has been used in this study to include those sites that have the most extensive and effective gas control systems, they have been defined in terms of the database fields:

Sites with Comprehensive Gas Extraction are defined by

[Extent of cap] > 90%
AND [Type of cap] = "Low permeability" OR "Synthetic"

The category of sites with "limited extraction" is then defined to include all sites that are more than 90% covered with a permeable cap, as well as sites that have between 50 and 90% coverage with any type of cap.

Sites with Limited Extraction are defined by

[Extent of cap] > 90%
NOT [Type of cap] = "Permeable"

OR 50% < [Extent of Cap] <= 90%

The definition of sites with "no gas extraction" reflects the observation from the measurements that sites with incomplete caps usually emit substantial quantities of methane around the edge of the cap.

Sites with No Gas Extraction are defined by

[Extent of cap] <= 50%
AND NOT [Closed] <1980

It is apparent from Figure 9 that the skew in the distribution towards the extremes means that these definitions are relatively insensitive to the choices of 50% and 90% cap as "cut off" points between the categories. The results from sub-dividing the database according to the extent of the cap are given in Table 12.

Table 12 - Extent of Cap at Different Sites

Extent of Cap	No of Sites and Calculated Waste Mass
Extent = 0	1589 sites / 235 Mt
0 < Extent <= 50%	191 sites / 63 Mt
50%< Extent <= 90%	237 sites / 126 Mt
90% < Extent	4594 sites / 485 Mt

*Only includes sites with Limited Data=No
Does not include 4 sites with no recorded waste mass.*

The results of applying the definitions to Stratification Number 2 are shown in Table 13.

Table 13 - Number of Sites and Calculated Mass of Waste for Stratification No 2

Site Category	No of Sites and Calculated Waste Mass
No Gas Control	1665 sites / 291 Mt
Limited Gas Control	4271 sites / 472 Mt
Comprehensive Gas Control	560 sites / 139 Mt
Old Sites	
<i>Only includes sites with Limited Data=No Data shown before correction for database coverage</i>	

The category of Old sites is more difficult to deal with since a straightforward use of the database appears to give results that are anomalously small. Only 0.5% of the mass of waste in the database is held in sites that were closed before 1980. This number is likely to be a very substantial underestimate because these sites will typically not have complete entries in the database. This issue is discussed further in Section 5.4.

The database also includes some information about the types of waste in each site. This is recorded in terms of a classification into four types: household (and commercial), industrial, inert and special. This classification is shown in Table 14 for each of the categories of site. The data for "Old" sites have not been included, because they are not covered comprehensively in the database.

Table 14 - Fractional Breakdown of Waste by Type for Stratification No 2

	No Gas Control	Limited Gas Control	Comprehensive Gas Control
Household and Commercial	8%	11%	21%
Industrial	24%	28%	32%
Inert	51%	58%	43%
Special	18%	3%	4%
<i>Only includes sites with Limited Data=No</i>			

5.3 Applying Data from the Landfill GIS Database

At the time that the data presented here were extracted from the Landfill GIS, it included information from 37 Waste Regulation Authorities (WRA's) in England. In order to make a correction for the 5 WRA's and the London Boroughs that have not been covered, it has been necessary to make a correction based on the population covered by the corresponding County Councils and Metropolitan Authorities. A

similar correction has been made for the population of Scotland, Wales and Northern Ireland. These corrections have been based on data from the 1991 census. Since there are very few landfill sites within the London Boroughs, their population has been re-distributed to the 5 surrounding WRA's that accept the majority of their waste.

Using this approach, the best estimate is that the information in the database covers a population of 38.5 million (or 69%) of the UK (55.8 million) as a whole. Hence the results described in Section 5.1 must be multiplied by a factor of 1.45 in order to form estimates of UK totals. (As described in Section 5.1, the results must also be multiplied by 1.19 to allow for the use of the subset of sites with [Limited data]=No.)

5.4 Estimating the Amount of Waste in "Old" Landfill Sites

The Landfill GIS does not contain any detailed information about sites that fall within the category defined in this work as "Old", because records of such sites do not in general exist. As the data described above show, only 7 Mt out of a total of 909 Mt is shown as being in sites that closed before 1980. Most of these older sites do not have a recorded starting date.

The reason that the site category old is used in this work is to account for those sites that have waste in them that is still emitting methane many years after it was placed in the site. Since there is no single value for the decay lifetime of waste in a landfill, we use a value of 20 years as a best estimate which is consistent with previous UK work [5].

The approach we have used to estimate the amount of waste in such sites is to sum the best estimate from available data [5] for the waste arising between 14 and 35 years before the date for which the estimate is required. Hence for the 1995 estimate, the mass of waste in Old sites is assumed to be equal to the sum of all waste arisings between 1981 and 1960. The 14-year endpoint was chosen to maintain consistency with the way the GIS data was treated in the previous section and because from the perspective of 1995 data it is close to the point at which the Control of Pollution Act imposed tighter controls over landfill sites. The 35-year start point was chosen to be consistent with typical estimated waste lifetimes of 20 years.

Adding the historic waste arisings estimated by Aitchison *et al* [4] (see section 6.2) over this 14 to 35-year interval yields a value of 2203 Mt for 1995. Since all of these 20-year totals for years ending between 1990 and 2010 values are within 3% of the 1995 value, it is sufficiently accurate for this work to use 2200 Mt in each case.

5.5 Best Estimate of Waste Masses in Place for 1995

The previous sections have described how data from the Landfill GIS has been used to estimate the number of sites and the mass of waste in the four categories defined by Stratification Number 2. In order to allow for the delay in acquiring the data for the Landfill GIS, we describe this estimate as being for the base year for this study which is 1995. The results are summarised in Table 15, showing the "raw" values from the database as well as the values after correction for the coverage and the use of the [Limited data]=No subset.

Table 15 - Calculation of UK Totals from Landfill GIS Database Results

Category	Raw Data from Landfill GIS [Mt]	Estimate for UK [Mt]
None	291	502
Ltd	472	814
Comp	139	240
Old	2200	2200
Total		3756

The raw data have been scaled by 1.45 (to allow for complete coverage of the UK) and 1.19 (to allow for the use of a subset of the database that does not have "limited data").

5.5 Estimating Waste in Place for 1990 to 2010

As described in the previous section, the measurements carried out for this study are assumed to apply to a base year of 1995. The requirements for this study also include an estimate of emissions for the years 1990, 2000, 2005 and 2010.

In order to calculate emissions for these other years, it is necessary to estimate the amount of waste placed in each category of landfill in the past and future. Since there is very little data available related to the fraction of waste that was sent to different types of landfill historically, this work has been based on the assumptions used by Aitchison *et al* [5]. Their work resulted in the profile for past and future waste arisings shown in Figure 10. This shows a decrease in total waste arising since 1996, which Aitchison *et al* expected as a result of the landfill tax. Since the measurements carried out for this work are necessarily representative of emissions from cumulative waste in place, the data in Figure 10 have been used to calculate the cumulative waste sent to landfill over the previous 14 years (Figure 11). This period of 14 years has been chosen in order to maintain consistency with the definition of "old" sites (in 1995) being those closed before 1980 (Section 5.4).

In addition to estimating the total mass of waste arising, Aitchison *et al* also took account of the best data sources for total historic waste arisings to estimate the fraction of this waste that was placed in "controlled" and "uncontrolled" sites. The definition used for controlled (or Type I) sites is given in Section 4.3. In order to apply the results of Aitchison *et al* to this study we have assumed that the trends shown by these "controlled" sites are the same as those shown by the "Comprehensive" site category used in this work. Similarly, the site category "None" has been scaled to follow the trend in the Type II sites. Since there was no "Limited" category used by Aitchison *et al*, it has been scaled in order to retain the correct trend for the total waste. This approach of using trends from previous work rather than the absolute values enables this work to retain consistency without having to use exactly the same definitions.

Figure 10 - Historic Waste Arising
(based on Aitchison *et al*)

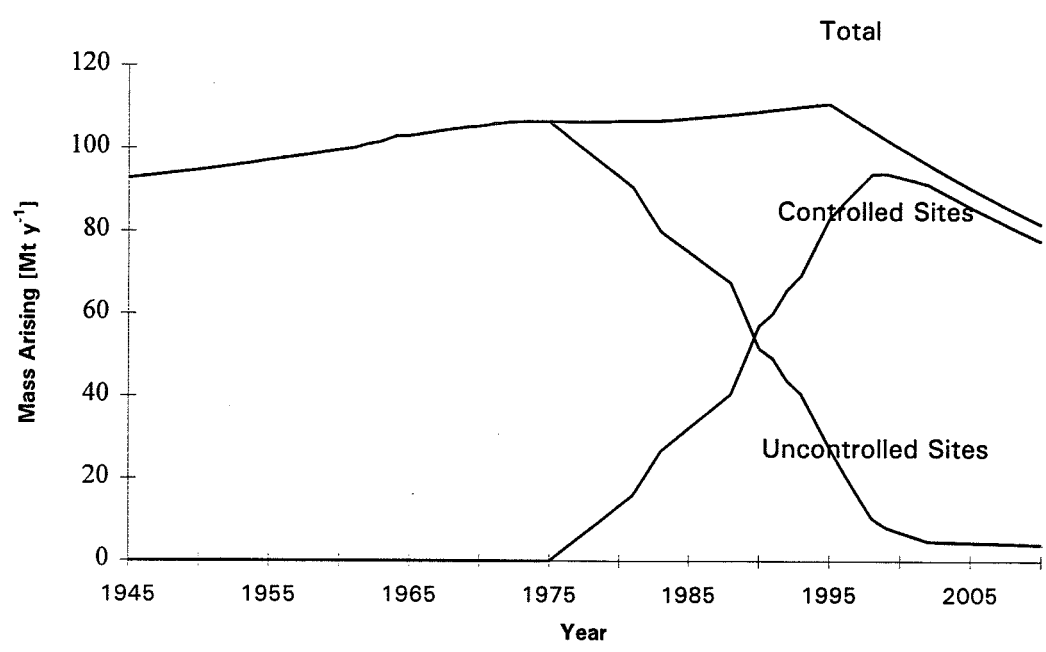


Figure 11 - Cumulative Waste to Landfill over Previous 14 Years

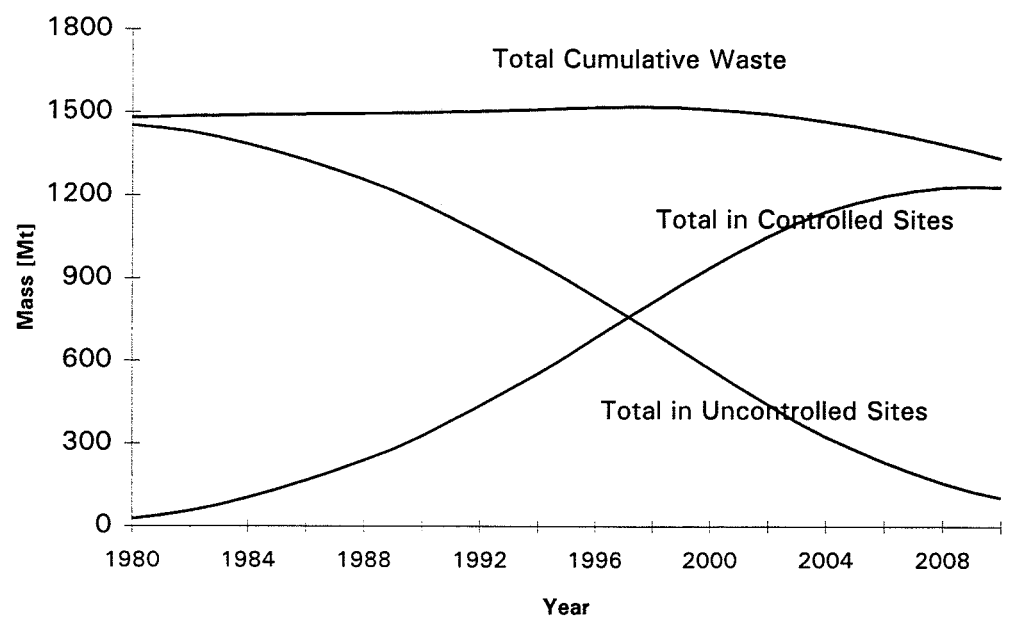


**Table 16 - Trends in Historic and Future Waste
in UK Landfills (Normalised to 1995)**

Site Category	Rationale	1990	1995	2000	2005	2010
A None	Follows Type II sites in [5]	1.3	1	0.63	0.31	0.12
B Ltd	Calculated to maintain correct total	0.93	1	1.07	1.08	1.02
C Comp	Follows Type I sites in [5]	0.53	1	1.55	1.91	2.00
D Old	see Section 5.4	1	1	1	1	1
Total	Follows Total in [5]	0.99	1	0.99	0.96	0.88

These scaling factors have been used in combination with the estimate for the base year (1995 shown in Table 15) to produce the data in Figure 12.

6 CALCULATING TOTAL EMISSIONS

6.1 Calculation of Emissions in the Base Year (1995)

Landfill methane emissions in the base year (1995) can be calculated by multiplying the measured average emissions for each category of site by the best estimate of the mass of waste in place in that category. This is done in Table 17.

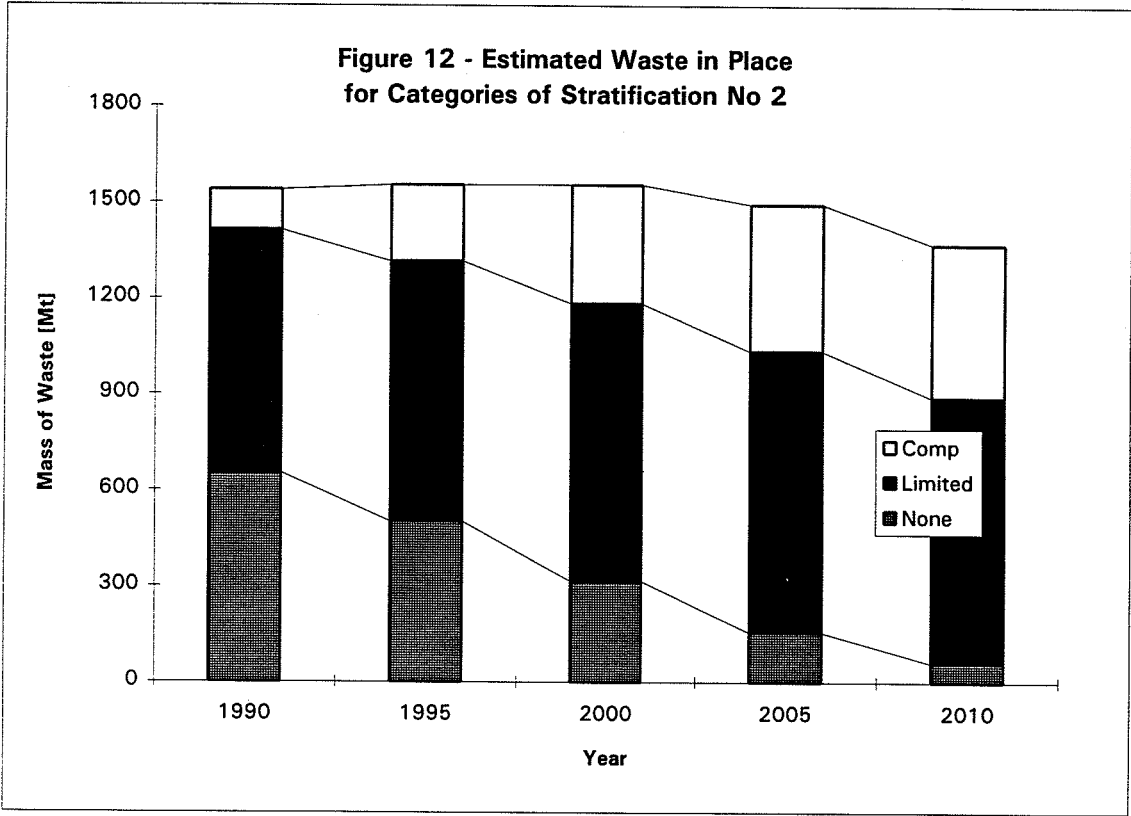
**Table 17 - Calculation of Methane Emissions for 1995
Based on Stratification Number 2**

Category	Specific Methane Emission [kg(CH ₄)/t(MSW)/y]	Total Mass in UK [Mt]	Methane Emitted kt(CH ₄)/y
A (None)	1.14	502	570
B (Ltd)	0.23	814	185
C (Comp)	0.09	240	21
D (Old)	0.05	2200	111
Total		3756	887

The distribution of total MSW between the four categories
is based on results from the Landfill GIS database.

This Table represents an estimate of emissions for the base year of this study. Taking into account the extent to which all of the data used is at least 1 or 2 years old, we label this "present" estimate as being most representative of emissions in 1995. A calculation of the uncertainty in this result is described in Section 7.

Figure 12 - Estimated Waste in Place
for Categories of Stratification No 2



6.2 Calculation of Emissions for Past and Future Years

The estimate of emissions for past and future years is based on the estimated waste masses shown in Table 16. For this calculation, we assume that the specific methane emission values derived from the measurements do not change. The results are shown in Figure 13 and are listed below:

Year	1990	1995	2000	2005	2010
Methane Emission [kty ⁻¹]	1039	887	699	507	349

6.3 Updating this Work in Future Years

In the future, it will be necessary to update the calculation of UK methane emission from landfill using the methodology developed in this study. This can be done as follows:

- the data for waste in place in each category should be updated in Table 15,
- the historic and future trends in waste should be updated in Table 16,

Both of these will involve taking account of the latest trends in waste management and their impact on the quantity of waste sent to landfill and the balance of it sent to the different categories. Following the incorporation of this updated data:

- Table 17 should be re-calculated using the updated data from Table 15,
- an updated time series should be calculated (following Section 6.2) using the updated data from Table 16.

Some consideration could be given to updating the average emission rates per unit volume of waste in each category. However, this would only be justifiable if it was based on a more extensive series of direct measurements than were carried out here.

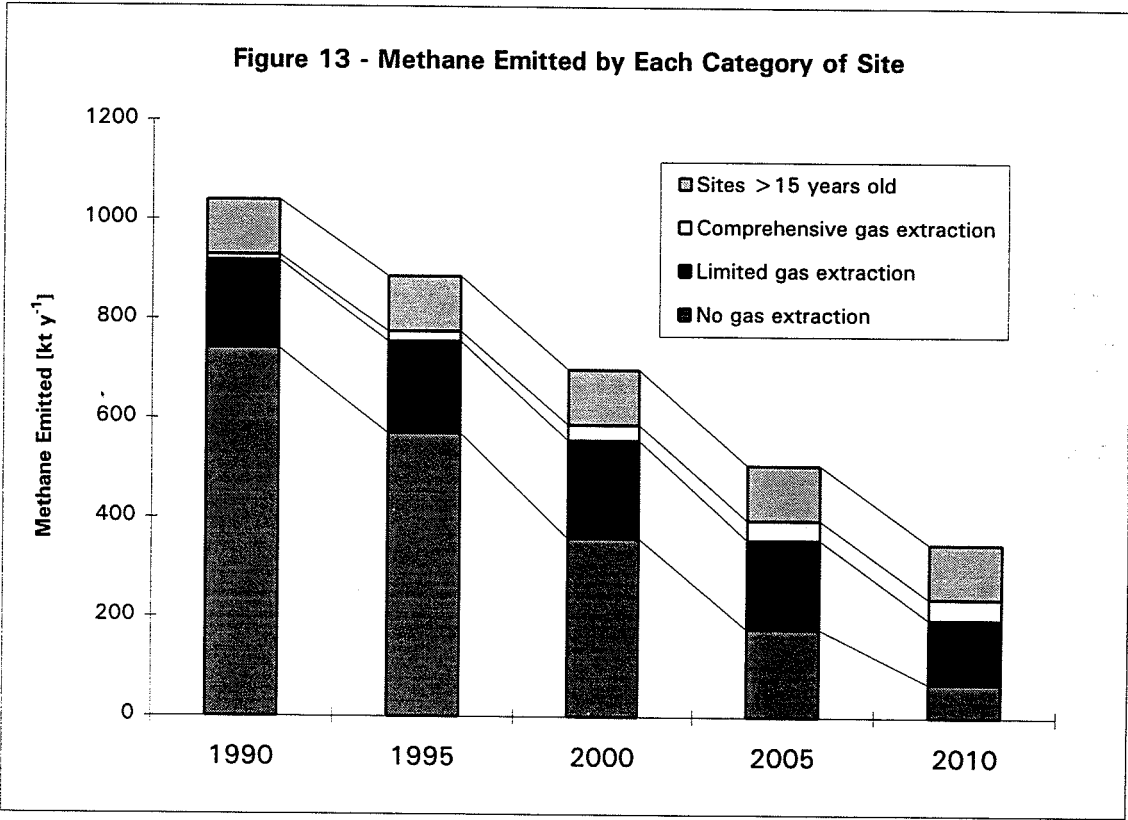
7 ESTIMATING THE UNCERTAINTY

7.1 Estimating Uncertainty

Previous calculations of methane emissions from UK landfills have included an estimate of the uncertainty in the final calculated result [4,5].

An examination of the spread of values for emissions established for each of the site categories indicates that the variability of the population measured is substantially greater than the uncertainty associated with the measurements themselves (which is typically in the range 20% to 30%).

Figure 13 - Methane Emitted by Each Category of Site



7.2 "Risk Analysis" Calculation

The most transparent way to apply a risk analysis type calculation to this work is by applying it to the results presented in Tables 4 and 15. The calculation works by replacing each of the values in these tables with an estimate of the probability distribution for these values. These distributions represent the uncertainty associated with each part of the calculation and are shown in Table 18.

Table 18 - Probability Distributions Used for Estimating the Uncertainty in the Final Result

Site Category	Specific Methane Emission [mg(CH ₄)/kg(MSW)]	Total Mass in UK [Mt]
None	N(0.045,0.003)	T(266,291,316)
Ltd	N(0.009,0.005)	T(382,407,432)
Comp	N(0.0034,0.002)	T(179,204,229)
Old	N(0.0020,0.0011)	U(1800,2600)

N(x,σ) is a normal distribution with mean x and standard deviation σ

T(a,x,b) is a triangular distribution with minimum a maximum b and most probable value x

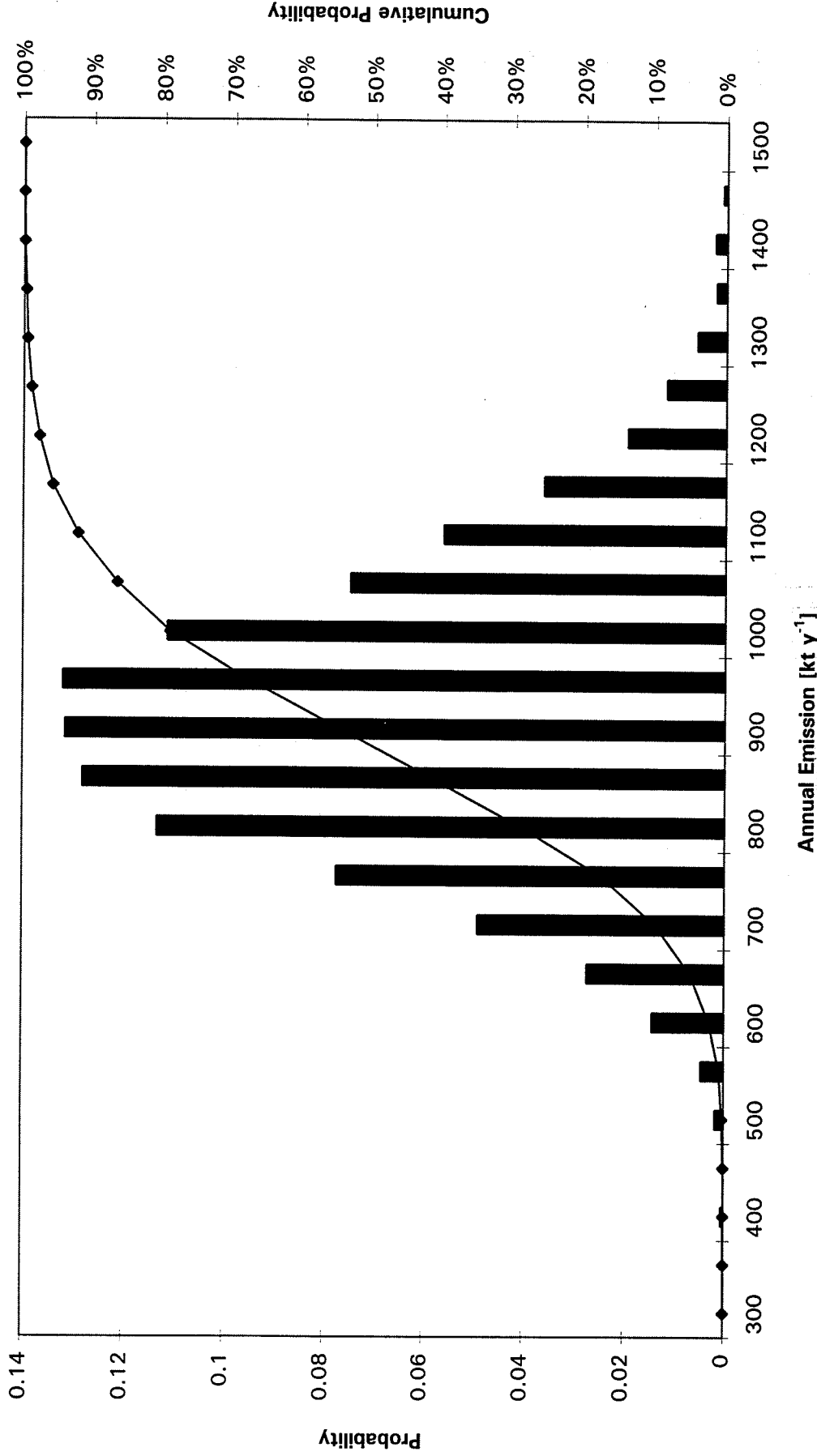
U(a,b) is a uniform distribution with minimum a and maximum b.

In addition to the distributions shown in Table 18, the factor used to multiply the data from the landfill GIS to give the UK totals has an estimated distribution of N(1.5,0.1), the "limited data" factor has a distribution of N(1.19,0.1) and the database factor of N(1.45,0.05). The average density of landfilled waste has an estimated distribution of N(0.8,0.03).

These parameters result in the estimated distribution for 1995 emissions shown in Figure 14. The distrubution has a mean of 887 kty⁻¹, and a 90% confidence interval spanning the range 652 kty⁻¹ to 1135 kty⁻¹. The largest single contribution to this overall uncertainty is from the average enission rate of sites with limited gas extraction.

The estimate of emissions in 2010 is more uncertain than the 1995 estimate because of the difficulty in estimating future emissions. We have accounted for this by use of a factor allowing for each of the time factors to be uncertain according to a normal distribution with a standard deviation of 20%. This results in an estimated distribution with a mean of 298 kty⁻¹ and a 90% confidence interval from 349 kty⁻¹ to 402 kty⁻¹.

Figure 14 - Probability Distribution of Estimated Emissions for 1995



8 SUMMARY AND CONCLUSIONS

8.1 Summary

The amount of methane emitted to the atmosphere by UK landfill sites has been estimated. This estimate is based on direct measurements of methane emissions fluxes carried at a representative set of sites. The measurement results have been analysed statistically to establish four categories of landfill sites. The measured sites have been placed in these categories according to specific characteristics (such as the presence of a comprehensive gas extraction system with a low permeability cap). The mean and standard deviation for the average methane emission per unit volume of waste from each category has been calculated.

Data about the population of UK landfills obtained from the Landfill GIS database has been used to estimate the mass of waste in each category of landfill. Additionally, the uncertainty in this estimate has been calculated. The estimate for the base year (1995) has been extended by the use of historic waste arisings to give an estimate for 1990. Projections based on established trends and known policy changes have been used to estimate future emissions through to 2010.

The best estimate of emissions in 1995 is 887 kty^{-1} , with a 90% confidence interval between 652 kty^{-1} and 1135 kty^{-1} . The largest single contribution to the overall uncertainty is from the average emission rate of sites with limited gas extraction.

8.2 Comparison with Previous Work

Previous estimates of emissions of methane from UK landfill sites include the work of Bellingham *et al* [4] that estimated emissions in 1994 to be 1.9 Mty^{-1} (with upper and lower bounds of 4.2 and 0.6 Mty^{-1}). Subsequently, the work of Aitchison *et al* [5] extended this work by using an exponential model to allow for the time decay of methane emissions. This resulted in an estimate for methane emissions from landfill in 1994 of 1.8 Mty^{-1} with an estimated 90% confidence interval between 1.1 Mty^{-1} and 2.2 Mty^{-1} .

The 90% confidence interval for methane emissions from landfill in 1995 derived from this work lies at the lower end of the range estimated by Aitchison *et al* [5]. This is principally because their work under-estimated the extent of emissions reductions as a result of the increase in "comprehensively extracted" sites.

8.3 Conclusions

8.3.1 Measurement Results

The set of measurements carried out for this work enables a number of observations about landfills to be made:

- measured emissions from uncontrolled sites with no gas extraction system are consistent with estimated values of the specific methane potential of UK waste.

- measurements of total emissions of methane from a landfill do not usually relate closely to surface emission rates (for instance, as measured with a flux enclosure).
- the most significant factor influencing methane emissions is the presence of an extraction system, together with a low permeability cap.
- methane emission through a good quality low permeability cap is sufficiently small that it can be ignored by comparison with other "leakage" sources.
- the relationship between methane emissions and depth of waste in place is sufficiently strong that we have been able to divide the measured surface emission rate (in $\text{mg m}^{-2} \text{s}^{-1}$) by the average depth to give an emission per unit volume of waste (in $\text{mg m}^{-3} \text{s}^{-1}$). It is this parameter that has led to the most satisfactory statistical analysis.
- emissions from a site that has not received waste for more than 15 years are estimated to be approximately a factor of 2 less than a corresponding site that is still receiving waste, but with a comprehensive gas extraction system, (or a factor of approximately 20 less than a site with no gas control measures).
- the spread of emission values from the population of sites measured is significantly larger than the uncertainty associated with the measurement method.

Consequently, we conclude that in order to minimise emissions of methane:

- sites should be fitted with a comprehensive gas extraction system (including a low permeability cap).
- the gas control measures should be fitted as soon as is possible after waste filling is complete.
- measures should be taken to minimise the leakage of gas from pipework and around the edges of sites that have low permeability caps.

8.3.2 Total UK Emissions

This work has resulted in an estimate of total UK emissions of methane from landfill in 1995 of 887 kty^{-1} , with a 90% confidence interval between 652 kty^{-1} and 1135 kty^{-1} . The largest single contribution to this overall uncertainty is from the average emission rate of sites with limited gas extraction. Emissions of methane from landfill in the period 1990 to 2010 have been estimated as:

Year	1990	1995	2000	2005	2010
Methane Emission [kty^{-1}]	1039	887	699	507	349

The estimate of emissions in 2010 is more uncertain than the 1995 estimate because of the difficulty in estimating future waste arisings. The estimated mean is 349 Mty⁻¹ with a 90% confidence interval from 298 Mty⁻¹ to 402 Mty⁻¹.

These estimates are at the lower end of the range estimated in previous studies [5]. This is principally because this work has been based on direct measurements and has therefore taken better account of the influence of comprehensive gas extraction systems (together with low permeability caps) in limiting emissions of methane to atmosphere from landfill sites.

REFERENCES

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- [3] *Greenhouse Gas Inventory Reference Manual*, Intergovernmental Panel on Climate Change, revised version due for publication in 1997.
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- [8] Landfill GIS database, sponsored by the UK Department of the Environment and the Environment Agency and operated by WRC PLC.

Annex A - Landfill Measurement Results

A1 INTRODUCTION

This Annex includes a description of the three techniques used to measure methane fluxes from landfill sites during this project. As the project proceeded, the advantages and disadvantages of each of these techniques became clear and they were each targeted on particular aspects of the measurement problem. In the following sections, the basic feature of the three techniques are described together with a summary of the measurement results.

A1.1 Record of Sites

During the course of this project, measurements were carried out at 28 different site locations. These 28 sites have been subdivided to include each different type of operation as a separate "site" part. For example, Site 14 has two different areas referred to as 14a and 14b. One of these is capped with more than 5 m of clay and has a comprehensive gas extraction system, but the other is only capped with "available material" and has a very limited extraction system. In this case, measurements have been made on each type of operation individually in order to extend the coverage of the field measurements. Where a series of engineered cells or phases of an operation have been filled in the same way they are treated as a single site.

A2 OPTICAL INTEGRATED-PATH MEASUREMENTS

The general principle of optical integrated-path techniques is that the extent of absorption of a beam of light is measured after it has travelled over a path in the atmosphere. The wavelength of the light is chosen so that it is absorbed by the selected target species, but not by any other gas that may be present. This enables the total amount of gas present along the path to be calculated by comparing the amount of light transmitted with the amount of light returned to the receiver. The instrument can be calibrated with a cell containing a known concentration of the target gas. Simultaneous measurements of the wind speed enable an integrated-path measurement to be integrated to give the average flux of gas across the measurement path. If a system of mirrors mounted on masts is used to make these measurements at various different heights, the total flux across a vertical plane downwind of a source can be measured, from which the area emission rate can be calculated.

NPL has developed an optical integrated-path monitor which uses an oscillating filter in order to modulate and analyze the transmitted light beam. Prior to this project it had been applied to the measurements of methane from cattle. In another set of experiments, the application of a related technique was demonstrated to measurements of landfill emissions (Partridge 1986).

A detailed description of the technique is included in Annex E which is a re-print of a conference paper "Minimum Emission rates Detectable from landfill Sites using Optical Integrated-Path Techniques". This paper illustrates how measurements made with this technique can be independent of any type of model and estimates the lowest flux that can be measured.

A2.1 Applications of Optical Integrated-Path Techniques

The advantages of the optical integrated-path technique are:

Measurements represent average values along the measurement path, which include all emissions from the site.

The results are independent of any type of meteorological or emission model.

It can provide measurements of sufficient consistency to quantify the extent of diurnal variations in the total emissions from sites.

The only disadvantages of the optical integrated-path techniques are that it can be complex to use and may not be feasible on sites with poor access or unusual topography.

A3 GAS FLUX SURVEY MEASUREMENTS

The gas flux survey method was developed as a rapid technique for the measurement of total landfill flux, although one that is more model-dependent than the optical integrated-path technique. It is based on the use of a portable gas monitor that is carried along well-defined measurement paths at a specific height above the surface of the site. Some of these paths are chosen to be upwind and downwind of the site, while others traverse the site in order to locate the position and magnitude of particularly high or low emitting regions. The concentration measurements are then combined with simultaneous measurements of wind speed and direction, together with an estimate of atmospheric stability that allows conversion of the concentration data into an area emission rate for the gas.

A3.1 Measurement Method

A portable monitor with a self-contained power and gas supply was used. In order to achieve the required sensitivity and accuracy two modifications were made to the commercial unit:

Zero drift with temperature due to solar radiation was reduced by covering the matt-black body of the instrument with polished aluminium foil.

The remaining drift was monitored by regularly checking the zero and sensitivity of the instrument by applying hydrocarbon-free and known concentration calibration gas standard mixture.

The monitor has a time response of around two seconds and its output signal was sampled at one second intervals and recorded digitally. Each record was automatically time stamped. All results, including zero and sensitivity checks were recorded in this way.

Data was collected by walking with the monitor along carefully selected paths. Specific landmark on the walk were precisely identified by "markers" recorded on an additional channel of the logger. The zero and sensitivity calibrations were performed at the start and end of each walk and the walk was interrupted and additional zero calibrations were made at every landmark. This resulted in a check of the zero level being performed every few minutes.

The aim of the measurements was to determine the atmospheric methane concentrations at upwind and downwind positions. Since the wind direction can change during the measurement period, measurements were made around the whole perimeter of the site and the relevant data selected during processing of the results. Traverses were also made across the site in order to allow the concentration increment with distance to be measured.

A3.2 Example of a Gas Flux Survey Measurement

An example of the results obtained when monitoring at Site 14 appears in Figure A1, A2 and A3.

Figure A1 shows the ground plan of the site with the landmark points marked by capital letters. The wind directions and speeds at specific times during the surveys are also shown as an indication of prevailing conditions.

In Figure A2, the concentrations measured around the perimeter of the site are shown. The upwind concentration occurred along C-D and has little fluctuation, being mainly the global background of 1.8 ppm with few local regions of methane emission. Downwind concentrations were obtained along paths A-B, E-F, F-G and G-A. In Figure A3 the concentrations measured when traversing directly from K to A are shown. The wind direction is close to parallel to the path which leads to a baseline concentration that increases as the walk progresses downwind.

The concentrations in Figures A2 and A3 show considerable fluctuations superimposed on a relatively steady baseline. The baseline concentration is essentially due to emissions from the whole site (plus the global background). In contrast, the fluctuations are largely due to sources close to the gas monitor. However, the flux of the local sources is generally very small as compared with the flux of the site as a whole, despite the high concentrations that they produce locally (unless there is a particularly strong emission due to special local circumstances). Therefore, the baseline concentration is used for the flux calculation. The data derived from Figures 2 and 3 yields an average flux over the whole site of $0.1 \text{ mg.m}^{-2}.\text{s}^{-1}$ in both cases.

A3.3 Applications of Gas Flux Survey Measurements

The advantages of the gas flux survey method are that it:

Measures the total emissions from a site including contributions from all possible sources.

Can cover large site areas quickly and at low cost.

The disadvantages of the gas flux survey method are that it:

May be difficult to apply in unfavourable meteorological conditions.

Requires very good monitor stability and accurate calibration in order to measure small changes in ambient concentrations.

During the course of the project, the gas flux survey method has been developed to become the most cost-effective method of measuring total site emissions.

A4 SURFACE FLUX ENCLOSURE MEASUREMENTS

The flux enclosure or "flux box" method is a technique that can be used under field conditions to determine the flux of a gas through a surface. This is achieved by placing an enclosure of known dimensions over a surface and measuring the rate of change of the concentration of the target gas within the enclosure.

The simplest design of flux enclosure is a closed system in which gases emitted through the enclosed surface accumulate passively. A problem arises with this approach if the monitor used to sample the build up of gas removes a significant quantity of gas during the course of the measurement. A more sophisticated design overcomes this problem by the use of forced ventilation to flush gas through the enclosure and to replace it with pure air. The flux is then calculated from measurements of the concentration of the gas removed from the enclosure.

Although this basic principle is very straightforward, the implementation of the flux box enclosures raises a lot of detailed measurement and calibration issues. These are discussed in Annex D, which includes a brief mathematical description of the build up of gas within a flux enclosure.

A4.1 Applications of Flux Enclosure Measurements

The advantages of the flux box method are:

Measurements can be made of the emission of a small well-defined surface with minimal interference from other sources.

Low flux values can be measured.

The disadvantages are:

Flux box measurements are only valid if they are carried out with an accurately calibrated and zeroed monitor. This is particularly important when low flux values are being measured or when ambient concentrations of methane are elevated above the expected background level.

Since emission rates vary significantly over the surface of a site, flux box measurements must be made sufficiently frequently to encompass the full variation of the measurement set in order to provide a valid average.

Methane emission through the surface of a landfill, as measured with a flux box, may only be a small fraction of total emissions from all of the possible sources on site. Hence, flux box measurements may not be representative of total site emissions.

A4.2 Role of Flux Enclosure Measurements in the Project

The flux enclosure measurements carried out as part of this project were planned to answer a number of questions:

How do emissions vary in response to changes in atmospheric pressure?

What is the influence of surface moisture on emissions through the cap?

What fraction of total site emissions are through the cap?

These are specifically addressed in Annex C.

A4.3 Time Series of Flux Enclosure Measurements

The majority of the flux enclosure measurements were carried out at Site 14 in order to provide a consistent set of data relating to the variation in emissions as a result of influences external to the site such as atmospheric pressure and temperature. This involved repeated measurements on four-precisely-defined areas and is described in Annex C.

A5 CONCLUSIONS

Sections A2, A3 and A4 of this Annex outlined the advantages and disadvantages of each of the measurement techniques together with a description of the measurement results achieved with each. In this section, the conclusions that have been drawn from these data are highlighted.

The measurements carried out with the optical integrated-path method lead to the following conclusions:

Methane emission rates from all of a site are reasonably constant over the timescales investigated during this work. This result is based on sets of

measurements carried out at sites 1 and 14.

Average methane emission rates measured with the gas flux survey technique are consistent with those measured using the optical integrated-path technique. (This is based on measurements carried out at Sites 1 and 9). This confirms that the assumptions used in each of the methods are robust and consistent.

The largest single data set acquired for this project used the gas flux survey method. It forms the basis for the comparison of emission between 28 different sites and includes at least 34 different types of landfill management practice. The principal conclusions are:

the major source of emissions in capped sites with gas extraction systems is usually not through the cap;

uncapped flanks and the faces of active (working) areas are often the largest sources.

The results of the time series measured at Site 14 are summarised in Annex C.

Reference

- [1] R.H.Partridge and I.H.Curtis, *Measurements made at New Park Landfill Site, Ugley, Stansted, Essex*, NPL Report Qu S26, 1986

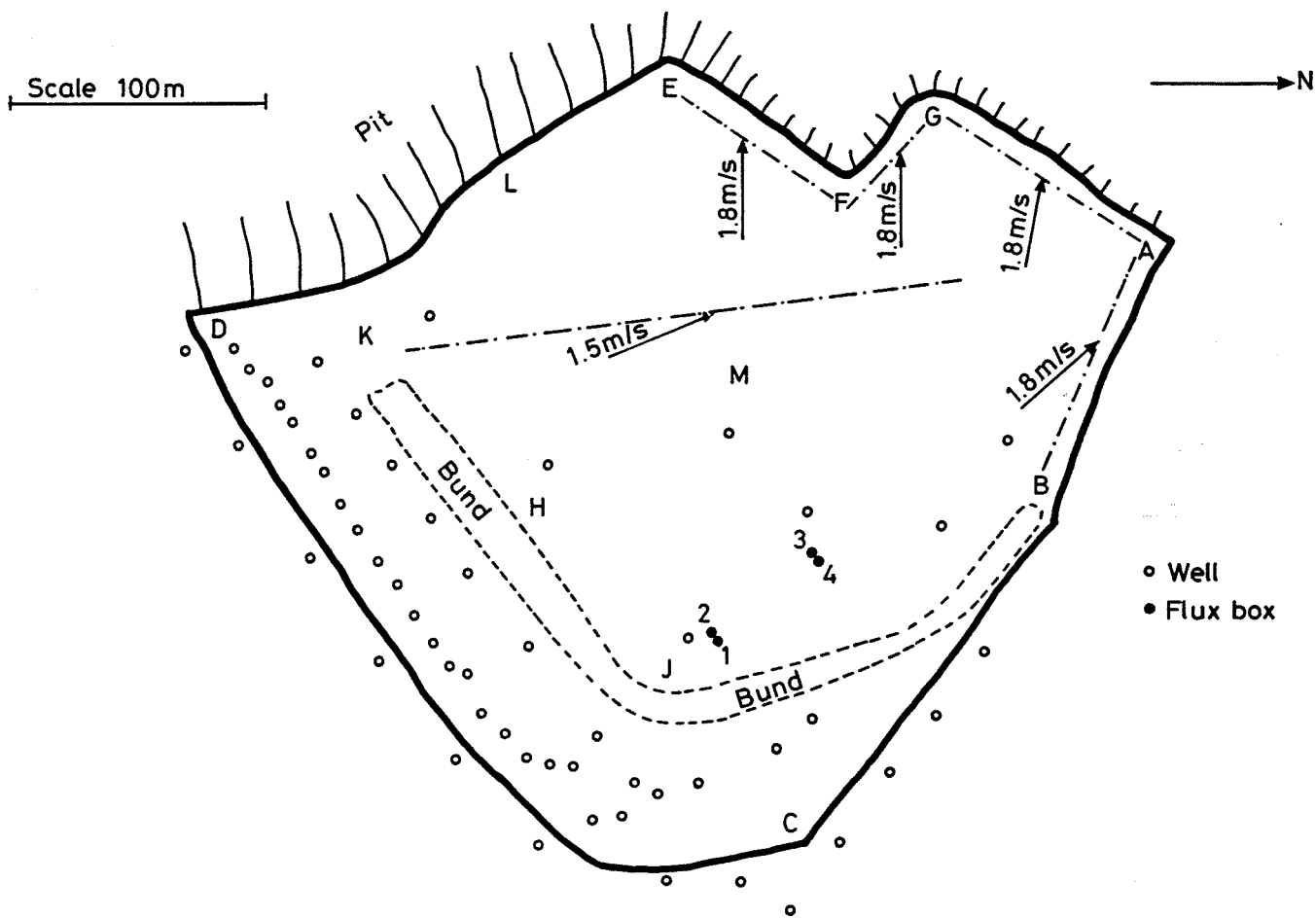


Figure A1 - Location of Measurements

Figure A2 - Gas Survey Record (21.3.96)

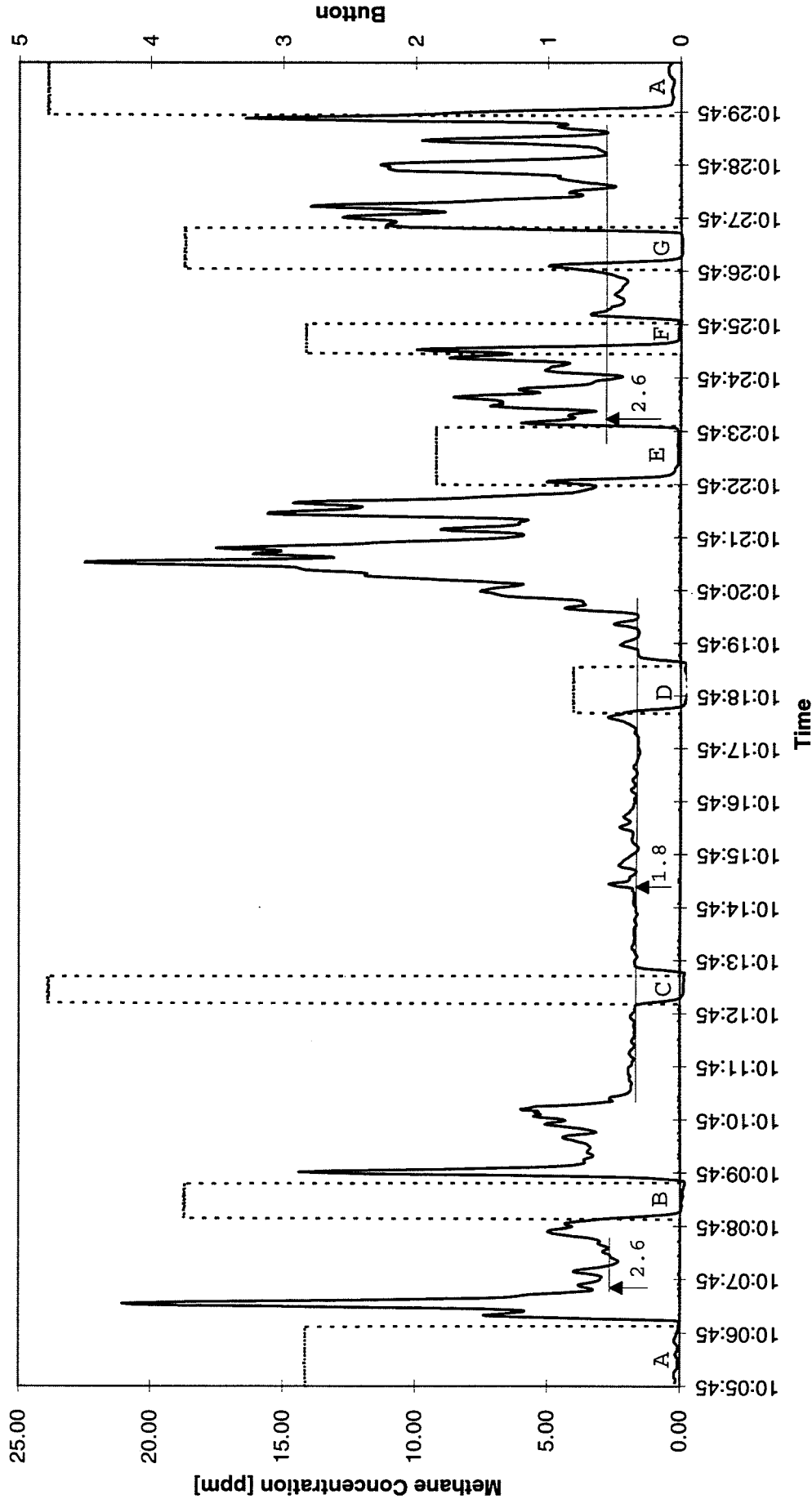
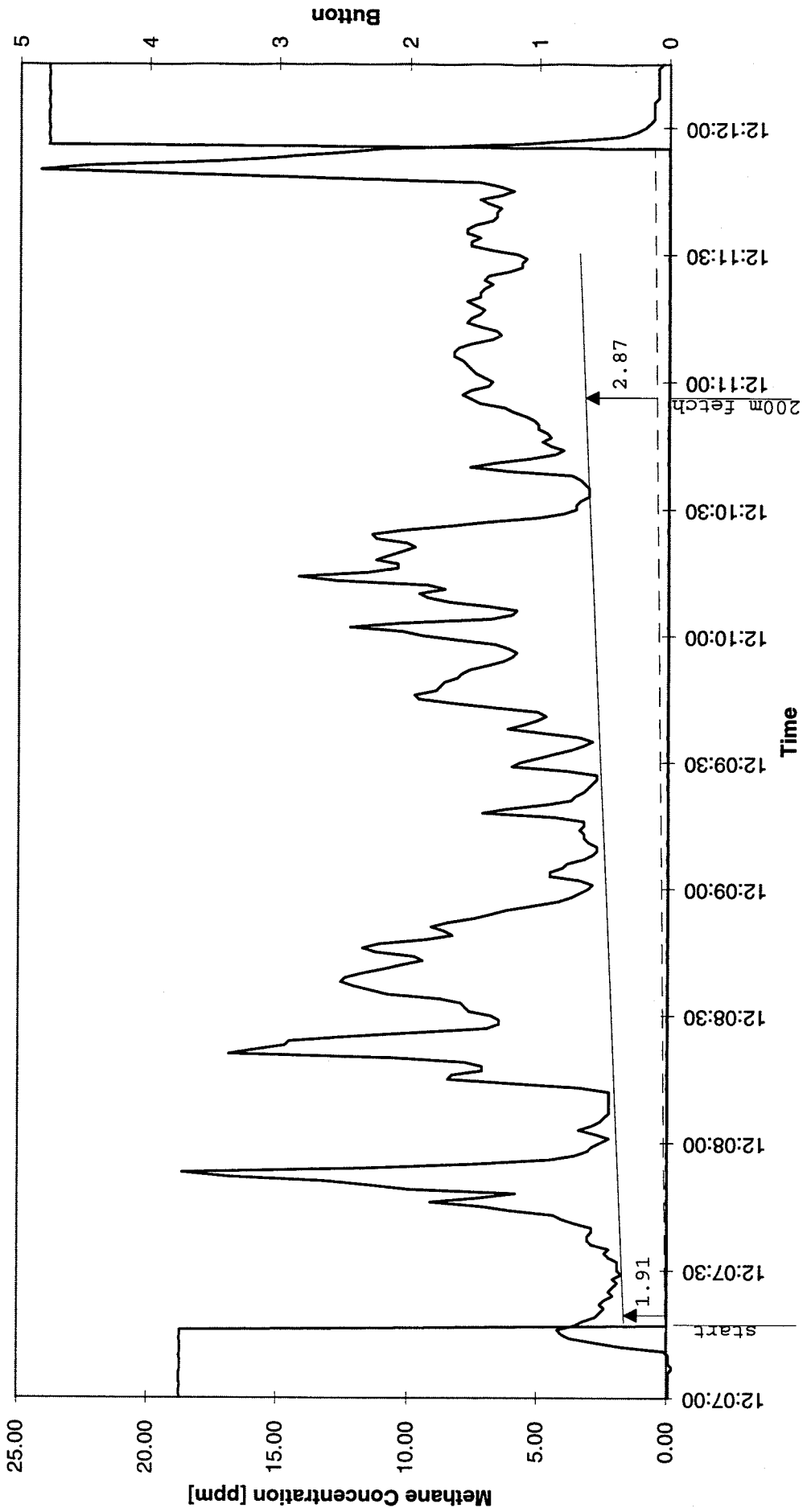


Figure A3 - Gas Survey Record (21.3.96)



Annex B - Landfill Site Measurement Summaries

This annex includes summaries of the measurements carried out for this study. Each sheet summarises basic information about the site which was obtained by the site operator. For each date for which measurements have been made, the part of the site measured, the measurement technique and the weather conditions are recorded. Where measurements were made at a site on several days, each of the measurements (with the appropriate weather information) are recorded.

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	1				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NONE			
	Recovery	PARTIAL			
	Input Rate				
	Moisture	DRY			
MEASUREMENT PERIOD(S)	27 MAR 96				
MEASUREMENT LOCATION	E and W edges and mound.				
WEATHER CONDITIONS	Pressure	1026.2mbar			
	Changes over 3 prior days	-5.9	+1.2	+7.5	
	Temperature	5°C			
	Cloud cover	100 - 20%			
	Wind direction	E			
	Wind speed	5m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	1.1mg.m ⁻² .s ⁻¹			
	Total Site Flux	550g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	1				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NONE			
	Recovery	PARTIAL			
	Input Rate				
	Moisture	DRY			
MEASUREMENT PERIOD(S)	18 APR 96				
MEASUREMENT LOCATION	25% into site from NE edge				
WEATHER CONDITIONS	Pressure	1013.8mbar			
	Changes over 3 prior days	-11.2	-6.4	+6.2	
	Temperature	13 - 15°C			
	Cloud cover	100%			
	Wind direction	SW			
	Wind speed	15m.s ⁻¹			
INSTRUMENTATION	Hawk, FID and portable FID				
RESULTS	Emission Rate	1.1mg.m ⁻² .s ⁻¹			
	Total Site Flux	560g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		2			
SITE LOCATION					
SITE TYPE	Contained				
	Impervious Cap	YES			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)		14 SEP 95			
MEASUREMENT LOCATION		N half, S perimeter and upwind off-site.			
WEATHER CONDITIONS	Pressure	1009.6 mbar			
	Changes over 3 prior days	+4.9	+3.4	-5.1	
	Temperature	19°C			
	Cloud cover	50%			
	Wind direction	S			
	Wind speed	3m.s ⁻¹			
INSTRUMENTATION		FID and portable FID			
RESULTS	Emission Rate	0.06mg.m ⁻² .s ⁻¹			
	Total Site Flux	56g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		2			
SITE LOCATION					
SITE TYPE	Contained				
	Impervious Cap	YES			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)		4 JUNE 96			
MEASUREMENT LOCATION		Centrally along line of wind direction.			
WEATHER CONDITIONS	Pressure	1026.6mbar			
	Changes over 3 prior days	+0.0	+1.8	+5.9	
	Temperature	23°C			
	Cloud cover	0%			
	Wind direction	SW			
	Wind speed	2 - 3m.s ⁻¹			
INSTRUMENTATION		FID			
RESULTS	Emission Rate	0.023mg.m ⁻² .s ⁻¹			
	Total Site Flux	21g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	3				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	NO. ACTIVE AREA			
	Recovery	NO			
	Input Rate				
	Moisture	WET			
MEASUREMENT PERIOD(S)	4 JAN 96				
MEASUREMENT LOCATION	CELL 7. Being actively tipped. Perimeter.				
WEATHER CONDITIONS	Pressure	1003.4mbar			
	Changes over 3 prior days	+15.3	+4.8	-15.4	
	Temperature	7°C			
	Cloud cover	100%			
	Wind direction	SSE			
	Wind speed	6m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	< 0.09mg.m ⁻² .s ⁻¹			
	Total Site Flux	< 1.8g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		5a			
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	YES			
	Recovery	YES			
	Input Rate				
	Moisture	DRY			
MEASUREMENT PERIOD(S)		24 MAY 96			
MEASUREMENT LOCATION		RESTORED AREA			
WEATHER CONDITIONS	Pressure	1007.3mbar			
	Changes over 3 prior days	-0.1	-1.7	-8.8	
	Temperature	12°C			
	Cloud cover	100% RAINING			
	Wind direction	SW			
	Wind speed	5.0m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.061 mg.m ⁻² .s ⁻¹			
	Total Site Flux	5.5 g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	5b				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	NO			
	Recovery	NO			
	Input Rate				
	Moisture	DRY			
MEASUREMENT PERIOD(S)	24 MAY 96				
MEASUREMENT LOCATION	Active area and exposed edge of restored section.				
WEATHER CONDITIONS	Pressure	1007.3mbar			
	Changes over 3 prior days	-0.1	-1.7	-8.8	
	Temperature	12°C			
	Cloud cover	100% Raining			
	Wind direction	SW			
	Wind speed	6.0m.s ⁻¹			
INSTRUMENTATION					
RESULTS	Emission Rate	0.67mg.m ⁻² .s ⁻¹			
	Total Site Flux	50g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		6			
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	SOIL			
	Recovery	PARTIAL			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)		29 MAR 95			
MEASUREMENT LOCATION		Road on south side			
WEATHER CONDITIONS	Pressure	1021.9mbar			
	Changes over 3 prior days	-3.5	-15.9	+23.5	
	Temperature	7°C			
	Cloud cover	50%			
	Wind direction	N			
	Wind speed	4m.s ⁻¹			
INSTRUMENTATION		FID			
RESULTS	Emission Rate	0.03mg.m ⁻² .s ⁻¹			
	Total Site Flux	Surface 3.8g.s ⁻¹ extraction 5.2 g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	6				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	SOIL			
	Recovery	EXTRACTED BUT NOT FLARED			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	26 OCT 95				
MEASUREMENT LOCATION	Perimeters of fields and downwind on housing estate.				
WEATHER CONDITIONS	Pressure	1010.4mbar			
	Changes over 3 prior days	-10.3	+0.9	-5.1	
	Temperature	15°C			
	Cloud cover	100%			
	Wind direction	SSW			
	Wind speed	2m.s ⁻¹			
INSTRUMENTATION	FID and portable FID				
RESULTS	Emission Rate	0.03mg.m ⁻² .s ⁻¹			
	Total Site Flux	surface 3.8g.s ⁻¹ extraction 5.2g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		7			
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NO			
	Recovery	PARTIAL			
	Input Rate				
	Moisture	DRY			
MEASUREMENT PERIOD(S)		3 MAY 95			
MEASUREMENT LOCATION		NW edge.			
WEATHER CONDITIONS	Pressure	1030.8mbar			
	Changes over 3 prior days	-3.6	+8.8	+7.8	
	Temperature	22°C			
	Cloud cover	Sunny, light haze.			
	Wind direction	E			
	Wind speed	3.5m.s ⁻¹			
INSTRUMENTATION		FIDs on mast, Hawk and portable FID.			
RESULTS	Emission Rate	0.1mg.m ⁻² .s ⁻¹			
	Total Site Flux	18g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	8				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	PARTIAL			
	Recovery	PARTIAL			
	Input Rate				
	Moisture	DRY			
MEASUREMENT PERIOD(S)	25 JUL 95				
MEASUREMENT LOCATION	Perimeter and area interfaces.				
WEATHER CONDITIONS	Pressure	1019.1mbar			
	Changes over 3 prior days	+1.8	-0.1	-3.8	
	Temperature	25 - 30°C			
	Cloud cover	0%			
	Wind direction	E			
	Wind speed	5m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	capped 0.2mg.m ⁻² .s ⁻¹ uncapped 0.4mg.m ⁻² .s ⁻¹			
	Total Site Flux	capped 60g.s ⁻¹ uncapped 15g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		9			
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NO			
	Recovery	NFFO 96			
	Input Rate				
	Moisture				
MEASUREMENT PERIOD(S)		27 JUN 95			
MEASUREMENT LOCATION		Mast at SW corner. Beam at plateau edge. Perimeter, beam and extensions.			
WEATHER CONDITIONS	Pressure	1024.9mbar			
	Changes over 3 prior days	+2.4	-0.8	-4.1	
	Temperature	19°C			
	Cloud cover	0%			
	Wind direction	NE to NNE			
	Wind speed	4m.s ⁻¹			
INSTRUMENTATION		FIDs on mast, Hawk and portable FID.			
RESULTS	Emission Rate	1.7mg.m ⁻² .s ⁻¹			
	Total Site Flux	680g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	10				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NO			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	21 JUN 95				
MEASUREMENT LOCATION	Perimeter and area interfaces.				
WEATHER CONDITIONS	Pressure	1027.3mbar			
	Changes over 3 prior days	+5.6	+0.7	+7.8	
	Temperature	29°C			
	Cloud cover	0%			
	Wind direction	N			
	Wind speed	3m.s ⁻¹			
INSTRUMENTATION					
RESULTS	Emission Rate	0.04mg.m ⁻² .s ⁻¹			
	Total Site Flux	11g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	11				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NO			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	21 JUN 95				
MEASUREMENT LOCATION	perimeter, plateau edge and peaks.				
WEATHER CONDITIONS	Pressure	1027.0mbar			
	Changes over 3 prior days	+5.6	+0.7	+7.6	
	Temperature	19°C			
	Cloud cover	Light haze			
	Wind direction	NE			
	Wind speed	3m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	< 0.034mg.m ⁻² .s ⁻¹			
	Total Site Flux	< 25g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	12				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NO			
	Recovery	YES			
	Input Rate				
	Moisture	SURFACE DAMP			
MEASUREMENT PERIOD(S)	9 JUN 95				
MEASUREMENT LOCATION	Perimeter and across wind.				
WEATHER CONDITIONS	Pressure	1019.6 mbar			
	Changes over 3 prior days	-7.2	+1.6	+1.1	
	Temperature	7°C			
	Cloud cover	100%			
	Wind direction	W to SW			
	Wind speed	1.2m.s ⁻¹			
INSTRUMENTATION	FID and portable FID				
RESULTS	Emission Rate	area < 0.008mg.m ⁻² .s ⁻¹			
	Total Site Flux	area < 0.8g.s ⁻¹ line 1.1g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	13				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	CLAY			
	Recovery	FLARE			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	9 JUN 95				
MEASUREMENT LOCATION	Perimeter and diagonals.				
WEATHER CONDITIONS	Pressure	999.2mbar			
	Changes over 3 prior days	-1.5	-11.5	-14.6	
	Temperature	13°C			
	Cloud cover	100%			
	Wind direction	W to SW			
	Wind speed	2m.s ⁻¹			
INSTRUMENTATION	FID and portable FID				
RESULTS	Emission Rate	< 0.007mg.m ⁻² .s ⁻¹			
	Total Site Flux	< 0.7g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	14a				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	YES			
	Recovery	YES			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	27 JUL 95				
MEASUREMENT LOCATION	Perimeter and centre axes of field A-B				
WEATHER CONDITIONS	Pressure	1004mbar			
	Changes over 3 prior days	-2.0	-10.1	+1.7	
	Temperature	24°C			
	Cloud cover	50 - 80%			
	Wind direction	S			
	Wind speed	0.9m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.015mg.m ⁻² .s ⁻¹			
	Total Site Flux	0.3g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	14b				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	THIN SOIL COVER ONLY			
	Recovery	S END ONLY			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	27 JUL 95				
MEASUREMENT LOCATION	Perimeter and centre axes.				
WEATHER CONDITIONS	Pressure	1004mbar			
	Changes over 3 prior days	-2.0	-10.1	+1.7	
	Temperature	24°C			
	Cloud cover	50 - 80%			
	Wind direction	S			
	Wind speed	0.9m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.15mg.m ⁻² .s ⁻¹			
	Total Site Flux	7.0g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	14b				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	THIN SOIL COVER ONLY			
	Recovery	S END ONLY			
	Input Rate	CLOSED			
	Moisture	WET			
MEASUREMENT PERIOD(S)	21 MAR 96				
MEASUREMENT LOCATION	Perimeter, centre axes and diagonals.				
WEATHER CONDITIONS	Pressure	1003.3mbar			
	Changes over 3 prior days	-0.5	-8.5	-5.0	
	Temperature	9°C			
	Cloud cover	100%			
	Wind direction	S to E			
	Wind speed	1.5m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.09mg.m ⁻² .s ⁻¹			
	Total Site Flux	4.2g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	14b				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	THIN SOIL COVER ONLY			
	Recovery	S END ONLY			
	Input Rate	CLOSED			
	Moisture	WET			
MEASUREMENT PERIOD(S)	30 MAY 96				
MEASUREMENT LOCATION	Perimeter, centre axes and diagonals.				
WEATHER CONDITIONS	Pressure	1008mbar			
	Changes over 3 prior days	+11.9	-3.9	-5.1	
	Temperature	20 - 22°C			
	Cloud cover	0%			
	Wind direction	S			
	Wind speed	2.9m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.29mg.m ⁻² .s ⁻¹			
	Total Site Flux	13.2g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	14b				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	THIN SOIL COVER ONLY			
	Recovery	S END ONLY			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	21 MAY 1996 AM & PM				
MEASUREMENT LOCATION	PERIMETER & GRID				
WEATHER CONDITIONS	Pressure	1009.0mbar			
	Changes over 3 prior days	-5.9	+11.9	+3.4	
	Temperature	14 °C			
	Cloud cover	20 to 60%			
	Wind direction	am SWW pm SSW			
	Wind speed	am 3.4 pm 3.3 m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	am 0.104 pm 0.084 mg.m ⁻² .s ⁻¹			
	Total Site Flux	am 4.7 pm 3.5 g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		15			
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	YES			
	Recovery	YES			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)		3 AUG 95			
MEASUREMENT LOCATION		Perimeter and traverses across wind.			
WEATHER CONDITIONS	Pressure	1018.1mbar			
	Changes over 3 prior days	-0.1	+4.1	-0.6	
	Temperature	30°C			
	Cloud cover	10%			
	Wind direction	E			
	Wind speed	4.5m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.13mg.m ⁻² .s ⁻¹			
	Total Site Flux	5.78g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	16				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	YES			
	Recovery	YES			
	Input Rate	YES			
	Moisture				
MEASUREMENT PERIOD(S)	8 AUG 95				
MEASUREMENT LOCATION	Gas extraction area.				
WEATHER CONDITIONS	Pressure	1025.7mbar			
	Changes over 3 prior days	+1.7	+3.4	+1.6	
	Temperature	20 - 26°C			
	Cloud cover	50% then clearing			
	Wind direction	NE			
	Wind speed	3.5m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.3mg.m ⁻² .s ⁻¹			
	Total Site Flux	20g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	17				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	YES			
	Recovery	YES			
	Input Rate				
	Moisture	SURFACE DRY			
MEASUREMENT PERIOD(S)	8 and 9 May 1996				
MEASUREMENT LOCATION	Perimeter, active fill area and test cells.				
WEATHER CONDITIONS	Pressure	8th:1025.5, 9th:1027.0			
	Changes over 3 prior days	-2.5	+3.2	+5.3	
	Temperature	10 - 13°C			
	Cloud cover	20 - 100%, variable.			
	Wind direction	NE			
	Wind speed	5 - 7m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.06mg.m ⁻² .s ⁻¹ whole site average			
	Total Site Flux	whole site average 64g.s ⁻¹ of which active area 47g.s ⁻¹ test cell area 5g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	18				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	YES			
	Recovery	YES			
	Input Rate				
	Moisture				
MEASUREMENT PERIOD(S)	9 AUG 95				
MEASUREMENT LOCATION	Across centre, parallel to wind.				
WEATHER CONDITIONS	Pressure	1025.2mbar			
	Changes over 3 prior days	+1.0	+2.1	+1.9	
	Temperature	25 - 27°C			
	Cloud cover	Sunny, 10% cover.			
	Wind direction	SE			
	Wind speed	1.3m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.1mg.m ⁻² .s ⁻¹			
	Total Site Flux	30g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		19a			
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	VARIABLE EARTH COVER			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)		1 SEP 95			
MEASUREMENT LOCATION		RESTORED SECTION FIELD. ACROSS WIND OVER LENGTH.			
WEATHER CONDITIONS	Pressure	1023.4			
	Changes over 3 prior days	+4.7	+1.1	-3.4	
	Temperature	20°C			
	Cloud cover	5%			
	Wind direction	N			
	Wind speed	3.0m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.33mg.m ⁻² .s ⁻¹			
	Total Site Flux	43g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	19a				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	VARIABLE EARTH AND CLAY			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	16 MAY 96				
MEASUREMENT LOCATION	RESTORED AND NEWLY CAPPED SECTIONS FIELD.				
WEATHER CONDITIONS	Pressure	1015.3mbar			
	Changes over 3 prior days	-3.3	-2.5	-5.4	
	Temperature	9°C			
	Cloud cover	100%			
	Wind direction	NEE			
	Wind speed	7.1m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	RESTORED 0.6 mg.m ⁻² .s ⁻¹ NEW CAP 0.2 mg.m ⁻² .s ⁻¹			
	Total Site Flux	RESTORED 78 g.s ⁻¹ NEW CAP 52 g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	19b				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	YES			
	Recovery	YES			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	16 MAY 96				
MEASUREMENT LOCATION	FIELD				
WEATHER CONDITIONS	Pressure	1015.3mbar			
	Changes over 3 prior days	-3.3	-2.5	-5.4	
	Temperature	9°C			
	Cloud cover	100%			
	Wind direction	NEE			
	Wind speed	7.1m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	< 0.04 mg.m ⁻² .s ⁻¹			
	Total Site Flux	< 0.027g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	19c				
SITE LOCATION					
SITE TYPE	Contained	YES			
	Impervious Cap	YES			
	Recovery	YES			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	16 MAY 96				
MEASUREMENT LOCATION	NORTH				
WEATHER CONDITIONS	Pressure	1015.3mbar			
	Changes over 3 prior days	-3.3	-2.5	-5.4	
	Temperature	9°C			
	Cloud cover	100%			
	Wind direction	NEE			
	Wind speed	7.1m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.018 mg.m ⁻² .s ⁻¹			
	Total Site Flux	4.5 g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	20a				
SITE LOCATION					
SITE TYPE	Contained	SHALE			
	Impervious Cap	SHALE			
	Recovery	YES, but OFF for 48 hours.			
	Input Rate	CLOSED			
	Moisture	WET			
MEASUREMENT PERIOD(S)	16 JAN 96				
MEASUREMENT LOCATION	Perimeter and across field adjacent to farm.				
WEATHER CONDITIONS	Pressure	1026.9			
	Changes over 3 prior days	+8.6	+11.0	+5.3	
	Temperature	7°C			
	Cloud cover	100%			
	Wind direction	N			
	Wind speed	1m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.14mg.m ⁻² .s ⁻¹			
	Total Site Flux	5.3g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	20a				
SITE LOCATION					
SITE TYPE	Contained	SHALE			
	Impervious Cap	SHALE			
	Recovery	YES, and operational.			
	Input Rate	CLOSED			
	Moisture	WET, raining during measurement			
MEASUREMENT PERIOD(S)	11 JUNE 96				
MEASUREMENT LOCATION	Perimeter and across field adjacent to farm.				
WEATHER CONDITIONS	Pressure	1026.9			
	Changes over 3 prior days	+8.6	+11.0	+5.3	
	Temperature	12.5°C			
	Cloud cover	100%			
	Wind direction	S			
	Wind speed	6.0m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	< 0.06mg.m ⁻² .s ⁻¹			
	Total Site Flux	<2.2g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		20b			
SITE LOCATION					
SITE TYPE	Contained	SHALE			
	Impervious Cap	NONE			
	Recovery	YES			
	Input Rate	CLOSED			
	Moisture	WET			
MEASUREMENT PERIOD(S)		16 JAN 96			
MEASUREMENT LOCATION		ACROSS WIND OVER WHOLE FIELD			
WEATHER CONDITIONS	Pressure	1026.9			
	Changes over 3 prior days	+8.6	+11.0	+5.3	
	Temperature	7°C			
	Cloud cover	100%			
	Wind direction	N			
	Wind speed	0.2m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.43mg.m ⁻² .s ⁻¹			
	Total Site Flux	3.2g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	21a				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	PEAT AND GRASS			
	Recovery	YES			
	Input Rate	CLOSED			
	Moisture	WET			
MEASUREMENT PERIOD(S)	18 JAN 96				
MEASUREMENT LOCATION	ACROSS WIND OVER WHOLE FIELD				
WEATHER CONDITIONS	Pressure	1015.1			
	Changes over 3 prior days	+6.5	-6.5	-3.9	
	Temperature	6.5°C			
	Cloud cover	100%			
	Wind direction	S			
	Wind speed	4m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.21mg.m ⁻² .s ⁻¹			
	Total Site Flux	10g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		21b			
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NONE			
	Recovery	YES			
	Input Rate	CLOSED			
	Moisture	WET			
MEASUREMENT PERIOD(S)		18 JAN 96			
MEASUREMENT LOCATION		ACROSS WIND OVER WHOLE FIELD			
WEATHER CONDITIONS	Pressure	1015.1			
	Changes over 3 prior days	+6.5	-6.5	-3.9	
	Temperature	6.5°C			
	Cloud cover	100%			
	Wind direction	S			
	Wind speed	4m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.16mg.m ⁻² .s ⁻¹			
	Total Site Flux	5.9g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	21c				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NONE			
	Recovery	NO			
	Input Rate				
	Moisture	WET			
MEASUREMENT PERIOD(S)	18 JAN 96				
MEASUREMENT LOCATION	DOWNWIND OF ACTIVE AND RECENTLY TIPPED AREA				
WEATHER CONDITIONS	Pressure	1015.1mbar			
	Changes over 3 prior days	+6.5	-6.5	-3.9	
	Temperature	6.5°C			
	Cloud cover	100%			
	Wind direction	S			
	Wind speed	4m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	2.1mg.m ⁻² .s ⁻¹			
	Total Site Flux	340g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		22			
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	CLAY			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)		10 JUNE 96			
MEASUREMENT LOCATION		PERIMETER AND GRID			
WEATHER CONDITIONS	Pressure	1019.3mbar			
	Changes over 3 prior days	+5.0	-0.3	-0.7	
	Temperature	20°C			
	Cloud cover	100%			
	Wind direction	SSW			
	Wind speed	2.5m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.048mg.m ⁻² .s ⁻¹			
	Total Site Flux	5.4g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	23				
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NO			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)	29 MAY 96				
MEASUREMENT LOCATION	PERIMETER AND ACROSS WIND				
WEATHER CONDITIONS	Pressure	1020.4mbar			
	Changes over 3 prior days	+1.1	+12.6	-4.6	
	Temperature	18°C			
	Cloud cover	10%			
	Wind direction	SW			
	Wind speed	2.7			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	< 0.016mg.m ⁻² .s ⁻¹			
	Total Site Flux	< 3.8g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		24a			
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	YES			
	Recovery	NO			
	Input Rate	CLOSED			
	Moisture	DRY			
MEASUREMENT PERIOD(S)		12 JUNE 96			
MEASUREMENT LOCATION		PHASE 1. PERIMETER AND GRID.			
WEATHER CONDITIONS	Pressure	1031.4mbar			
	Changes over 3 prior days	-1.4	-1.6	+16.4	
	Temperature	14.5°C			
	Cloud cover	80%			
	Wind direction	NW			
	Wind speed	m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.2mg.m ⁻² .s ⁻¹			
	Total Site Flux	27g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	24b				
SITE LOCATION					
SITE TYPE	Contained	No			
	Impervious Cap	No			
	Recovery	No			
	Input Rate				
	Moisture	DRY			
MEASUREMENT PERIOD(S)	12 JUNE 96				
MEASUREMENT LOCATION	PHASE 2. PERIMETER AND GRID.				
WEATHER CONDITIONS	Pressure	1031.4mbar			
	Changes over 3 prior days	-1.4	-1.6	+16.4	
	Temperature	14.5°C			
	Cloud cover	50%			
	Wind direction	NW			
	Wind speed	6.0m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	0.8mg.m ⁻² .s ⁻¹			
	Total Site Flux	167g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		24c			
SITE LOCATION					
SITE TYPE	Contained	NO			
	Impervious Cap	NO			
	Recovery	NO			
	Input Rate				
	Moisture	WET			
MEASUREMENT PERIOD(S)		12 JUNE 96			
MEASUREMENT LOCATION		ACTIVE FILL AREA. INCLUDING SEWAGE SLUDGE.			
WEATHER CONDITIONS	Pressure	1031.4mbar			
	Changes over 3 prior days	-1.4	-1.6	+16.4	
	Temperature	14.5°C			
	Cloud cover	50%			
	Wind direction	W			
	Wind speed	6.5m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.98mg.m ⁻² .s ⁻¹			
	Total Site Flux	196g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF	25				
SITE LOCATION					
SITE TYPE	Contained	No			
	Impervious Cap	Clay			
	Recovery	Yes			
	Input Rate	200			
	Moisture	Very Wet			
MEASUREMENT PERIOD(S)	4 July 1996				
MEASUREMENT LOCATION	Perimeter, traverses and upwind				
WEATHER CONDITIONS	Pressure	995.8mbar			
	Changes over 3 prior days	+4.8	-7.5	-2.2	
	Temperature	18°C			
	Cloud cover	80%			
	Wind direction	ESE			
	Wind speed	6 m.s ⁻¹			
INSTRUMENTATION	Portable FID				
RESULTS	Emission Rate	<0.02mg.m ⁻² .s ⁻¹			
	Total Site Flux	<3.6g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		26			
SITE LOCATION					
SITE TYPE	Contained	No			
	Impervious Cap	Some Clay			
	Recovery	Yes			
	Input Rate	150-200			
	Moisture	Wet			
MEASUREMENT PERIOD(S)		3 July 1996			
MEASUREMENT LOCATION		Perimeter and traverses			
WEATHER CONDITIONS	Pressure	998.0mbar			
	Changes over 3 prior days	-7.4	+4.8	-7.5	
	Temperature	14°C			
	Cloud cover	100%			
	Wind direction	S			
	Wind speed	5.3m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.1mg.m ⁻² .s ⁻¹			
	Total Site Flux	5.0g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		27			
SITE LOCATION					
SITE TYPE	Contained	No			
	Impervious Cap	Clay			
	Recovery	Yes			
	Input Rate	100			
	Moisture	Dry			
MEASUREMENT PERIOD(S)		3 July 1996			
MEASUREMENT LOCATION		Perimeter and traverses			
WEATHER CONDITIONS	Pressure	998.0mbar			
	Changes over 3 prior days	-7.4	+4.8	-7.5	
	Temperature	14°C			
	Cloud cover	100%			
	Wind direction	S			
	Wind speed	3.0m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.05mg.m ⁻² .s ⁻¹			
	Total Site Flux	1.0g.s ⁻¹			

LANDFILL SITE MEASUREMENT SUMMARY					Issue 220896
SITE NAME / REF		28			
SITE LOCATION					
SITE TYPE	Contained	No			
	Impervious Cap	No			
	Recovery	None			
	Input Rate	20-30			
	Moisture	Wet			
MEASUREMENT PERIOD(S)		2 July 1996			
MEASUREMENT LOCATION		Perimeter and traverses			
WEATHER CONDITIONS	Pressure	1005.5mbar			
	Changes over 3 prior days	-0.5	-7.4	+4.8	
	Temperature	13°C			
	Cloud cover	Variable			
	Wind direction	E			
	Wind speed	1.5m.s ⁻¹			
INSTRUMENTATION		Portable FID			
RESULTS	Emission Rate	0.024mg.m ⁻² .s ⁻¹			
	Total Site Flux	1.0g.s ⁻¹			

Annex C - Measurements of Spatial and Temporal Variations in Surface Methane Flux from a Landfill Site

ABSTRACT

A series of measurements of the surface flux of methane from a landfill site have been made in order to quantify the extent of spatial and temporal variations in emissions. These variations have been found to be very substantial. No correlation has been observed with atmospheric pressure, temperature or soil moisture. However, the variations in the surface flux at particular points appear to be correlated with variations in total site emissions.

1 SITE DETAILS

The site is divided into four fields covering a total area of approximately six hectares (Figure 1). It was originally used for sand extraction, and was dug down to about one metre above the water table.

Waste was deposited in fields A and B (Figure 1) throughout the 1970's and until their closure in 1980. Fields C and D received waste during the 1980's, and were closed in 1990. The waste was about 50% of household type and 25% of relatively inert industrial type, with the rest undefined. The final depth of the waste was around 30 m, with a maximum of 35 m. The waste was covered daily with local earth during the tipping process, giving a layered configuration of earth and waste. Although the bottom of the site is just above the water table the waste itself is generally damp, due to upwards permeation of water through the waste. The site has no liner of any type.

The portion of the site chosen for the flux box measurements was fields C and D which are the most recently tipped areas. These fields, which have a combined size of approximately 200 m by 200 m, were covered with a layer of local soil (earth mixed with sand) to a depth of about 0.3 m after the cessation of tipping in 1990. This is not intended to be the final cap, since it is still planned to add further waste after ground settlement has ceased.

A gas extraction and flaring system operates on the site, but only eight wells are located on Fields C and D combined and not all of these are operational. The main concentration of wells, about 40, are situated on the south and east edges of Field C (see Figure 2) to prevent gas migration towards the local area of housing. The waste here (to the east of the bund in Figure 2) has a cap of earth mixed with clay about 1 m deep, thus being three times thicker than that of the rest of Field C. The extraction system removes about 1400 m³/h of gas, of which around 25 % is methane. The site operator reported that this flow rate does not vary significantly between seasons or with atmospheric pressure changes.

All of the gas extracted from the site is flared, although a power generation system may be installed at a later date.

2 OBJECTIVES OF FLUX BOX MEASUREMENTS

The objectives of the flux box measurements reported in this Annex were to study:

the time-variation of methane flux from the surface the site, over periods of hours, days and weeks.

the spatial variation of methane emission on the site.

any effects of atmospheric pressure changes on the methane flux.

any effects of precipitation or atmospheric temperature on the methane flux.

the relationship between the small area measurements of the flux boxes and the wide area flux measurements made by traversing the site with a portable monitor.

3. CHOICE OF MEASUREMENT SITE

The site was chosen for this detailed study because:

- i) it contains a considerable depth of waste (around 30 m average)
- ii) methane was not significantly extracted from it over the chosen measurement area (although a gas extraction system was installed it had only eight extraction wells in the field chosen for measurement, and most of these were shut off).
- iii) it has a permeable soil covering, which is expected to emit more uniformly than a site with an impermeable cap that would emit preferentially through cracks or around the edges of the cap.
- iv) a site manager was available at most times, from whom site information and current monitoring data could be obtained.

In the site category scheme adopted in the main body of this report this site is classified as having a "limited extraction" system.

4 MEASUREMENT EQUIPMENT

4.1 NPL Flux Box

The NPL flux box is a cylindrical metal container of 0.33 m diameter and 0.21 m height, with one of its ends open in order to be placed against the ground. To ensure a good seal with the ground a metal cylinder, of the same circumference as the box, was sunk into the ground to a depth of about 0.1 m leaving about 0.05 m protruding

above the ground. A length of soft rubber gasket was fitted to the upper edge of this cylinder, such that a gastight seal was formed between the box and the cylinder. The total internal volume of the flux box and cylinder was approximately 25 litres. Three metal brackets attached to the side of the flux box ensured that the box would always be accurately located on top of the cylinder in the ground. The overall arrangement ensured that exactly the same piece of ground would be examined in all repeated measurements, and that there would be no penetration of the flux box by wind.

The methane concentration inside the flux box was measured with a Gas-tec Mk II instrument incorporating a flame ionisation detector (FID), which was connected to the box by a 1 m length of plastic tubing. The Gas-tec continuously extracted gas from the flux box, via its own pump, for measurement.

In most flux box designs the box is fitted with a bleed pipe, whose purpose is either to release gas from inside the box (if the rate of landfill gas ingress is high) or to allow in-flow of gas from outside (if the methane-measuring instrument is extracting gas at a higher rate than the landfill is supplying it). The measurements reported here showed that the rate of total gas emission (methane plus other gases) from the ground was so low that it could be considered negligible over a typical measurement time of a few minutes (Section 6.1). In order to eliminate any influence due to the extraction of gas from the box by the Gas-tec, the outlet pipe from the Gas-tec was connected back into the flux box. This allowed a continuous circulation of flux box gas, without the need for any bleed to the atmosphere around the box. Possible measurement errors due to pulling in methane-laden local air were therefore eliminated. Tests showed that the flow rate of the gas returned to the box from the Gas-tec was the same as that removed from it, within a few percent, giving negligible gas loss in the flux box enclosure over the few minutes required for a measurement.

The passage of the methane-laden landfill gas through the FID of the Gas-tec may produce some conversion of the methane into other gases, including hydrocarbons. Since this gas mixture is then re-injected into the flux box it was important to establish the level of "cross-interference" caused by it. Therefore a standard mixture of methane in air was injected into the NPL Gas-tec and the output gas was passed into an "AUTOFIM" instrument (similar to the Gas-tec). It was found that the hydrocarbon content of the gas expelled by the Gas-tec was such as to produce a Gas-tec reading of around 85% that of the methane injected into it. The Gas-tec extracts about 0.8 litre/min of gas, or about 2.5 litres over a typical three minute measurement. This is about 10 % of the volume of the flux box. Since about 15 % of the methane entering the Gas-tec is lost before re-injection this represents a methane loss of 1.5 % over three minutes, if there is no gain or loss of methane in the box due to fluxes through the surface being measured. Although the hydrocarbon returned after its passage through the FID was probably not only methane, the fact that it gave a nearly similar response to the original methane drawn into the Gas-tec enabled valid measurements over the measurement times used.

4.2 NETCEN Flux Boxes

The two NETCEN flux boxes were of rectangular configuration, with a volume of about 190 litres and dimensions approximately 0.75 m long by 0.5 m wide by 0.5 m high. The design evolved somewhat during the course of the contract, mainly in order to improve the sealing of the boxes to the ground and to avoid the drawing in of ambient air due to sample extraction by the Gas-tec instrument measuring the

methane concentration inside the boxes.

4.3 Gas-tec Calibration

In order to ensure accurate and consistent measurements by the Gas-tec the zero of the NPL instrument was checked before and after each flux measurement with artificial air (BOC Ltd, BTCA 178) having a hydrocarbon content (analyzed at NPL by gas chromatography) to be less than 0.1 ppm. The Gas-tec was then injected with a calibration gas of methane in artificial air, to define the span sensitivity of the instrument. The concentration of the calibration gas was selected in relation to the required methane concentration range of the instrument. The calibration gases were prepared at NPL at concentrations near to 10, 100 and 1000 ppm by mole fraction, and to an accuracy of 1.0 %. The calibration measurements and all of the flux box measurements were recorded digitally every two seconds.

5 MEASUREMENT STRATEGY

5.1 NPL Measurements

Since a major objective of the flux box measurements was to study time-variations in methane fluxes, a choice was made of four measurement locations on the site which were used throughout the series of measurements. A cylinder was pressed into the ground at each location (Section 4.1) to locate the position accurately and to act as a base for the flux box.

The four measurement locations were arranged in two pairs, with the centres of each pair about 0.5 m apart. The positions were in Field C and were labelled 1, 2, 3 and 4 (see Figure 2). They were chosen in an area where appreciable amounts of methane emission had been observed in previous NPL and NETCEN surveys. The locations were chosen in patches of ground with limited grass cover, to allow ready insertion of the fixed cylinders on which the flux boxes could be positioned (Section 4.1). The close spacing of the members of each pair was chosen partly to enable the flux box to be rapidly moved between each member after each measurement, so minimising the overall measurement time. It was also used to give an indication of the spatial variability of methane emissions on the site, since preliminary measurements had indicated that positions on the ground only one metre apart could still give very different amounts of methane emission.

It should be noted that locations 1 and 2 were within 5 m of an extraction well (see Figure 2). This well has not produced significant amounts of methane and has thus been isolated from the site's methane extraction system by the Site Manager. Locations 3 and 4 were fairly close to another well which is sufficiently productive that its pressure is always high, and thus very little pumping is required to extract the methane.

The methane flux at the chosen locations was measured repetitively by NPL, over time scales of hours, days and weeks. It was also deliberately measured during periods when there were substantial changes in atmospheric pressure. On each occasion when flux box measurements were made a separate measurement was also made of the total emission of methane from the whole field (Fields C and D), using the Gas-tec walkover technique described in Annex A. This was done in order to

provide a direct comparison between the results of the two different techniques.

5.2 NETCEN Measurements

The NETCEN flux box measurements were made initially in four locations in Field C. One of these spanned the location pair 1 and 2 used by NPL (the smaller NPL flux box fitted within the "footprint" of the larger NETCEN box for both 1 and 2) while a second spanned locations 3 and 4. The third and fourth NETCEN locations are marked 5 and 6 on Figure 2. However, these latter two locations showed very little methane emission so subsequent measurements were made only at locations 1, 2 and 3, 4.

6 MEASUREMENT RESULTS

6.1 General

Several general measurement results are of interest:

1. Attempts by NPL to measure gas flow into the flux box from the ground were unsuccessful. A horizontal plastic tube of 3 mm internal diameter was attached to the flux box. A soap bubble was blown in the plastic tube to act as a flow measurement device of very low impedance. Although there were no other gas outlets from the box no movement of the soap bubble could be detected over a period up to one hour. Since a bubble movement of 1 mm could have been readily detected this indicates that the flow rate was less than 7 microlitres per hour out of the box, or less than 80 microlitres/m²/h out of the ground. Despite this very low flow rate the flux box still subsequently indicated a substantial amount of ground emission of methane, with the methane concentration rising to around 1000 ppm in about three minutes soon after the attempt at flow measurement. It seems, therefore, that in this case any gas evolution from this site is dominated by diffusive exchange of gas between the soil and the atmosphere rather than a substantial upwelling of gas from the ground.
2. Flux box measurements that started with appreciable amounts of methane in the box (from local atmosphere trapped in the box at the start of each measurement) occasionally showed a fall in methane concentration rather than a rise with time. This may have been due to direct chemical reaction of the methane with the ground (including biological reaction). However, it is more likely to be a manifestation of the diffusive exchange process suggested above, with a relatively high trapped concentration of methane slowly exchanging with (at that time) methane-poor air in the ground. (This process is described mathematically in Annex D).
3. There was a very marked spatial variation of methane flux over distances along the ground of less than a metre. For instance, flux measurements were routinely made which alternated between locations 1 and 2, with a time between successive measurements of about 15 minutes. Although the centres of those locations were only 0.5 metre apart, the measured methane fluxes sometimes differed by a factor of as much as 10 (see Figure 3).

6.2 Flux Measurements at Fixed Locations as a Function of Time

As a result of the observation of the strong spatial variation of methane flux over very short distances, all of the subsequent flux measurements were made at the precisely-identified locations marked on Figure 2. These measurements were used to quantify the temporal variation of the methane flux over different time scales. Location 4 in fact showed no measurable methane values in any of the NPL studies, despite being only 0.5 m from location 3. Likewise, locations 5 and 6 used by NETCEN showed no emissions, and are thus not included in the data presented here.

6.2.1 Hourly Variations

The short term variation of the methane flux at locations 1 and 2 on three different days is shown in Figures 3, 4 and 5, where each graph shows the individual measurements made during a single day. It can be seen that on some occasions the emission from a location was reasonably steady, with a fluctuation typically about 25% of the mean for the day. However, on other occasions there was a sudden change in flux value, by a factor of up to 10 on occasions. Such changes sometimes occurred during a measurement run, as shown, for example, in Figure 6 where the change in gradient of the concentration within the flux box indicates a change in flux.

It must be concluded that the gas emission from the site is inherently irregular on a short time scale, with substantial changes (both increases and decreases) occurring on a timescale of minutes to hours. This may be due to the extreme heterogeneity of the waste and earth layers in the site, presenting a path of very variable impedance to the migrating gas along which the gas pressure can build up and decay.

6.2.2 Daily to Weekly Variations

6.2.2.1 Flux Measurements by Flux Box and by Site Walk

A series of flux measurements was made daily for a week, together with other measurements over longer timescales. The measurements were made both by site walks with a Gas-tec and with the NPL flux box. A part of the measurement period was chosen to coincide with an atmospheric depression that was expected to pass over the site, in order to identify any correlation between methane flux and atmospheric pressure (see Section 6.2.2.2).

The flux box results, for locations 1, 2 and 3, are presented in Figure 7. The flux values shown are averages of all the measurements made on each day. The total site flux for each measurement day is also shown in Figure 7, as produced by the standard Gas-tec survey method.

The flux box data from the different locations is not identical, but it does show a reasonable degree of correlation. Likewise there is a distinct correlation between the flux box data and that for the overall site flux. For instance, all the data shows low values on 12 July, following higher values on 9 July. The fluxes then increase, somewhat erratically, until about 29 July and then fall off. The sharp minimum in the site flux data on 22 and 23 July is at least partially matched by a shoulder, and some fall, in all of the flux box values at that time.

6.2.2.2 Flux Measurement as a Function of Atmospheric Pressure

The hourly variations of methane flux described in Section 6.2.1 would not be expected to be affected by gross changes in the ambient conditions of the site. However, such variations might occur on daily or weekly timescales, due in particular to changes in atmospheric pressure.

To search for a possible correlation between site flux and pressure the atmospheric pressure at the time of the flux measurements is shown in Figure 7 beside the flux results. The pressure data was obtained from the Meteorological Office, as taken at a station 9 miles from the site.

It can be seen that the flux values in Figure 7 do not correlate well with changes in atmospheric pressure. A fall in pressure might be expected to draw gas out of the landfill, with some finite time lag, and indeed the long fall in pressure from 16 to 23 July does appear to be matched by a marked rise in methane flux from about 18 to 26 July for locations 1 and 2. However, the high flux values on 27 June occurred at a time of relatively high atmospheric pressure. Furthermore, despite a sharp increase in pressure from 23 to 25 July there is no real decrease in methane flux until about 28 July. Likewise the very sharp fall in methane flux between about 29 June and 2 August is difficult to correlate with any atmospheric pressure changes.

It must be concluded that the observed daily variations in methane flux on this site are not primarily caused by changes in atmospheric pressure, although this remains a possible contributing factor.

6.2.3 Weekly to Monthly Variations

The possible correlation of methane flux emissions on a weekly to monthly basis was examined in the NETCEN flux measurements. The fluxes over a period of ten weeks are shown in Figure 8, as compared with the atmospheric pressure variations over a somewhat greater period. Once again no clear correlation with atmospheric pressure is apparent. Despite a substantial fall in average pressure from 1 March to 21 March the first flux measurement showed a low value at both locations used. Likewise, the substantial pressure rise from about 19 May onwards was accompanied by a strong rise of methane emission also, especially at position 2.

6.3 Flux Measurements at Fixed Locations as a Function of Soil Moisture

It is possible that variable amounts of moisture in the top layer of soil on a site could influence the rate of methane emission, by affecting the gas permeability of the soil. The moisture content of the soil at the test areas of the site during the NPL flux measurement period was therefore measured with a simple soil moisture meter. The meter gave an uncalibrated soil moisture output on a scale from 0 (dry) to 10.

The soil moisture readings are shown on Figure 9, which should be compared with the flux measurements of Figure 7. During the NPL flux measurements there was negligible precipitation on the site initially, but some rain occurred on 28/29 July. The moisture readings reflect this, with the soil in locations 1 and 2 having considerable moisture only between 29 July and the end of measurements on 7

August.

Comparison of Figures 7 and 9 shows no clear correlation of methane flux increase, or of flux inhibition, with moisture. Locations 1 and 3 recorded their highest fluxes of the measurement period on the first of the damp days, so clearly no immediate inhibition was occurring, although by 2 August when the soil remained damp the flux was very low. It is doubtful, therefore, that the methane flux is primarily influenced by the moisture of the top layer of site soil, at least on a short term basis.

6.4 Flux Measurements at Fixed Locations as a Function of Air Temperature

It is conceivable that the methane flux could be influenced by the temperature of the ambient air, perhaps through changes in the physical state of the top soil of the site. Figure 10 shows the ambient air temperature for the measurement period of each day, as compared with the flux values. Again no clear trend is apparent. A very hot day on 22 July showed an appreciable increase in methane emission at all locations, as compared with four days earlier. However, the appreciable fall in temperature two days later showed a further flux increase at location 1, with no particular change at locations 2 and 3.

6.5 Daily Flux Measurements by Long-Path Optical Instrument

On sites 1 and 9, flux measurements were made during one day by the long-path optical "Hawk" instrument (Annex A). This had the great advantage of spatially integrating the site flux over a distance of more than 100 m, thus avoiding the strong spatial variation of flux noticed with the flux boxes (Section 6.1).

The Hawk measurements at Site 1 are shown in Figure 11, which indicates a smooth increase and then decrease in emission during the day. The atmospheric pressure during this time did not vary significantly, as also shown on the Figure. The corresponding results for Site 9 in Figure 12 show little significant variation during the day.

6.5 Flux Box Measurement Summary

The flux box measurements reported here cannot be regarded as definitive in terms of correlation with possible local stimuli, since the resources of the project limited the intensive and long-term measurements. However, it may be concluded that the methane emission from the site surface was not significantly correlated with either long or short term variations in:

- Atmospheric pressure
- Top-soil moisture
- Atmospheric temperature

Extrapolation of the data from this site to other landfill sites may not necessarily be warranted. However, the above conclusions make it unnecessary, in our view, to attempt to apply any corrections to the methane fluxes measured on other sites for

variations in season, pressure, temperature or soil moisture. Those results are therefore presented elsewhere in this report as directly measured.

7 CONCLUSIONS FROM FLUX BOX MEASUREMENTS

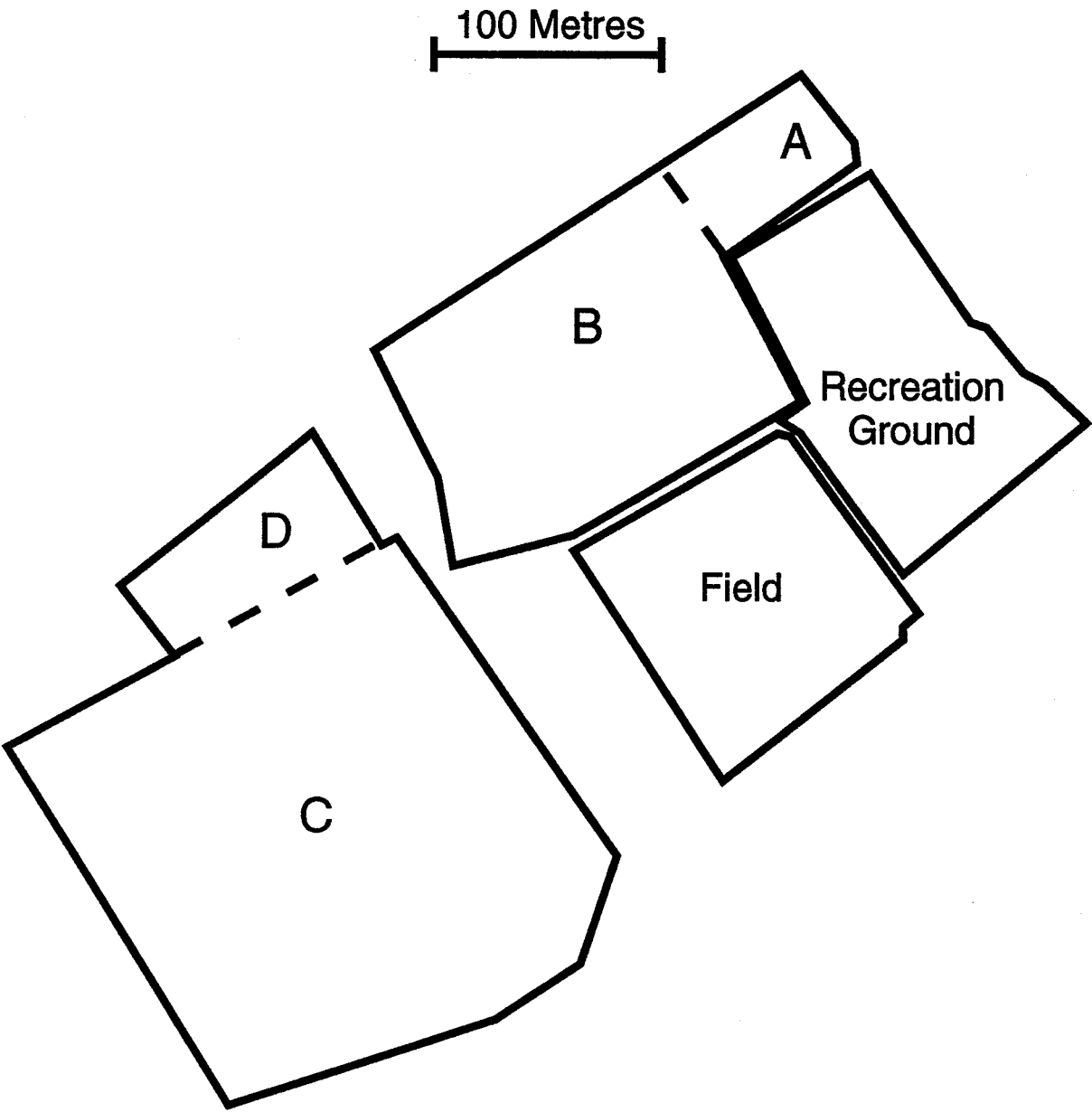
The following were the main conclusions of the flux box measurement programme carried out at a single site in this programme:

7.1 Measurement Technique

- * Good flux box measurements can be obtained with simple apparatus, but it is essential that the flux box is well sealed to the ground.
- * It was found to be very effective to employ a re-circulating gas monitor attached to the flux box, which does not remove significant amounts of gas from the box during flux measurement.
- * Careful and frequent calibration and zeroing of the gas monitor is essential to the production of accurate flux data.

7.2 Measurement Results

- * The rate of flow of gas from the ground into the atmosphere was found to be negligible, at less than $80 \mu\text{l}/\text{m}^2/\text{h}$ for one of the standard measurement positions.
- * Substantial methane emission was observed from the site, despite the very low gas flow rate. This was presumably largely due to a diffusive exchange of gas between the ground and the atmosphere.
- * There was a very marked spatial variation of methane emission, with differences of as much as a factor of ten at positions only 0.5 metres apart.
- * The rate of methane emission at a given site position was sometimes constant but at other times could vary by a factor of up to ten within a few minutes, presumably due to the extreme spatial heterogeneity of the waste in the site.
- * Despite the strong variation of methane flux with ground position, there was considerable correlation between the daily-average variations of methane flux at different positions over a period of weeks.
- * An appreciable correlation was also observed between the methane flux from the entire site and the flux from the various small areas measured by flux box.
- * No strong correlation was observed between methane flux and atmospheric pressure, although this does not rule out a weak association that might be uncovered by more extensive measurements.
- * No correlation could be detected between methane flux and soil moisture content or atmospheric temperature.



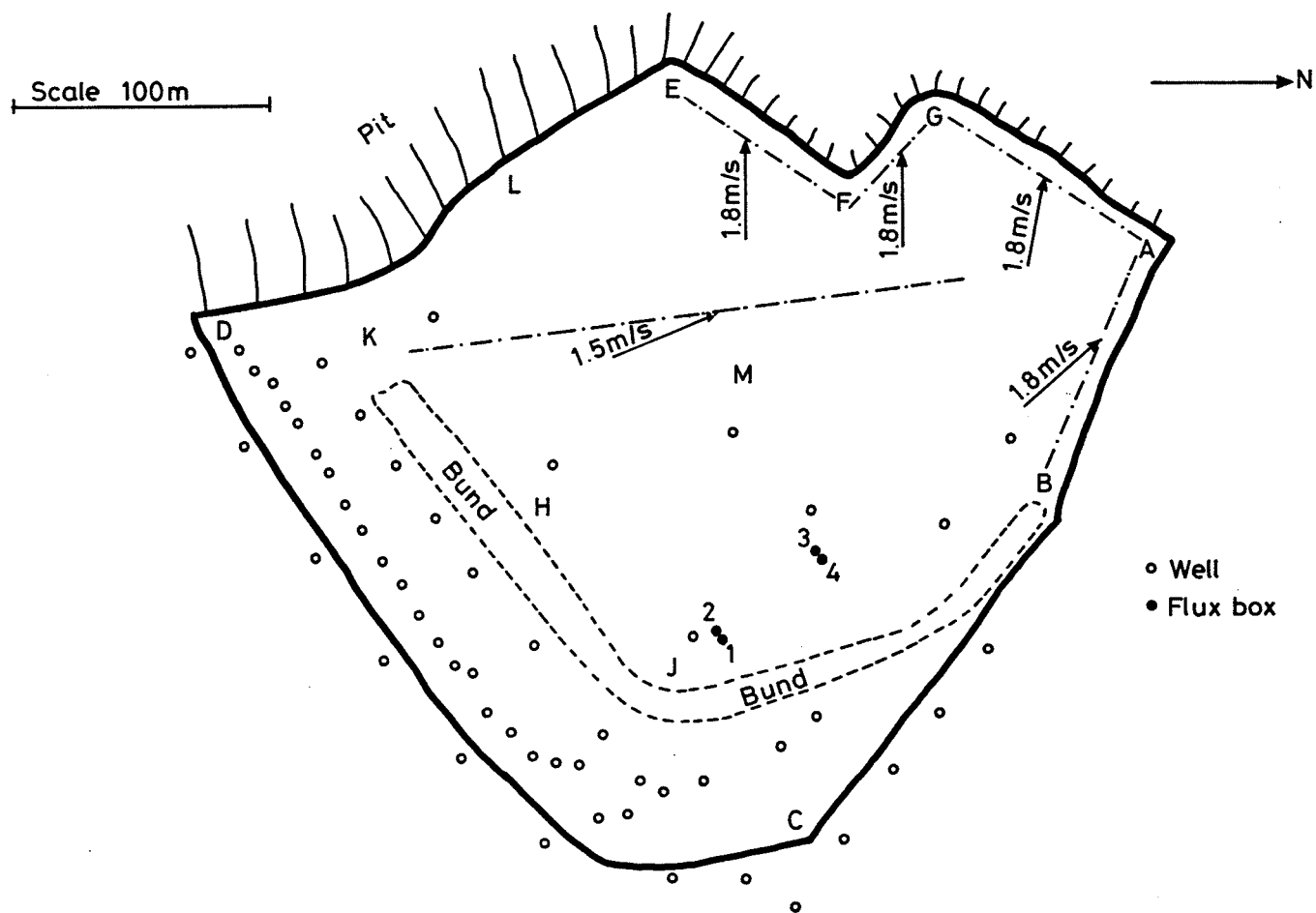


Figure C2 - Location of Measurements

Figure C3 - Flux Box Results 9.7.96

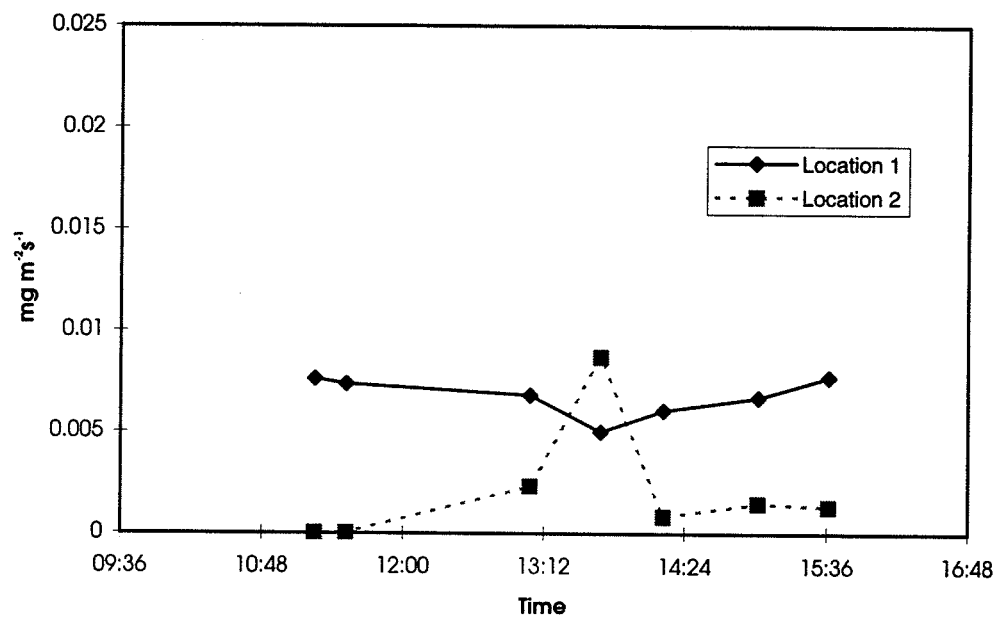


Figure C4 - Flux Box Results 22.7.96

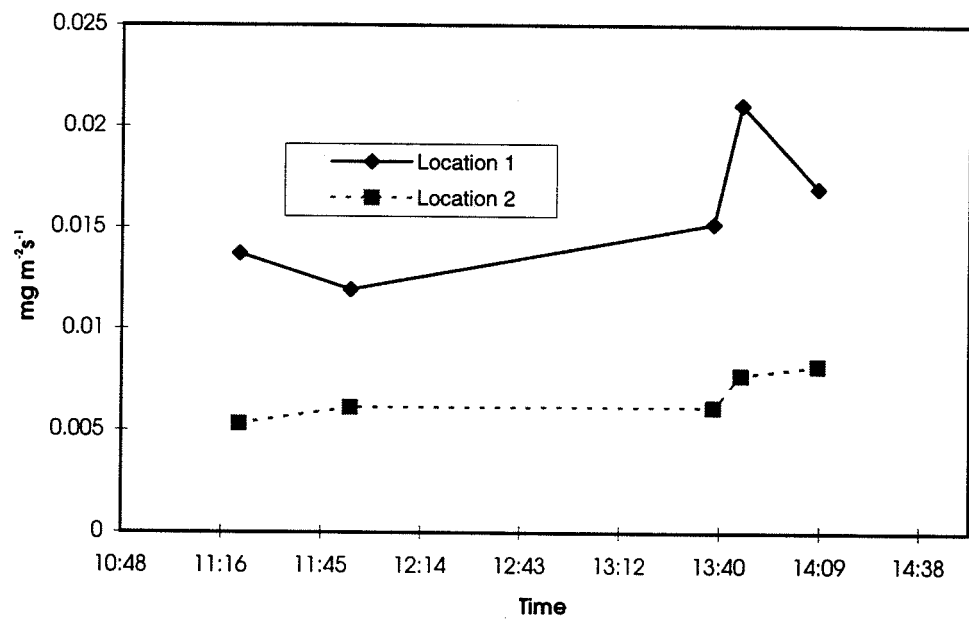


Figure C5 - Flux Box Results 7.8.96

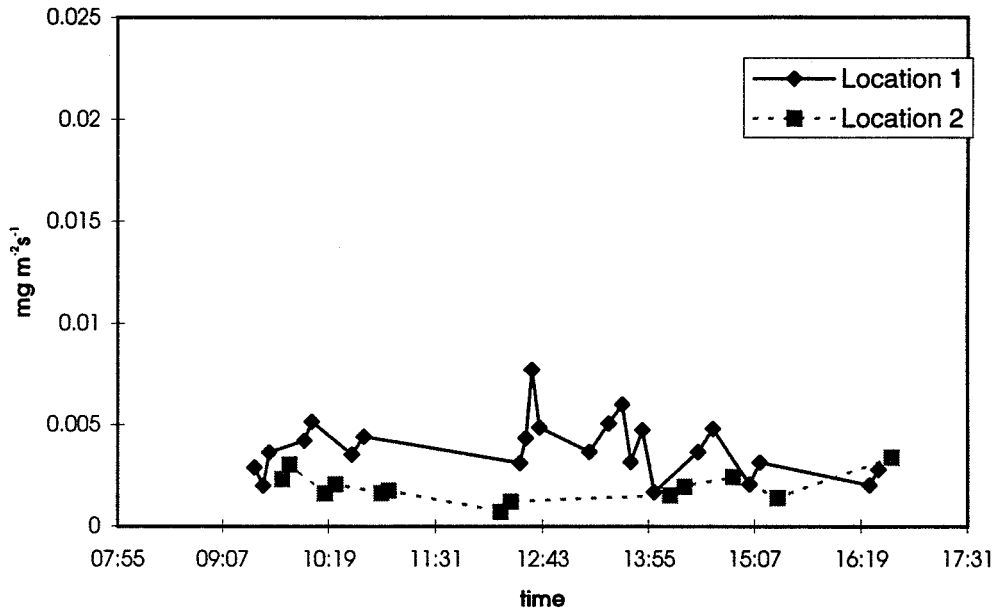


Figure C6 - Flux Box Results

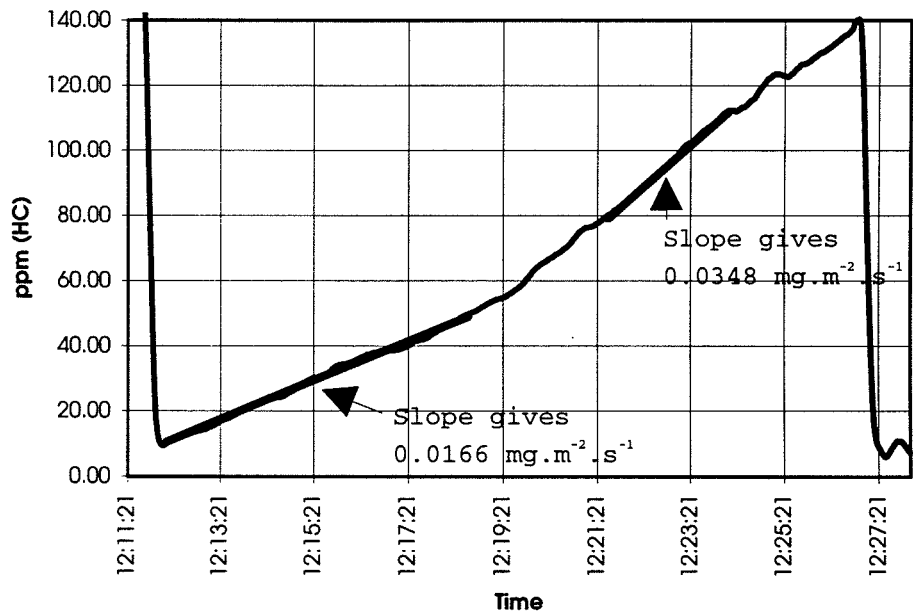


Figure C7 - Landfill Area Survey, Flux Box and Pressure data.

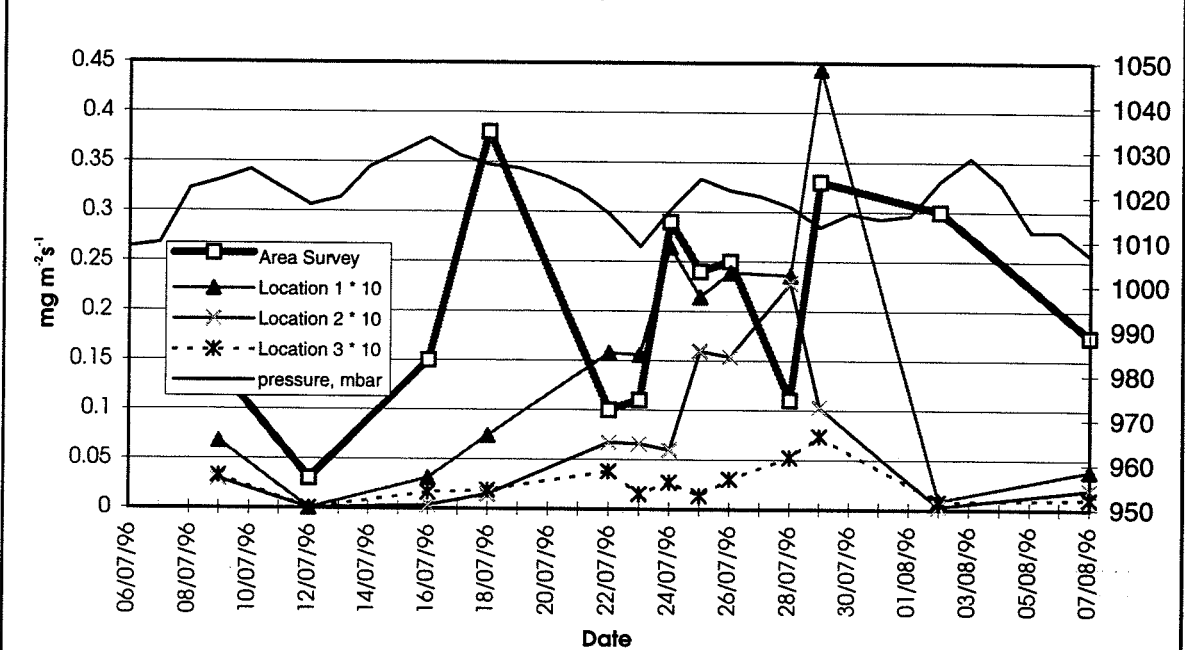


Figure C8 - Landfill Flux Box Results.

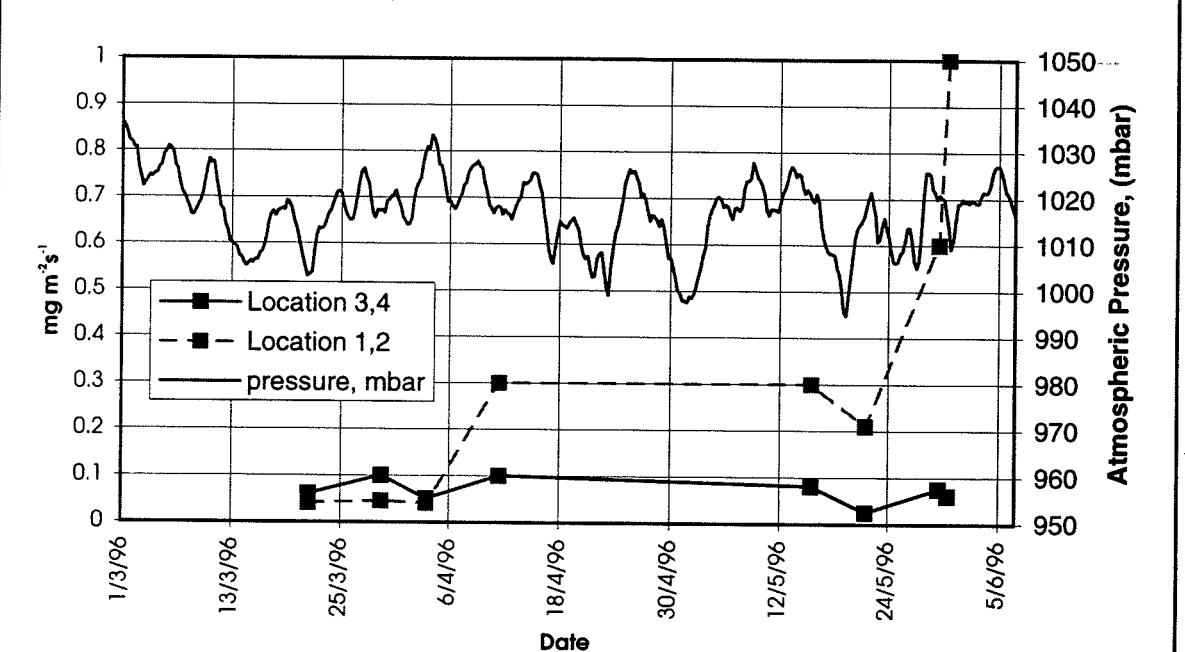


Figure C9 - Landfill Ground Moisture Levels at Flux Box Locations.

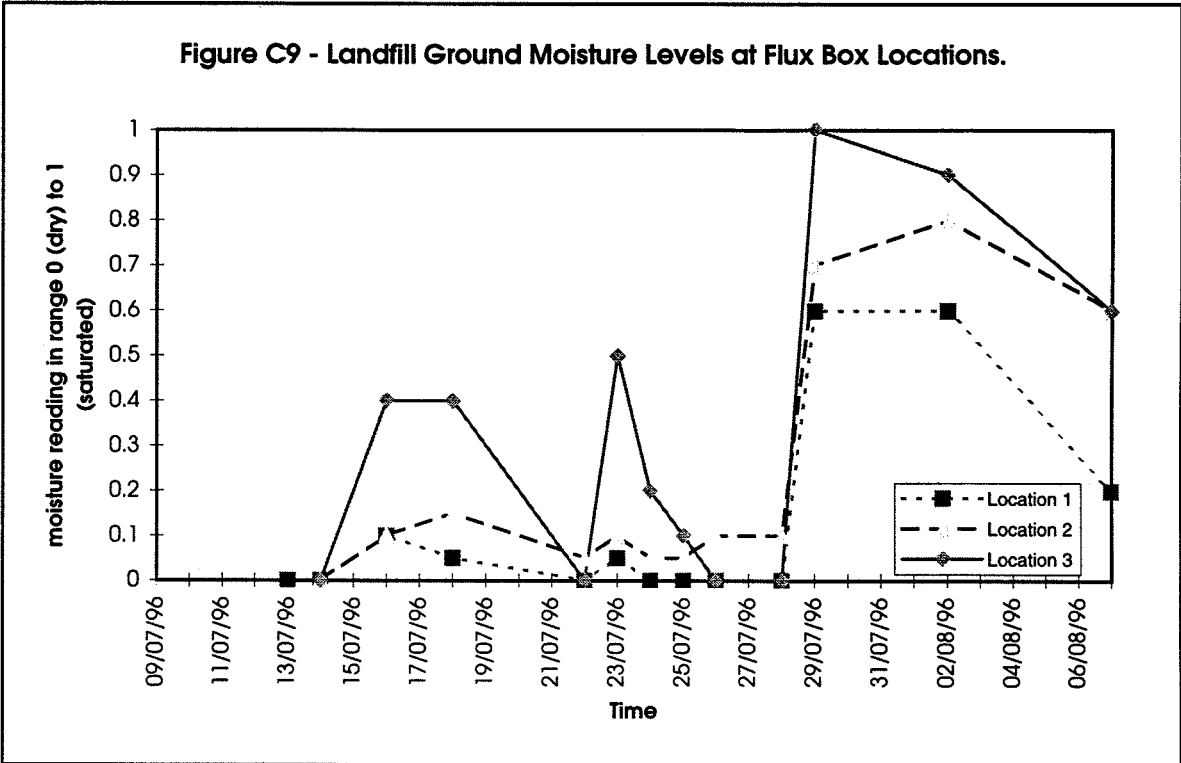


Figure C10 - Landfill Area Survey, Flux Box and Temperature data.

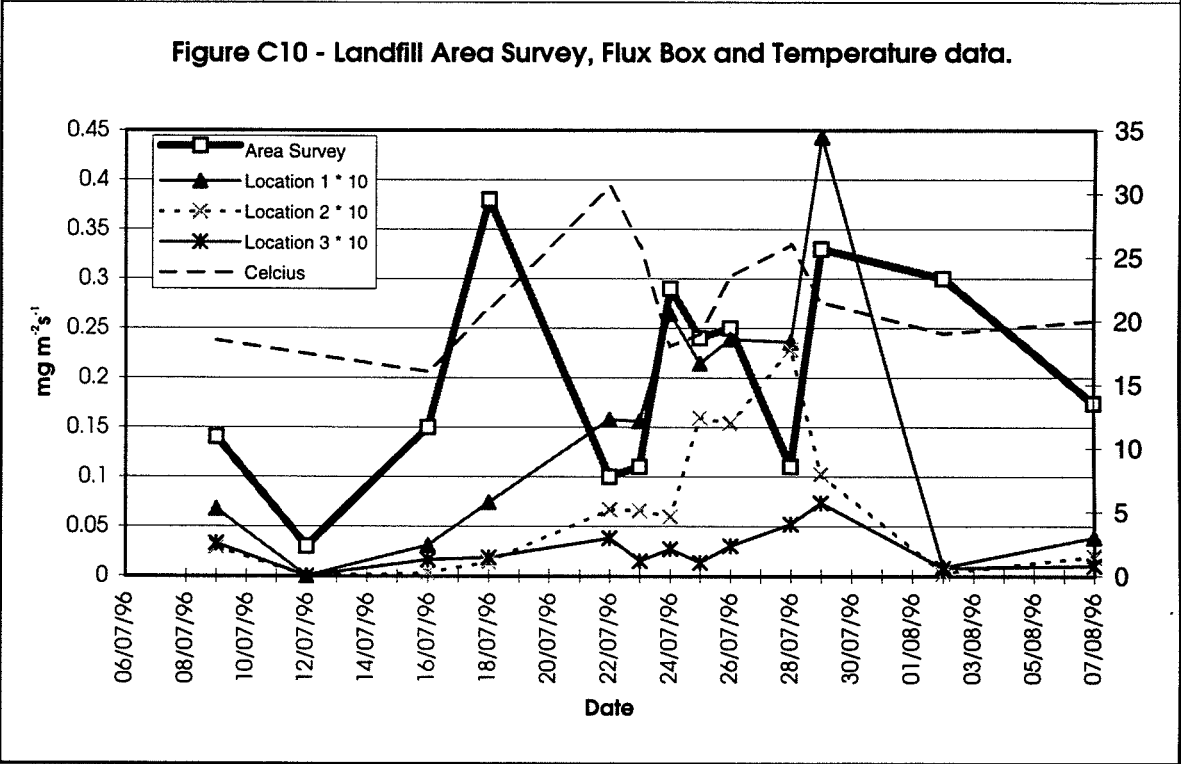


Figure C11 - Methane Flux by Long Path Monitor and Atmospheric Pressure at Site No. 1.

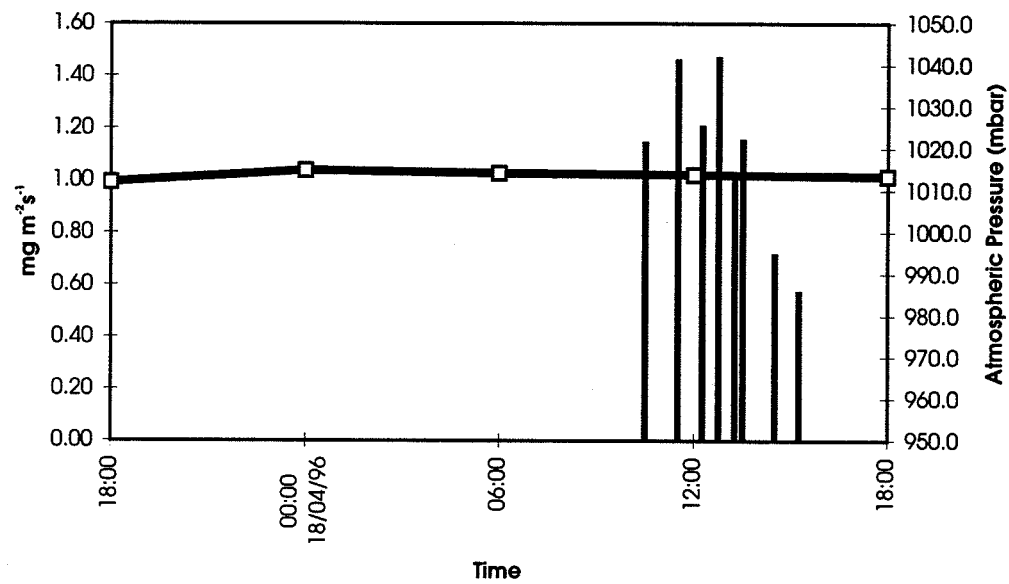
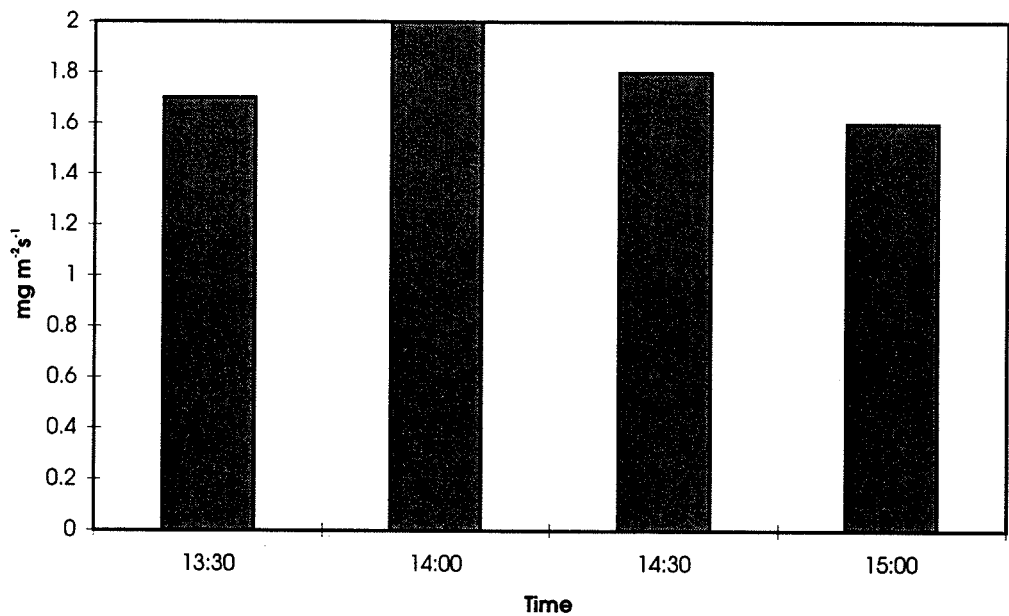


Figure C12 - Methane Flux by Long-Path Monitor, 27.6.95, Site No. 9



Annex D - Measurement of Surface Emission Fluxes Using a Flux Box

Executive Summary

Flux boxes are a widely-used method for measuring the flux of gases from surfaces. In this annex, the basic equations describing the change in concentration in a flux box are explained. A particular application of the method to the measurement of methane through the surface of a landfill site is given.

Introduction

A flux box (or flux enclosure) is a conceptually straightforward method for measuring the flux of a gas through a surface. It works by capturing the gas that flows through a surface into an enclosure with a fixed volume and then measuring the resulting increase in the concentration. Despite its apparent simplicity, there are many details in the implementation of the method that can give rise to inaccurate results.

In this report, we give a mathematical description of the variation of concentration with time within a flux box, and give an example of a measurement carried out with a simple flux box.

The Gas Balance Equation within a Flux Box

A flux box is an enclosure that possesses a flat open bottom which can be placed on a horizontal surface in order to measure the flux of gas. The enclosure has at least one gas port through which gas can be added or removed, in order to maintain the pressure in the box close to that of the surrounding atmosphere.

In general the gas entering the flux box from a surface will be a mixture of several pure gases, one of which is the gas whose flux is to be measured. In this report we refer to the example of this target gas being methane.

In order to measure the change in concentration of methane within the box a methane detector is attached to it. Ideally this detector will measure the methane concentration directly and continuously within the box, but in most real situations it will need extract a sample of gas from the box in order to make the concentration measurement. This will require another gas port and a suitable connection. The extracted gas sample is usually vented to the ambient atmosphere by the detector after the measurement.

Let the gas mixture flow through the horizontal surface and into the flux box at a rate of L (in units of m^3/s). Let the methane monitor remove gas from the box at a rate of R (m^3/s). If $R > L$ then extra gas must be introduced into the box at a rate B in order to maintain atmospheric pressure within the box. This leads to a balance in the

gas flows given by:

$$R = L + B \quad (1)$$

The bleed gas should not contain methane, or any other gas that might be measured as methane by the methane detector.

Let the volume fraction of methane in the gas mixture being emitted by the horizontal surface be z . Let the volume fraction of methane in the flux box at any time be $C(t)$, where the methane is assumed to be uniformly mixed within the box at all times.

If the volume of the flux box is V then the volume of methane (at atmospheric pressure) within the box at time t will be $VC(t)$. In a further time dt an extra methane volume of $zL.dt$ will be introduced to the box through the horizontal surface, while a volume of $RC(t).dt$ will be removed from it by the monitor. Thus:

$$\text{Net increase in methane volume in box} = [zL - CR] dt$$

This increased methane volume is reflected in an increased methane volume fraction in the box of dC , corresponding to an increased methane volume of $V.dC$. Equating the methane volume changes:

$$V dC = (zL - CR) dt \quad (2)$$

Differential Equation

Equation (2) can be re-arranged to form a differential equation which governs the variation of concentration within the box:

$$\frac{dC}{dt} + C\left(\frac{R}{V}\right) = \left(\frac{zL}{V}\right) \quad (3)$$

The general solution of equation (3) describes the variation of the concentration with time:

$$C(t) = \left[\left(\frac{zL}{R} \right) - C_0 \right] [1 - e^{-\left(\frac{R}{V}\right)t}] + C_0 \quad (4)$$

where the initial concentration $C(t=0)$ is C_0 . Alternatively, it can be written as:

After a time t , which is much larger than V/R , the concentration tends towards its

$$C(t) = \left(\frac{ZL}{R} \right) \left[1 - \left(1 - C_0 \frac{R}{ZL} \right) e^{-\left(\frac{R}{V} \right) t} \right] \quad (5)$$

terminal value.

$$C_{\infty} = \frac{ZL}{R} \quad (6)$$

In the special case where there is a net outflow of landfill gas from the box (equivalent to a negative value for B with a concentration C(t)), then

$$C_{\infty} = Z \quad (7)$$

Concentration Gradient

The flux box measurement technique relies on determining the rate of change of concentration in the box. This can be determined by differentiating equation (4) (or by substituting into equation (3)). The initial gradient is

$$\left(\frac{dC}{dt} \right)_{t=0} = \left(\frac{ZL}{V} \right) \left(1 - \frac{C_0}{C_{\infty}} \right) = \frac{ZL}{V} - \frac{RC_0}{V} \quad (8)$$

If the measurement starts with the box full of zero gas (with no methane concentration), then $C_0=0$ and the initial gradient is given by:

$$\left(\frac{dC}{dt} \right)_{t=0} = \left(\frac{ZL}{V} \right) \quad (9)$$

When the measurement period starts with a finite amount of methane within the box, it is possible that the initial gradient will be negative. This will occur when $C_0 > C_{\infty}$. This situation often arises when measurements are made in the presence of high ambient concentrations which could be trapped within the box when the measurement starts. In any circumstance when C_0 is not zero, then equation (6) can be used to calculate the true gradient if R (the sample flow rate) is known.

References

D.R. Reinhart, D.C. Cooper and B.L. Walker, "Flux chamber design and operation for the measurement of municipal solid waste landfill gas emission rates", J. Air Waste Manage Assoc **42** (1992) 1067-1070.

B. Eklund, "Practical guidance for flux chamber measurements of fugitive volatile organic emission rates", J. Air Waste Manage Assoc **42** (1992) 1583-1591.

Appendix 1 Symbols Used

$C(t)$	=	concentration of methane at time t , expressed as a volume fraction
C_0	=	initial concentration of methane (volume fraction) at time $t=0$
C_∞	=	terminal concentration of methane (volume fraction)
L	=	flow rate of gas into the box from the surface being measured (m^3/s)
R	=	rate of flow of sample gas to monitor from box (m^3/s)
z	=	volume fraction of methane in LFG
V	=	volume of box (m^3)
A	=	area of the box covering the surface being measured (m^2)

Annex E - Minimum Emission Rates Detectable from Landfill Sites using Optical Integrated-Path Techniques

Abstract

The measurement of average emission rates from area sources such as landfill sites is an important step in the development of emission inventories. Average emission rates from area sources can be calculated by performing an optical integrated-path concentration measurement of the gas plume downwind of the source and combining it with an appropriate measurement of the wind speed. We show that the minimum emission rate detectable with this technique depends on the wind speed, the atmospheric stability and the width of the site in the upwind direction. Optical integrated-path measurements performed on a landfill site confirm the accuracy of these calculations.

1 Introduction

Optical integrated-path techniques are being used increasingly widely to measure the ambient concentration of gases emitted by area sources such as landfill sites, water treatment works and sewage plants. In many cases, the quantities of greatest interest in these applications are the average flux per unit area and the average flux from the entire source. These have conventionally been measured by the use of "flux enclosures" [1] which monitor the build up of gas in an enclosed volume above a small part of the source. This type of method can give an accurate value for the emission rate of the area sampled, but can not give an accurate estimate of the total emission from an area source if it is not approximately homogeneous.

Optical integrated-path techniques are capable of overcoming this limitation by taking measurements along extended paths that average the inhomogeneous nature of the emission source. They are usually used to determine the average flux by making measurements along the downwind edge of the source and combining them with measurements of the wind speed across the same plane. If the measurements are carried out at several heights so as to "capture" the entire vertical extent of the plume, then a value for the emission flux can be calculated which is independent of any assumptions about plume dispersion. If it is not possible to measure all of the plume directly then a dispersion model can be used to estimate the extent of the plume above the measurement paths, and hence the total flux [2,3,4].

The smallest emission rate that can be measured by this technique is determined by the lowest concentration of gas in the plume that can be measured. We have used a dispersion model to calculate the emission rates that correspond to the minimum detection limits of our measurement instrument. The results are supported by measurements carried out on a real landfill site.

2 Gas Dispersion Model for Area Sources

The relationship between the ambient concentration of gas downwind of an area

emission source and the average emission flux depends on the shape and size of the source, the distance to the source and the meteorological conditions. In order to demonstrate the validity of our approach to estimating emission rates we have modelled the dispersion of gas from an area source using the UK Advanced Dispersion Modelling System (ADMS) [5]. This model uses a dispersion model that characterises the boundary layer structure by reference to the boundary layer height and the Monin-Obukhov length (a length scale dependent on the friction velocity and heat flux at the surface).

For this work, the atmospheric stability has been characterised by choosing default values for these parameters that are representative of Pasquill-Gifford stability classes B, C, D and E. The use of Pasquill-Gifford stability classes does not significantly limit the accuracy of this work because the model is being applied to the dispersion of a source at ground level. Other workers have shown how a related SF_6 tracer experiment can be used to determine the stability class [2]. (In the future, we will use sonic anemometry to determine the Monin-Obukhov length directly and radio sondes to measure the boundary layer height.)

The model has been used to calculate the vertical concentration profile of the plume along the downwind edge of the site and at distances of 10, 20 and 50 metres (Figure 1). Figure 2a is an example of the concentration profile in stability class C with a wind speed of 4 m s^{-1} . The corresponding cumulative concentration profile is shown in 2b. (These have been calculated for an area emission rate of $1 \text{ unit m}^{-2} \text{ s}^{-1}$.) A characteristic of the atmosphere when modelled this way is that the shape of the vertical profile of concentration does not vary with wind speed, although the actual values scale in proportion to maintain a constant flux.

3 Calculated Plume Heights

The plume dispersion model predicts the vertical concentration profile which is established at given distances downwind of the source under any particular set of atmospheric conditions. The total flux from the source is the integral over this profile multiplied by an appropriate estimate of the wind speed. If a sufficient number of measurements are made to enable the complete profile to be characterised, then the total flux from the site can be calculated directly. In this case, the result is independent of any model and is based solely on measured data.

The results of the model show that, for example, in Pasquill stability class D (which describes "neutral" atmospheric conditions and is typical of overcast conditions in the UK), 99% of the plume will be below a height of 30 metres at the site edge. As the atmosphere becomes less stable it moves through class C to B and the plume is forced up by convective turbulence at the surface caused by solar heating. Class B corresponds to a still sunny day in UK conditions and represents the least favourable conditions for this type of measurement. In these conditions, 75% of the plume from a site 600 metres wide is below 30 metres.

The values in Figure 3 summarise the modelled plume heights over the range of conditions we have considered.

4 Plume Capture and Model Inversion Methods

In the discussion above, the principle of measuring the entire vertical extent of the plume was discussed. It leads to a flux determination that is independent of any assumptions underlying a dispersion model. If the complete vertical extent of the plume cannot be measured, then a model can be used to estimate it. This approach can be regarded as an "inversion" method [7] since it is an example of a technique that works back from a measurement result to evaluate the corresponding source terms.

In the next section, we calculate the minimum flux detectable with an optical integrated-path instrument. The results of this calculation are equally applicable to measurements that have captured all of the plume and those that rely on a smaller number of measurements followed by model inversion. However, the approaches that capture all of the plume will usually be more accurate for two reasons:-

- they use more independent measurements of the plume, hence they will average atmospheric variations better,
- the final result will be less sensitive to noise, since it is not calculated through a series of non-linear mathematical operations (which usually amplify noise in the input data).

5 Minimum Detectable Flux

The minimum flux that can be detected using any particular optical integrated-path instrument is the flux that gives rise to a plume concentration corresponding to the detection limit of the instrument. It is possible to deduce this minimum detectable flux by using the model to calculate the emission rate that gives rise to plume concentrations at the detection limit of the instrument. Consider the example of an instrument that can resolve a point concentration of 0.2 ppm of methane (in excess of the atmospheric background). In the case of a site 400 metres wide (in the downwind direction) in Pasquill C conditions, the emission rate would have to be $0.05 \text{ mg m}^{-2} \text{ s}^{-1}$ in order to establish an excess concentration of 0.2 ppm in a wind speed of 4 m s^{-1} .

Figure 4 shows the minimum detectable flux for 200 and 600 metre sites in 4 different atmospheric stability classes. These calculations apply to a wind speed of 4 m s^{-1} and can be scaled to any other wind speed. The results span the range from 0.02 to $0.1 \text{ mg m}^{-2} \text{ s}^{-1}$. If we consider wind speeds of 2 and 6 m s^{-1} , then they would cover the range 0.01 to $1.3 \text{ mg m}^{-2} \text{ s}^{-1}$.

6 Measurements at a Landfill Site

NPL has been involved in measuring methane emissions from landfill sites for nearly 10 years. Early work [8] used a cryogenically-cooled lead-salt diode laser. More recently, measurements have been carried out using the HAWK monitor. This instrument works in the 2 to $5 \mu\text{m}$ spectral region and uses an oscillating filter to define and modulate the wavelength of the probe beam. It uses an optical bandwidth

of approximately 50 cm^{-1} which enables it to measure a range of hydrocarbons including methane. It is portable and significantly less expensive and complex than the FTIR instrument. It uses a retro-reflecting mirror and can make measurements over paths up to 400 metres.

At present, NPL is undertaking a comprehensive set of measurements of methane emissions from UK landfill sites with the objective of forming an accurate estimate of total UK methane emissions from this source [9]. These measurements are being carried out using the HAWK with a retro-reflector mounted on a mobile mast to access the top of the plume. Initial work used a second mast to define a set of horizontal optical paths up to a height of 12 metres. More recently, a slant path has been used because it is much simpler to implement and does not introduce significant errors if the vertical profile of the plume is constant along the measurement path. This has enabled measurements to be made up to a height of 30 metres with a typical path length of 140 metres.

A particular difficulty incurred when using optical integrated-path techniques is in defining the "zero" level for the measurement. In this work we have calibrated the zero level with measurements carried out with a portable flame-ionisation detector (FID).

7 Emission Flux Measurements

We present here some emission flux measurements made at a former chalk quarry which now contains 12 Mt of domestic waste filled to a depth of 35 metres. The measurement path was situated close to the centre of the site, but clear of the operational area.

The integrated-path concentrations measured with the HAWK are shown for one measurement period in Table 1. The measurements were taken alternately along a path at ground level and along a path towards the top of the mast. the excess concentration in the plume was then calculated by subtracting consecutive measurements. The corresponding flux through the measurement plane was calculated using measured values for the wind speed and direction.

The measured flux is converted into an area emission rate by calculating the area of the site that is upwind of the measurement plane. In this case, the estimated emission rate is $1.7 \text{ mg m}^{-2} \text{ s}^{-1}$ which corresponds to a total emission of 700 g s^{-1} ($= 22 \text{ kt per year}$) for the entire site.

8 Plume Profile Measurements and Comparison with Point Detection

As we discussed in the introduction, optical integrated-path techniques are potentially the most accurate method of determining fluxes from inhomogeneous sources. We have found that it is useful to augment the optical technique with measurements carried out with a portable FID. This has three particular applications:

- it is capable of measuring very low fluxes,

- it can be used to check the uniformity of the whole site,
- it can provide a "zero" level for the ground-level measurement path.

In order to confirm the accuracy of the model, the vertical profile of the plume was measured with an FID sampling on the mast at ground level and heights of 16 and 25 metres. The results are shown in Figure 5 together with predictions from the model for four sets of appropriate atmospheric conditions. This example illustrates how the predictions made by the model do not depend sensitively on the atmospheric stability class.

9 Conclusions

We have calculated the minimum methane flux detectable from an area source with an instrument capable of measuring 0.2 ppm above the background to be in the range 0.01 to 1.3 mg m⁻² s⁻¹. The exact result depends on the atmospheric conditions and the exact size and shape of the site.

Our calculations of plume profiles show that in Pasquill stability classes C and D (with wind speeds of 3 m/s or greater) measurements carried out at heights up to 30 metres will catch a representative fraction of the plume. In such conditions, direct measurements of the entire plume can be made and hence the flux can be established without use of a dispersion model.

We have made measurements with the HAWK optical integrated-path monitor of emissions from a landfill site. These measurements used an angled path, which has some practical advantages over a strictly horizontal one.

The sensitivity of the HAWK in this application makes it well suited to measuring methane emissions from landfill sites that make important contributions to national emission inventories.

10 References

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Table 1 - Optical-Integrated Path Measurements with HAWK

Time Period	Path	Result [ppm.m]	G-T [ppm.m]	Wind Speed [m s ⁻¹]	Wind Direction [degree]	Flux [Kg/s]
11:53 - 13:06	G	1165		9.5	15	
			350			130
13:06 - 13:38	T	815		9.5	20	
			245			150
13:38 - 14:14	G	1060		9.5	21	
			265			140
14:14 - 15:40	T	795		9.0	22	
			380			120
15:40 - 16:07	G	1175		9.0	23	
			460			96
16:07 - 16:18	T	715		9.0	25	

Figure 1

Plume Model Calculations

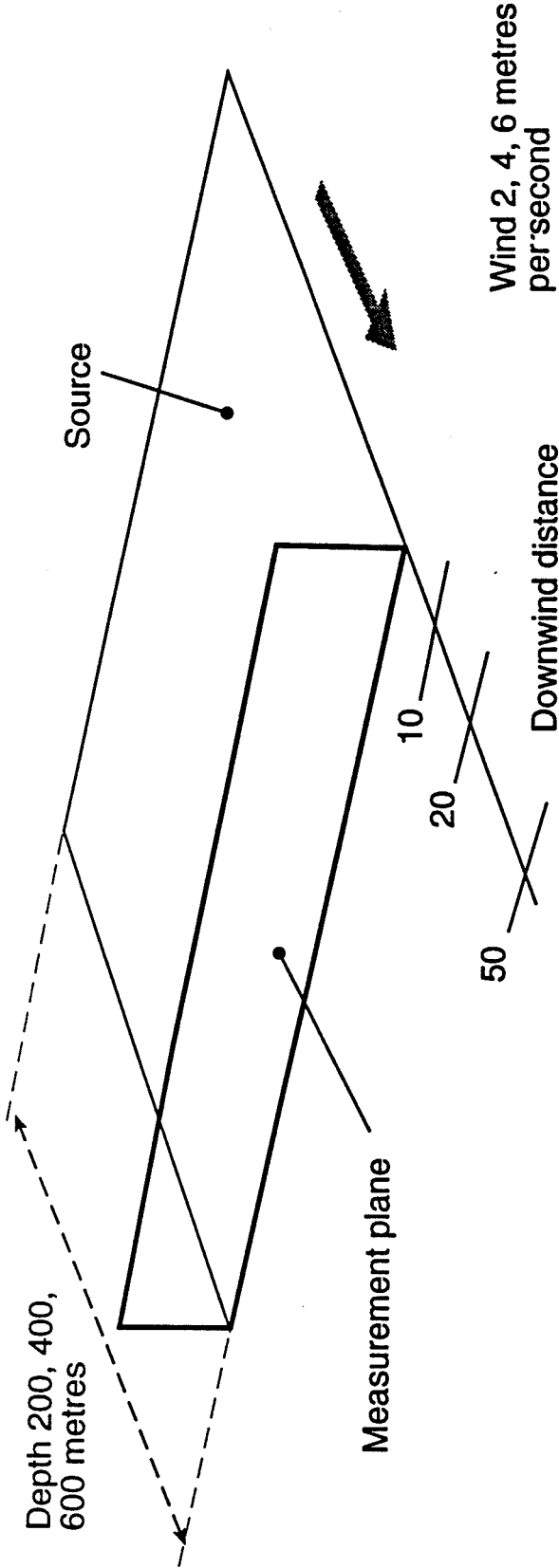
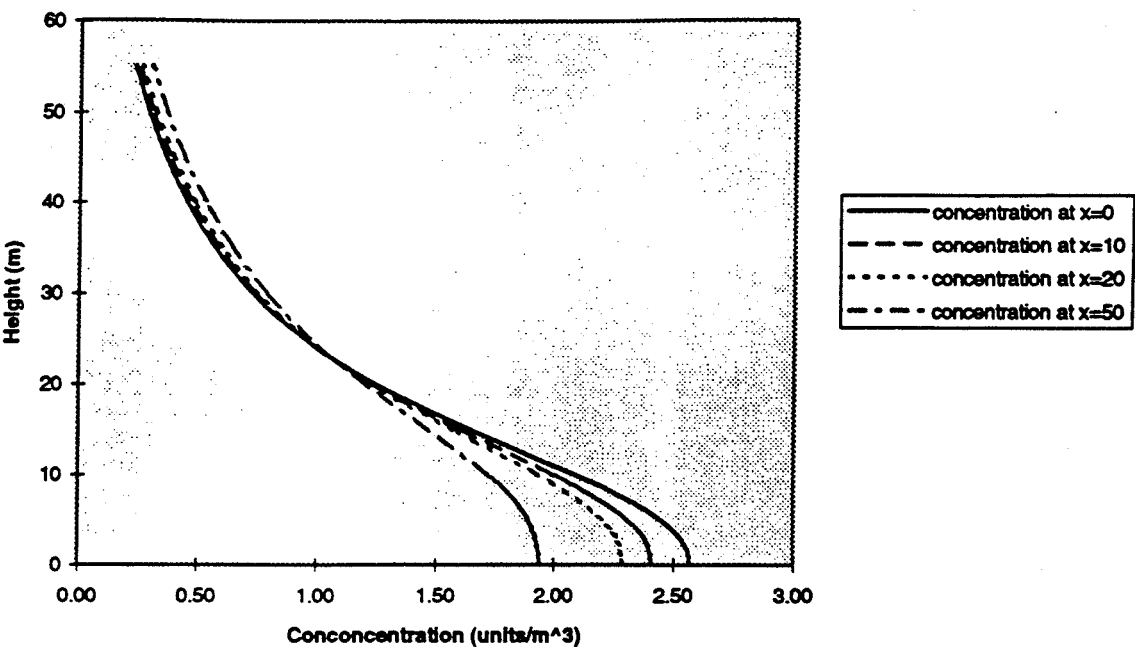


Figure 2

Vertical Profile of Plume
Pasquill C, Wind speed = 4 ms⁻¹



Vertical Profile of Plume
Pasquill C, Wind speed = 4 ms⁻¹

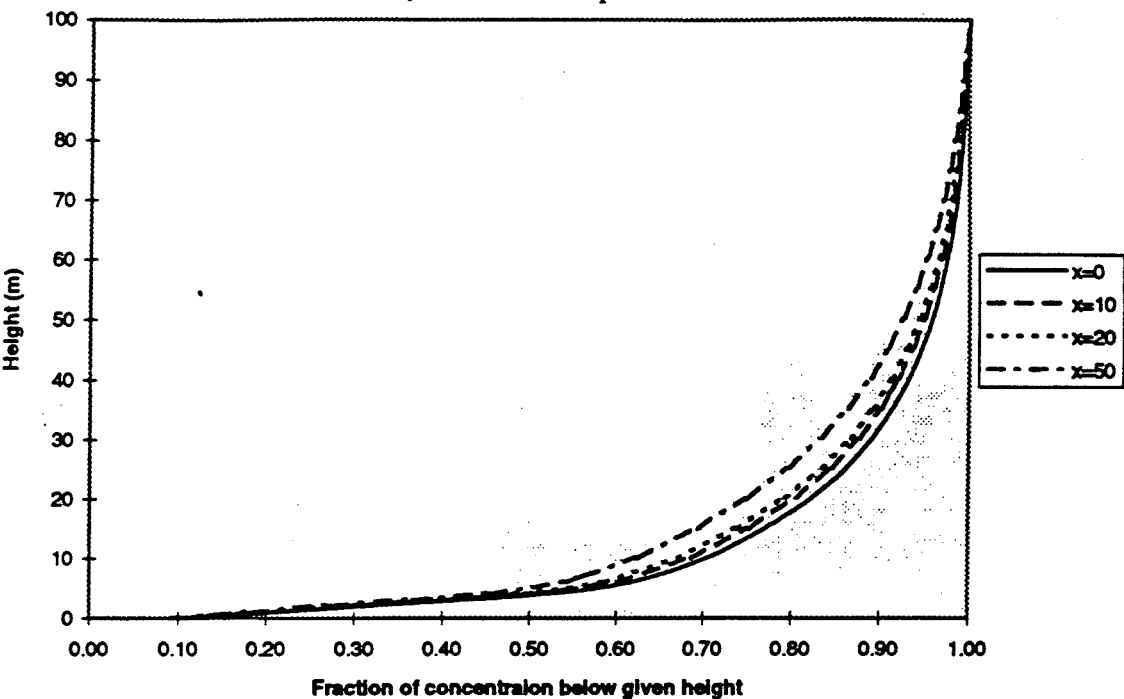


Figure 3 Calculated Plume Height
Windspeed of 4 m/s

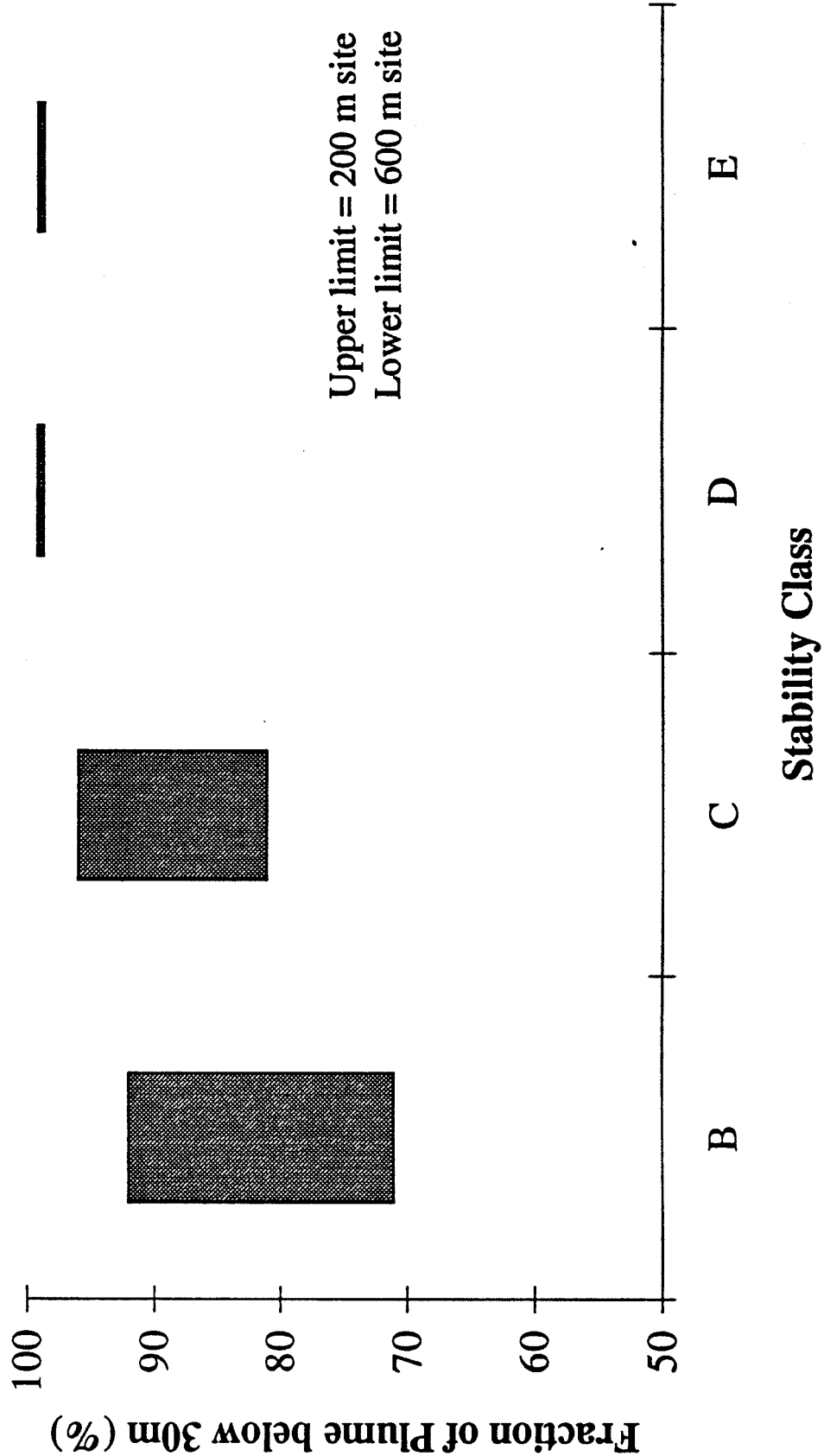


Figure 4 Minimum Detectable Flux
Windspeed of 4 m/s

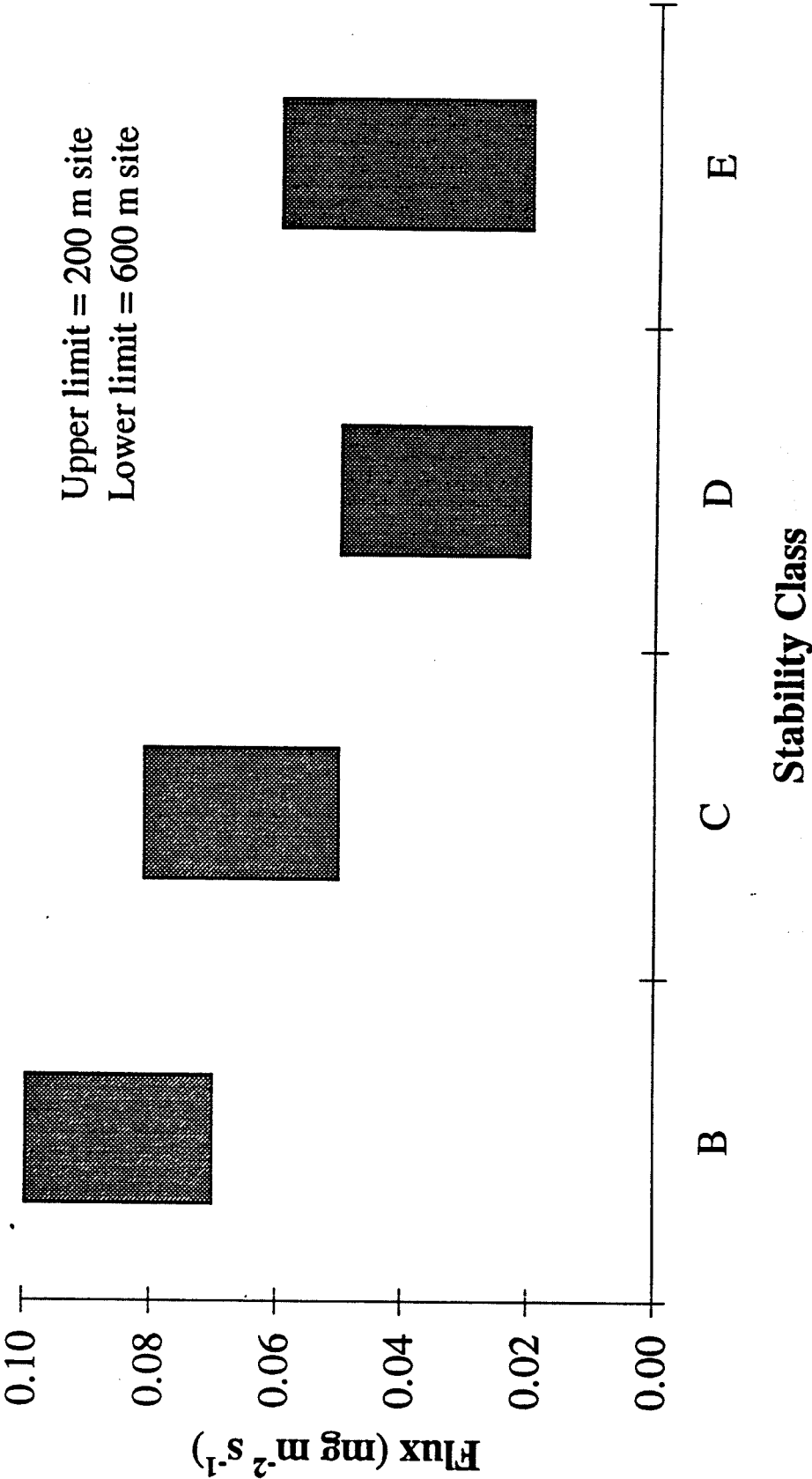
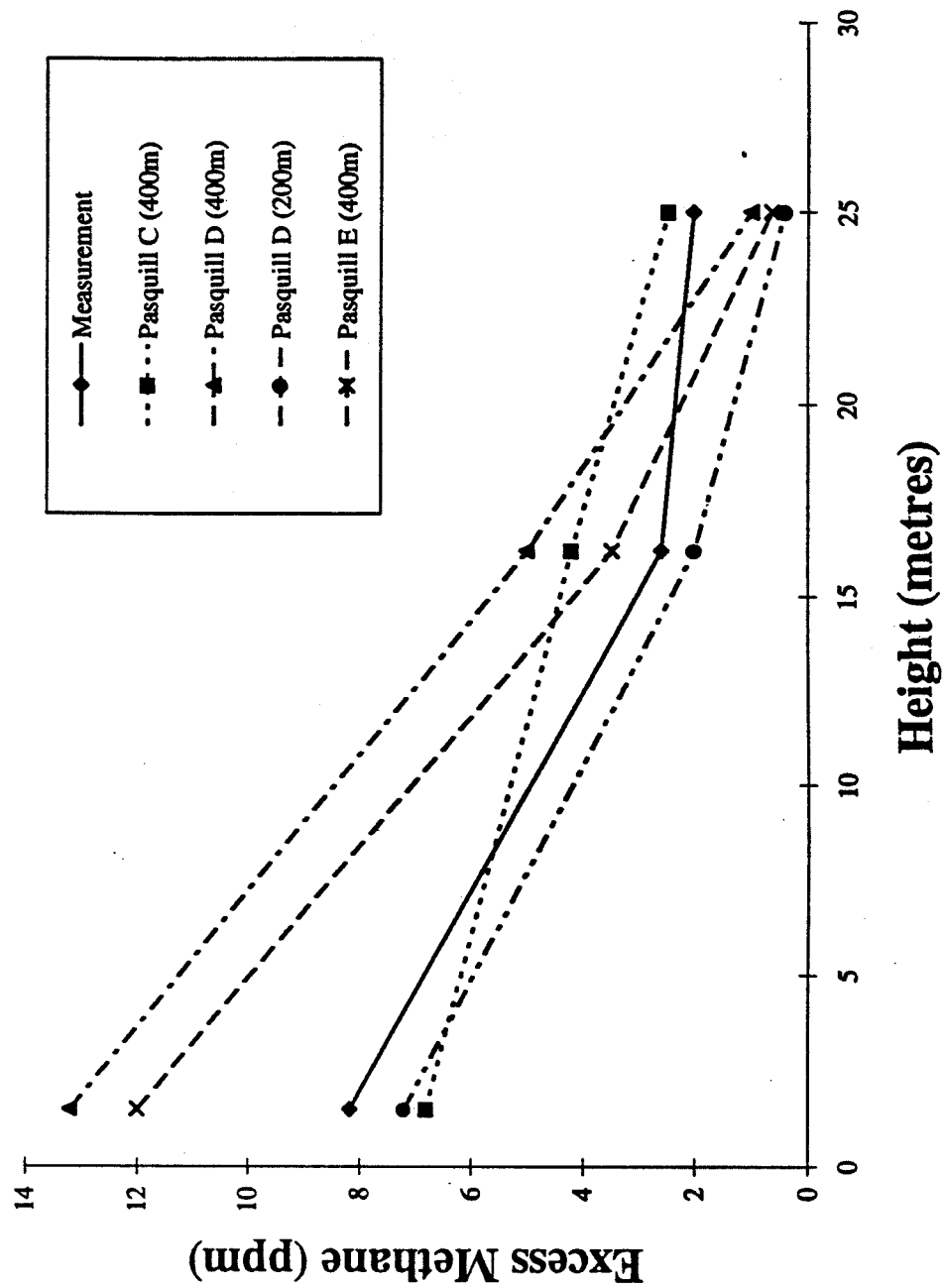


Figure 5 Methane Plume
(Windspeed = 6 m/s)



Audit Trail

	File Name
Main Text	LNDFLPT3.FIN/Meth 6 Corrected 11/97
Figures 1 to 8	ANNO2 and ANNO3.XLS
Figure 9	WRCQUERY.XLS
Figures 10 to 12	HARISING.XLS
Figure 13	ANNODOE.XLS
Figure 14	RSKRES3.XLS
Annex A	ANXA.REP/Meth 6
Figures A2 and A3	ALTTEC1 & 3.XLS
Annex B	Centurian e:landfill/sitesum Corrected 8/97
Annex C	ALTONB.TXT/Meth 4
Figures C3 to C12	FLUXSUM1.XLS
Annex D	BOX.EQN/Meth 3
Annex E	sanfhawk.rep/Papers IV
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