Methane Emissions from Different Landfill Categories

Research and Development

Technical Report
P233a

ENVIRONMENT AGENCY

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R&D Technical Report P233a

Research Contractor:
W S Atkins Environment

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This report provides an assessment of methane emissions from different categories of UK landfill sites, verified by appropriate field measurements. This assessment will aid the Agency in developing a strategy for methane emissions reduction and help reduce uncertainties on emissions estimates by quantifying emissions from each category. The assessment methodology is also applicable for landfill site operators to determine site specific emissions and appropriate remedial works.

Research Contractor

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EXECUTIVE SUMMARY

Methane is considered the second most important anthropogenic (human influenced) greenhouse gas, after carbon dioxide. The UK is committed to develop and publish national inventories of greenhouse gases and to take measures aimed at returning emissions of each greenhouse gas to 1990 levels by 2000. Additionally the UK has agreed to a reduction of 12.5% in greenhouse gas emissions (relative to 1990 levels) by 2010. This is part of a burden-sharing arrangement within the European Union to meet legally binding targets for reductions in greenhouse gas emissions agreed with the United Nations Framework Convention on Climate Change at Kyoto in December 1997.

The aim of this project is to provide the Environment Agency (the Agency) with an assessment methodology for surface methane (CH_4) emissions from different categories of UK landfill sites, verified by appropriate field measurements. This will aid the Agency in developing a strategy for methane emissions reduction and help reduce uncertainties on emissions estimates by quantifying emissions from each category. The assessment methodology was to be applicable to site operators for determining site specific emissions and appropriate remedial works. This project complements related studies, funded by the then Department of the Environment, to estimate total UK landfill methane emissions based on field measurement.

Surface methane flux was measured at 247 positions on 26 landfill sites using specifically designed enclosed chambers (flux boxes). Some measurements were repeated at different times of the year. Methane emissions ranged between 10^{-6} mg m^{-2} s^{-1} and 2 mg m^{-2} s^{-1} and formed a skewed distribution with a peak between 10^{-5} and $3x10^{-4}$ mg m^{-2} s^{-1}. More than 80% of the flux box results were less than 10^{-3} mg m^{-2} s^{-1}. The median result was just over 10^{-4} mg m^{-2} s^{-1}, which equates to about 5 litres CH_4 per hectare per hour. These results, particularly the wide range of emissions, compare well with other international studies.

Measurement of methane flux at different types of landfill site showed that:

- a good quality cap and full site gas control are highly effective for controlling methane emissions;
- methane emissions are influenced primarily by gas control and cover characteristics. Other site features such as waste depth, surface area, underlying geology, hydrogeology and containment/lining are secondary;
- a well operated gas collection system and a good cap can reduce emissions by around two orders of magnitude, i.e., 90-99%;

- absolute methane emissions are site specific and it is difficult to quantify the effects of a variety of practices on different sites.

A landfill site with a well-engineered cap free of defects, and a well-operated gas control system can achieve methane emissions as low as 10^{-4} mg m^{-2} s^{-1}. Sites without these systems may have surface methane emissions three orders of magnitude higher. In practice a target of 1×10^{-3} mg m^{-2} s^{-1} over a defect-free cap would seem reasonable. The need for emissions reduction would then impact on the top 20% of landfill emitters. An assessment protocol is being devised in a follow-up project to help identify these high methane-emitting landfills.

The estimated cost of methane emissions abatement for landfilled waste ranges from £0.02 to £0.05 m^{-3} methane (£28 to £70 $tonne^{-1}$ methane).

ACKNOWLEDGEMENTS

The authors would like to thank Dr Martin Meadows for his stewardship of the project on behalf of the Agency, Dr Paul Nathanail, formerly Nottingham Trent University, now Nottingham University, for his contribution to the spatial and statistical analysis of data, and Dr Martin Milton, National Physical Laboratory, for collaboration with the Global Atmosphere Division project.

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ABBREVIATIONS

CH_4	methane
CO_2	carbon dioxide
COPA	Control of Pollution Act 1974
DIAL	differential absorption LIDAR
DOE	Department of the Environment
EPA	Environmental Protection Act 1990
EU	European Union
FID	flame ionisation detector
GAD	Global Atmosphere Division
GWP	global warming potential
LAWDC	local authority waste disposal company
LDPE	low density polyethylene
LEL	lower explosive limit
LFG	landfill gas
LIDAR	light detection and ranging
MSW	municipal solid waste
NAMGAS	National Assessment Model of Landfill Gas Production
NMH	non-methane hydrocarbons
NPL	National Physical Laboratory
PFA	pulverised fuel ash
ppm	parts per million
WSA	WS Atkins

GLOSSARY

advection	gas transfer by the horizontal flow of air across a landfill surface
capping	containment layer on surface of landfill
diffusion	the migration of species from a region of high concentration to a more dilute region by natural movement of their particles
flame ionisation detector	detector for GLC based on conduction by ions produced when an analyte is ionised in a hydrogen/air flame, the resulting voltage change is proportional to the concentration of the analyte
flux box	chamber and analytic equipment used to determine the flux of gas to or from a the area of landfill on which it is placed
gas chromatograph	analytical method that utilises a gaseous mobile phase with either a liquid (GLC) or solid stationary (GSC) phase
geomembrane/synthetic	an engineered polymeric material fabricated to be virtually impermeable
geotextile	geotextile is a geosynthetic which is fabricated to be permeable
insolation	radiation from the sun
landfill gas	gas generated within the landfill which contains products from the anaerobic digestion of organic matter and volatile organics
LIDAR	quantitative remote detection of airborne species using a laser source
methane gradient	variation in the methane concentration with depth in a landfill
methanotrophs	bacteria that use methane as a carbon and energy source
micrometeorology	atmospheric characteristics in the immediate vicinity of the study area
porosity	the percentage of void space in earth material such as soil or rock
spiker survey	measurement of methane gradient with one data point and an assumed zero at the surface

1. INTRODUCTION

Wastes Technical Division of the Department of the Environment (DoE) commissioned this report, under Contract no. CL0225 EPG 1/7/28. From 1 April 1996 it became the Waste Management and Regulation Policy Group of the Environment Agency (the Agency). Surrey County Council Waste Regulation provided co-funding. It too became part of the Agency on 1 April 1996. WS Atkins Environment undertook the work (WSA) over the period January 1995 to January 1997.

The aim of the project is to provide the Agency with an assessment of methane emissions from different categories of UK landfill sites, verified by appropriate field measurements. This assessment will aid the Agency in any appraisal for methane emissions reduction and reduce uncertainties on emissions estimates. The assessment methodology is also applicable for site operators to determine site specific emissions and appropriate remedial works. The study was co-ordinated with related research sponsored by Global Atmosphere Division (GAD) in DoE and performed by the National Physical Laboratory (NPL).

1.1 Policy Framework

The United Nations Framework Convention on Climate Change, ratified by the UK in December 1993, committed the UK to develop and publish National Inventories of greenhouse gases, and to take measures aimed at returning emissions of each greenhouse gas to 1990 levels by the year 2000 (DoE, 1997). Methane is considered the second most important anthropogenic (human influenced) greenhouse gas, after carbon dioxide.

Furthermore, in 1997, signatory nations to the Kyoto Protocol of the Framework Convention on Climate Change (FCCC) agreed a legally binding target for developing countries to reduce emissions of the six principal man made greenhouse gases (GHGs). The target is an overall reduction of 5.2% below 1990 levels over the period 2008 to 2012.

Under this agreement the Member States of the European Community agreed jointly to undertake an 8% reduction. Subsequently the national target for each member state has been varied, taking into account each members projections for future GHG emissions, including economic growth factors and the effort required to meet the Kyoto target. The UK agreed to take on a reduction target of 12.5%. The UK's target is binding and must be met even under adverse conditions.

Important features of methane include the following:

- Global Warming Potential (GWP) of methane is between 21 and 62 (cf. CO_2 has GWP of 1), depending on the period considered.
- Stabilisation of methane concentration in the atmosphere could be reached by a reduction of 10% of annual global anthropogenic emissions
- Methane stays in the atmosphere for 12-17 years against 500-2000 years for CO_2
- Methane from landfill makes up approximately 31% of the total European Union (EU) inventory of methane emissions (EC, 1990).

In November 1996 the European Commission (EC) presented a strategy paper for reducing methane emissions (EC, 1996). Measures must be taken to reduce emissions of methane in the three main anthropogenic sources, namely the farming industry, waste and energy sectors. The Commission claims the strategy would lead to a 30% reduction in emissions by 2005 and 40% by 2010 on 1990 levels.

Emissions from waste treatment and disposal represent the second largest source of methane emissions in the EU and were estimated to be 7.3 million tonnes (Mt) in 1990. If the emissions from unmanaged and unaccounted open dumps are taken into consideration, landfills might become the most significant methane emitter in the EU. For the waste sector the proposed policy measures for mitigating emissions are:

- reduction of organic waste streams to landfill;
- methane recovery and utilisation schemes in new landfills; and
- retrofitting of gas control measures to existing landfills where possible.

Estimates of total landfill methane emissions range from about 2 million tonnes per year between 1990 and 1994 (Salway 1996) to about 1 million tonnes in 1995 (Milton *et al.* 1997). Earlier estimates were based on computer models only while later estimates reflect a growing database of field measurements. This project was co-ordinated with a complementary project funded by DoE's Global Atmosphere Division (GAD) to estimate total methane emissions from UK landfill sites based on direct measurements. The National Physical Laboratory (NPL) carried out the DoE

project. The two projects contributed to the CH_4 from Landfill Steering Group and co-ordinated their field work to visit sites simultaneously to allow comparison of the techniques employed.

Estimates of national landfill methane emissions are uncertain (Bogner *et al.*, 1998). Factors influencing the rate and quantity of methane produced in landfilled waste, and the migration of methane emissions, are site specific. Methane emissions from different landfill sites are likely to vary greatly according to, for example:

- waste quantity;
- composition;
- age and depth:
- site filling regime;
- type of cap and/or cover; and
- efficiency of the landfill gas collection system, if present.

The outputs from this project are expected to contribute to the following:

- Agency guidance to waste regulators and landfill operators on the most effective approach to reducing current methane emissions from individual landfill sites;

- assessment of the scope for overall UK methane emissions reductions from landfills; and

- reduction of some uncertainties associated with estimating UK landfill methane emissions.

1.2 Project Objectives

The project objectives, related to the development of a protocol for the assessment of UK landfill methane emissions by the relevant regulation authorities, were as follows:

1) To review available information on methods for measuring methane flux from land surfaces.

2) To define landfill categories likely to have different methane emissions characteristics, and prioritise the likely contribution to UK methane emissions of each landfill category.

3) To produce a protocol for measuring methane emission fluxes from different landfill categories.

4) To measure methane emission fluxes from a range of sites in Surrey and other counties, as appropriate, to verify and, if necessary, revise the priorities assigned in objective 2 above.

5) To recommend landfill management practices, appropriate for the different landfill categories defined above, that will reduce current methane emissions from UK landfills. To estimate the costs and benefits of the recommended management practices.

6) To quantify the effect of these management practices at individual sites, and gross up individual site effects to their potential impact on UK emissions as a whole.

7) To recommend a protocol, appropriate for use by waste regulators and operators alike, for monitoring landfill methane emissions.

1.3 Structure of this report

Section 2 provides a review of some common methods available for sampling and measuring methane flux from land surfaces, and discusses the pros and cons of the selected methods. **Section 3** describes the field flux measurement programme and presents the corresponding observed flux results. The results of the monitoring are considered in relation to key site variables and comparisons are made with other studies. A categorisation of landfill types is required to standardise decision making on remedial measures for other landfill sites. **Section 4** presents this. **Section 5** provides recommendations for effective landfill management practices to reduce emissions and quantifies likely costs and benefits.

Appendix 1 is a description of direct and indirect flux measurement techniques, with a rationale for the choice of methods for comparative trials. **Appendix 2** describes the practical work, **Appendix 3** gives the results. Appendix 2 is intended to 'stand alone' as a protocol for the future use of regulators and operators.

2. FLUX MEASUREMENT AND ANALYSIS OF RESULTS

2.1 Introduction

This section presents the outcome of the comparative trials to select one of three flux measurement techniques:

- flux boxes;
- spiker surveys; and
- depth profiling.

Appendix 1 describes these methods. It also describes which methods we judged to be unsuitable for the project requirements. This section also provides the results of the main trials with the chosen technique. An analysis of the correlation of flux with key variables affecting methane emissions is presented. Appendix 2 presents a description of the field work in the emission flux measurement protocol. Appendix 3 presents the detailed flux data (summarised below and in Table 2.4a).

2.2 Initial Comparative Trials

After the measurement method review phase of the project, which identified three suitable emission measurement techniques, we undertook comparative trials. At each of three landfill sites, A, B and C, flux boxes and spiker surveys were attempted with varying degrees of success. We undertook depth profiling landfill site A but gave up due to the variability of results and difficulty of interpretation. Table 2.2a shows the results obtained from these trials.

Spiker survey data gave higher calculated fluxes than do flux boxes, for the same area of study. Methane gradient profile data span the range of flux box and spiker survey data. This was interpreted as a function of the mathematics used to convert concentrations into fluxes (Appendix 1). The selection of different default values, for whatever reasons, could make calculated fluxes lower or higher still.

The mathematics that converts probe measurements to fluxes is more complex and is empirical in nature. To calculate flux, samples are required to be tested for soil porosity and water filled porosity, or volumetric moisture content, for example. Then empirical factors of tortuosity need to be applied. Although default values may be used (as they have been used in this study), the difference between calculated fluxes by probe measurements and fluxes by flux box measurements,

may simply represent the difference between two methods of calculations, and the number of assumptions made for each method.

Table 2.2a. Results from comparative trials

Site	Method	Lowest flux ($mg\ m^{-2}\ s^{-1}$)	Highest flux ($mg\ m^{-2}\ s^{-1}$)	Average flux ($mg\ m^{-2}\ s^{-1}$)
A	Flux box	$2.2x10^{-4}$	$2.5x10^{-4}$	$2.4x10^{-4}$
	Spiker survey	$<1x10^{-3}$	$1.8x10^{-2}$	$4.0x10^{-3}$
	Depth profile	$4.3x10^{-6}$	$1.9x10^{-2}$	$2.1x10^{-3}$
B	Flux box	$1.0x10^{-4}$	$4.4x10^{-4}$	$3.0x10^{-4}$
	Spiker survey	$<1x10^{-4}$	$1.8x10^{-3}$	$4.0x10^{-4}$
C	Flux box	$8.5x10^{-5}$	$1.2x10^{-4}$	$1.0x10^{-4}$
	Spiker survey	$2.9x10^{-5}$	$1.3x10^{-1}$	$3.7x10^{-3}$

Note: The units used for reporting fluxes are mg m^{-2} s^{-1} which is the most suitably sized unit and accepted standard for the low fluxes met. Multiplying by site area and period of concern can produce estimates of site contribution to national methane inventory (volumetric). 10^{-4} mg m^{-2} s^{-1} approximates to 5 litres ha^{-1} hr^{-1} of methane.

Flux boxes measure methane emissions from a relatively large surface area (compared with probes). The mathematics is only dependent upon time, concentration, volume and surface area, all of which can be measured simply with reasonable accuracy. Variations in volume and surface area between different flux boxes are minimal. Temperature and pressure corrections are ignored, as they only affect the concentration value by a few per cent at the most. Changes in concentration are usually measurable with a flame ionisation detector (FID).

From a mathematical viewpoint the flux box approach is to be preferred. In summary:

- flux boxes directly measure variables to calculate flux. No assumptions or defaults are needed;
- other methods require assumptions and defaults because they calculate flux using more complex variables;

- there are fewer areas of uncertainty in flux box measurements;
- uncertainties are known and therefore errors understood;
- flux boxes are good for testing the integrity of cover materials.

Additionally flux boxes are more robust and simpler to use.

2.3 Main data set

2.3.1 Introduction

Using flux boxes, we measured methane emission flux at twenty three landfill sites in England and Scotland. These comprise nine privately operated sites and fourteen local authority waste disposal companies (LAWDCs). However, with replicate seasonal visits and sites having more than one landfilled area, we made a total of thirty monitoring visits (to sixteen private operators, fourteen LAWDCs). The geographical spread of sites:

- Bedfordshire;
- East Riding;
- Essex;
- Kent;
- Lanarkshire;
- Lancashire;
- Lincolnshire;
- Oxfordshire;
- Suffolk;
- Surrey; and
- Warwickshire; (see Figure 2.3a)

should reduce the effect on methane emissions of any differences in site management and local climate.

Figure 2.3a. Geographical spread of sites monitored

It should be noted that in this document the following definitions will apply:

- sites: a single landfill site
- site areas: sub-sections of sites
- sets: a group of flux boxes used concurrently on a site area

2.3.2 Sites chosen for measurements

The sites chosen for study largely characterise the variety of sites, closed and operational, in the UK. Following an initial review of factors believed to influence landfill gas production (Section 3.2), we made measurements on sites with different cap types, varying degrees of gas control, type and depth of waste and a range of ages.

Table 3.4a shows the key features of these sites, which also shows the set results discussed below.

The total UK methane emissions inventory is also of importance. This is an area covered by DoE's Global Atmosphere Division. It contracted the National Physical Laboratory (NPL) to formulate an estimate of total methane emissions from UK landfill sites, based on direct measurements. Section 3.5 presents NPL's measurements compared with the results from this project.

2.3.3 Distribution of data

In all there are 247 individual flux box results. The actual fluxes measured range from 10^{-6} to 10^{0} mg m^{-2} s^{-1}.

We have sorted these results into ascending order and plotted against position within the range of results. Figures 2.3a and 2.3b show that the majority, about 80%, of positive flux box results are in the range 10^{-5} to $5x10^{-4}$ mg m^{-2} s^{-1}. The fiftieth percentile, the median of the population of individual flux box results, is approximately 10^{-4} mg m^{-2} s^{-1}. At the limit of detection, about 10^{-6} mg m^{-2} s^{-1}, emissions would approximate to 0.2 m^3 CH_4 per hectare per hour. For the top 20% of data, the highest methane emitters, emissions of 10^{-3} to 10^{0} mg $m^{-2}s^{-1}$ approximate to 180 to 180,000 m^3 CH_4 per hectare per hour. This upper figure is very high and was influenced by the presence of discrete fractures in the cap, due to poor design/engineering and maintenance.

Staff from the Centre for Research into the Built Environment (CRBE) of The Nottingham Trent University[1] assessed the statistical characteristics of the results. We have sorted the sites into different classes of methane emitting potential to examine the distribution of methane fluxes. Cumulative frequency allows significant changes in behaviour to be detected.

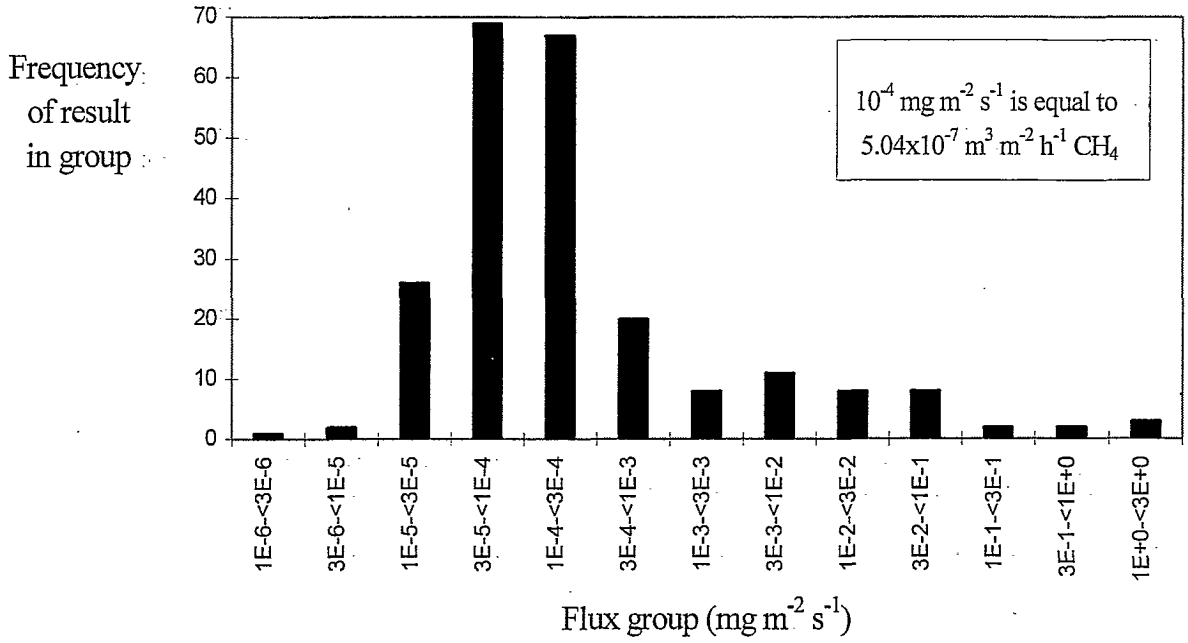

Figure 2.3b. Distribution graph of flux box results

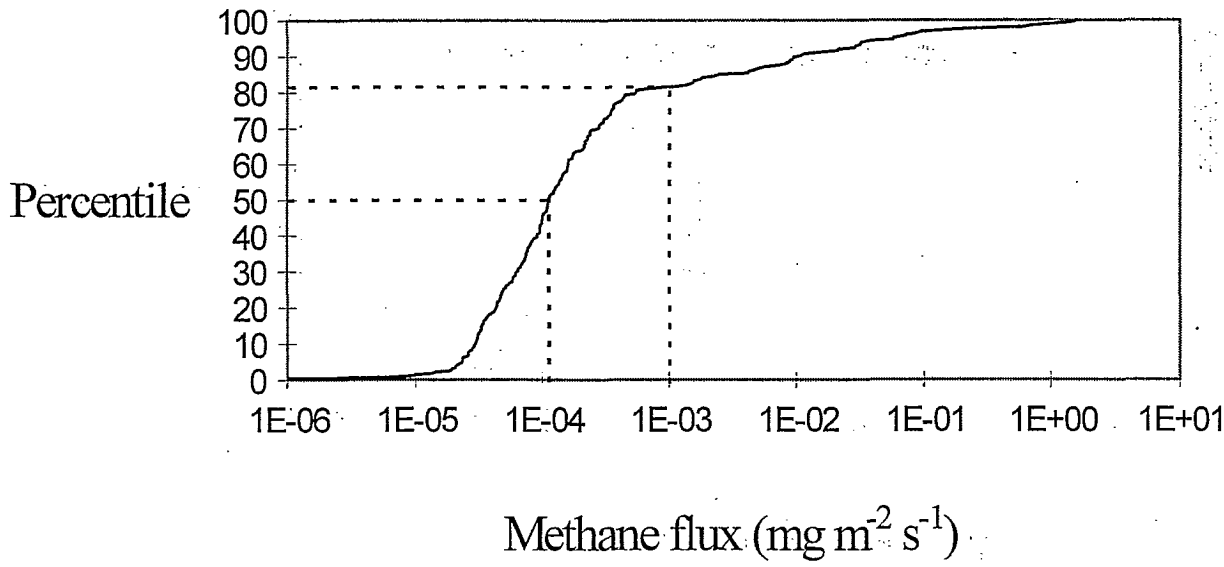

Figure 2.3c. Cumulative distribution of flux box results

[1] Now at Land Quality Management at The University of Nottingham

The methane flux for all sites shows a strong skew with respect to a normal distribution beyond the 80th percentile. There are many more measurements of fluxes greater than $1x10^{-3}$ mg m^{-2} s^{-1} than would be expected by extrapolating from lower fluxes assuming a normal distribution. Indeed, extrapolation from lower fluxes would predict a maximum flux of about $1x10^{-2}$ mg m^{-2} s^{-1}.

2.4 Analysis of data

This section presents an analysis of the statistical characteristics of the measurement distribution, before relating the results to factors believed to affect methane emission fluxes. Table 2.4a summarises average flux box results.

The average result for each area can be overlain on the distribution graph (Figure 2.3b) to assess the relative importance of each site to emission results.

- Seven site areas have average fluxes in the range 10^{-6} to 10^{-4} mg m^{-2} s^{-1}.
- Fourteen site areas have average fluxes within the narrower range of 10^{-4} to 10^{-3} mg m^{-2} s^{-1}.
- The remaining nine site areas have average fluxes in the top band of 10^{-3} to 10^{0} mg m^{-2} s^{-1}.

It is instructive to know the spread within each set of results. Appendix 3 presents the frequency distribution of results for each site (summarised in Table 2.4b).

For some sites the arithmetic mean and the median results may differ by a couple of orders of magnitude, where the median is the value of the middle observation. This happens when there are one or two outlying values that are significantly higher than the majority of that sites data, such as at sites G, R, and S (see Appendix 3 for results). This has important implications when calculating the site total emissions, as the higher values may only pertain to a small area of the site. However, for the purposes of this study the spread of results reflects the uniformity of cap quality and the mean result indicates the overall standard of the site. If the data are evenly spread over the range then the mean and median results are generally similar.

Table 2.4a. Summary of site features and flux box results by measurement set

GENERAL			MEASUREMENT SPECIFIC									RESULTS			
SITE	LOCATION	PERIOD OF OPERATION	WASTE TYPE (as described by operator)	GEOLOGY	CONTAINMENT	CAP TYPE	PERIMETER GAS CONTROL	FULL GAS CONTROL	DEPTH OF WASTE (m)	AGE OF WASTE (years)	ENV SIT'N	AVERAGE FLUX ($mgm^{-2}s^{-1}$) WINTER	STANDARD DEVIATION OF SAMPLE	AVERAGE FLUX ($mgm^{-2}s^{-1}$) SUMMER	STANDARD DEVIATION OF SAMPLE
A	Surrey	90-95	H & I	gravels	Natural	Clay	None	None	5-10	5+	Quarry	9.93E-05	1.81E-05	2.35E-04	1.05E-05
				over clay								9.70E-05	1.49E-05		
B	Surrey	90-present	50% inert,	Sandgate	Unlined	Sand/LDPE		Full	15	<5	Quarry	6.19E-05	2.38E-06	3.00E-04	1.23E-04
			50% Dom/C&I	Beds						<4		5.96E-05	1.55E-05		
C1	Surrey	Late 1970s	50% C&I	Folkestone	Unlined	Soil 1m	Limited	N		20+	Quarry	1.01E-04	1.02E-05		
C2		1980s-1990	50% Dom	Beds		Soil 0.3m			30	6-15				3.92E-01	6.05E-01
D	Kent	Mid 70s to 81	Inert	Ragstone	Minimal	Soil		Flare	15-18	20+	Quarry	2.38E-05	1.39E-05		
E	Oxfordshire	83-94	H & I		Eng'd cells	PFA	Passive venting		10-25	<13		9.03E-03	1.31E-02		
							Pumped			< 5		4.70E-05	2.87E-05		
F	Oxfordshire	77-82	H & I	gravel pit	clay/pfa	None	Some		6	15+	Quarry	4.39E-02	4.68E-02		
						Clay & PFA						2.30E-03	3.54E-03		
G	Oxfordshire	81/2,surcharge	H & I		Clay lined	Clay	None	None	8-9	15 + 2		5.02E-02	1.04E-01		
H	Oxfordshire	86-87	H & I	Clay	Clay lined	PFA	Passive venting		18	10		7.82E-05	2.08E-04		
I	Bedfordshire	68-present	H & I	Clay pit	Clay lined	Clay	5 passive venting wells		<25	< 5		7.05E-05	7.30E-05		
J	Bedfordshire	22-present	40% Inert, 35% Dom,	Chalk	Grate ash	Clay	None	None	up to 35	recent	Quarry	8.05E-03	1.19E-02		
			25% C&I			Clay & soil			about 20	15		1.42E-04	1.25E-04		
K	Bedfordshire	late 80s-now	H & I	Oxford clay	Natural attenuation	Clay		Full plus energy	20	4		4.16E-05	7.81E-06		
								recovery		6		4.88E-05	8.85E-06		

NB: H&I: Household and Industrial wastes
C&I: Commercial and Industrial wastes
MSW: Municipal Solid Waste
Dom: Domestic waste

GENERAL			MEASUREMENT SPECIFIC									RESULTS			
SITE	LOCATION	PERIOD OF OPERATION	WASTE TYPE (as described by operator)	GEOLOGY	CONTAINMENT	CAP TYPE	PERIMETER GAS CONTROL	FULL GAS CONTROL	DEPTH OF WASTE (m)	AGE OF WASTE (years)	ENV SIT'N	AVERAGE FLUX ($mgm^{-2}s^{-1}$) WINTER	STANDARD DEVIATION OF SAMPLE	AVERAGE FLUX ($mgm^{-2}s^{-1}$) SUMMER	STANDARD DEVIATION OF SAMPLE
L	Lancashire	1980 -	Dom/ Comm	Shales overlaid	Natural geology	Clay 1m		Full plus	<30	3-6	Quarry	3.32E-04	7.69E-05	3.64E-05	1.62E-05
		present		with Haslingden		Clay 2m		energy	<20	6-12		1.52E-04	7.62E-05		
				flagstone		Clay 2m wet		recovery	<20	5-8		2.58E-05	2.80E-05		
M	Lanarkshire	1990 -	Dom / Com	open cast with	Natural geology	1m material		Full plus energy	10	4.5-6		8.50E-05	3.65E-05		
		present		clay extraction		(peat)		recovery		1.5-3		5.20E-04	6.15E-04		
N	Essex	upto 1985	Household			soil + 0.5m	Passive venting		10	>11	Landraise			1.96E-03	
		85-87				unworked clay			13-15	9-11				1.31E-03	
O	Suffolk	1980 to 92	Dom / C&I	Chalk		Plastic	small flare most of site		20	4-16		2.99E-04	5.22E-04		
P	Suffolk	1969 to80	50% Dom	gravel pit		boulder clay	flare	none	12	>15		3.19E-04	4.00E-05		
Q	Suffolk	1983 to 92	64 % dom	Chalk/clay		Soil (min)	comprehensive flare		20-30	4-13		3.34E-04	3.34E-04		
R	Warwickshir	Early 60s to 1967	Mixed	Sand & gravel pits	None	Approx 1m material	None	None	13	30+	Quarry			6.01E-02	1.89E-01
S	Lancashire	Phase 2 Dec 89				Clay minimal		None	20	<5	Landraise			4.63E-02	4.00E-02
		to summer 93				Clay 0.3m			10					1.22E-03	3.01E-03
T	East Riding	-present	baled MSW	chalk quarry	rubble/liner to sides only	Clay 1m plus subsoil .5 m	Flare		15	<5	Quarry			1.05E-04	2.80E-05
U	Lincolnshire	1988-present	MSW , C&I		clay lined cells	HDPE &	Flare		<20	<5				1.68E-04	8.41E-05
						restor'n mat'l								4.48E-05	6.77E-05
V	East Riding	1963-95	MSW & commercial		clay liner	clay & plastic	Passive venting		9	15				1.48E-04	2.18E-04
W	Lincolnshire	1981-present	MSW &			clay		Full plus	<36	15				1.24E-03	2.44E-03
			commercial			and		energy		8				1.55E-05	2.32E-05
						soils		recovery		4				5.17E-05	7.92E-05
X	Surrey	Early 1970s	Household	Weald Clay	Natural	None	None	None	<8	20+				1.39E-04	5.51E-05
Y	Surrey	70s/80s	Household	Chalk pit	Natural	Soil	None	None	25	10+	Quarry			1.09E-04	2.46E-05
Z	Surrey	1960s to 1990	C & I	gravel	Natural	No cap	Vent trenches		<10	14	Quarry			All negative	
				extraction						2				8.95E-04	

Table 2.4b. Frequency distribution by site of flux box result and ratio of mean to median results (results in mg methane m^{-2} s^{-1}).

Range / Site	-ve flux	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	Max	Min (+ve)	Mean	Median	Mean / Median
	Number of results in each flux order of magnitude								Fluxes (mg m^{-2} s^{-1})				
A_S				6					$2.50x10^{-4}$	$2.20x10^{-4}$	$2.35x10^{-4}$	$2.35x10^{-4}$	1
A_W				5					$1.24x10^{-4}$	$7.51x10^{-5}$	$9.81x10^{-5}$	$9.83x10^{-5}$	0.999
B_S				6					$4.40x10^{-4}$	$1.02x10^{-4}$	$3.00x10^{-4}$	$3.20x10^{-4}$	0.94
B_W			10						$7.71x10^{-5}$	$3.47x10^{-5}$	$6.07x10^{-5}$	$6.19x10^{-5}$	0.98
C_1			3	3					$1.15x10^{-4}$	$8.53x10^{-5}$	$1.01x10^{-4}$	$9.85x10^{-5}$	1.03
C_2	1		1		2	5	1	3	1.61	$2.81x10^{-5}$	$3.92x10^{-1}$	$3.56x10^{-2}$	11.01
D	1	1	10						$4.22x10^{-5}$	$6.06x10^{-6}$	$2.38x10^{-5}$	$3.08x10^{-5}$	0.77
E	1		6		2	1			$3.16x10^{-2}$	$1.97x10^{-5}$	$4.53x10^{-3}$	$3.81x10^{-5}$	118.90
F			2	4	3	5	1		$1.43x10^{-1}$	$7.48x10^{-5}$	$2.73x10^{-2}$	$8.76x10^{-3}$	3.12
G				3		1	1		$2.36x10^{-1}$	$1.12x10^{-4}$	$5.02x10^{-2}$	$1.85x10^{-4}$	271.35
H	2		2	1					$3.30x10^{-4}$	$2.84x10^{-5}$	$7.83x10^{-5}$	$3.31x10^{-5}$	22.72
I	1		2	2					$1.59x10^{-4}$	$3.34x10^{-5}$	$7.05x10^{-5}$	$9.03x10^{-5}$	0.78
J			3	3	3	1			$2.90x10^{-2}$	$4.68x10^{-5}$	$4.09x10^{-3}$	$4.56x10^{-4}$	8.97
K			10						$5.53x10^{-5}$	$3.2x10^{-5}$	$4.52x10^{-5}$	$4.76x10^{-5}$	0.95
L_W		1	5	9					$4.27x10^{-1}$	$1.02x10^{-6}$	$1.7x10^{-1}$	$1.59x10^{-1}$	1.07
L_S			5						$6.87x10^{-5}$	$2.61x10^{-5}$	$3.64x10^{-5}$	$4.41x10^{-5}$	0.83
M	1		3	5	1				$1.56x10^{-3}$	$4.85x10^{-5}$	$2.97x10^{-4}$	$1.34x10^{-4}$	2.22
N	1		4	2	3				$9.51x10^{-3}$	$2.36x10^{-5}$	$1.37x10^{-3}$	$2.16x10^{-4}$	6.34
O			5	2	1				$4.05x10^{-3}$	$2.91x10^{-5}$	$2.99x10^{-4}$	$5.95x10^{-5}$	5.03
P				2					$3.47x10^{-4}$	$2.91x10^{-4}$	$3.19x10^{-4}$	$3.19x10^{-4}$	1
Q				1							$3.34x10^{-4}$	$3.34x10^{-4}$	1
R		1	2	6			1		$5.99x10^{-1}$	$9.91x10^{-6}$	$6.01x10^{-2}$	$1.57x10^{-4}$	382.80
S				6	1	3			$9.59x10^{-2}$	$1.38x10^{-4}$	$1.48x10^{-2}$	$4.62x10^{-4}$	32.03
T			2	3					$1.47x10^{-4}$	$7.19x10^{-5}$	$1.05x10^{-4}$	$1.00x10^{-4}$	1.05
U	2		2	6					$2.83x10^{-4}$	$3.15x10^{-5}$	$1.73x10^{-4}$	$1.41x10^{-4}$	1.23
V			4	1					$5.36x10^{-4}$	$2.92x10^{-5}$	$1.48x10^{-4}$	$5.93x10^{-5}$	2.50
W	4		6	4	1				$5.61x10^{-3}$	$2.33x10^{-5}$	$1.08x10^{-3}$	$9.68x10^{-5}$	11.16
X			1	4					$2.04x10^{-4}$	$6.79x10^{-5}$	$1.39x10^{-4}$	$1.45x10^{-4}$	0.96
Y			2	3					$1.44x10^{-4}$	$8.12x10^{-5}$	$1.03x10^{-4}$	$1.14x10^{-4}$	0.90
Z	6				2				$1.82x10^{-3}$	$1.75x10^{-3}$	$3.70x10^{-4}$	$3.7x10^{-4}$	1

Twenty flux box results were still negative after correction for ambient air concentrations (see eqn 4, Appendix 1). A negative flux means that the methane concentrations in the sealed flux box decreased with time (i.e. a negative gradient was observed). This suggests that there was a process taking place that removed methane from the flux box. This process may be operating at the same time as

normal methane emissions but at a far lower rate. The evidence for the process was seen only when net methane emissions were at or below the limit of detection of the FID.

Although not proven by direct measurement in the soil, methane oxidation in the upper layers of the capping material could account for these measured negative fluxes. This is particularly when there is an established population of methane oxidising bacteria available to use the reservoir of methane trapped in the flux box.

As the negative methane fluxes were very small, back diffusion from the flux box into the cap (and consequently oxidation to carbon dioxide) also appears a slow process. There is certainly no direct flux box evidence for methane oxidation at sites where high methane emissions are recorded. However, at sites where lower methane fluxes are observed, the likelihood of recording negative methane fluxes alongside positive ones increases. It would appear that oxidation of much of the methane entering the cap only happens where the diffusion gradient through the cap is very small. The diffusion gradient may be the determining factor for methane oxidation in the cap being a significant process. Old, relatively low gassing rate landfills could require only the encouragement of methane oxidation in the cap to achieve low methane emissions. Newer, gassing landfills with higher diffusion gradients in the cap, or with occasional advective pressure-driven releases of gas through cracks in the cap and the sides of the fill, would require either active gas control or engineered containment to control emissions.

A breakdown by variables of the flux results is in Table 2.4c. Appendix 3 presents individual site results.

The following section considers the flux results by analysing the effect of one variable at a time. However, in reality more than one variable may be affecting fluxes at any given point, so obscuring any clear cause-effect relationships. For example, there is not a particularly strong relationship between flux and age in the single variable analysis (Section 2.4.5). But Figure 2.4a shows that the fluxes, when considered for specific cap and gas control combinations tend to be higher for the older (pre-Control of Pollution. Act (COPA)) sites.

Table 2.4c. Summary of results by variable affecting methane flux

Fluxes (mg m^{-2} s^{-1})	No.	Max	Min	Mean	Summary
All sites	45	$3.92x10^{-1}$	$2.38x10^{-5}$	$1.4x10^{-2}$	
Season					Mean of fluxes recorded in summer is approximately one order of magnitude higher than those recorded in winter.
Winter	25	$5.02x10^{-2}$	$2.38x10^{-5}$	$4.66x10^{-3}$	
Summer	20	$3.92x10^{-1}$	$1.55x10^{-5}$	$2.81x10^{-2}$	
Cap type					Poor covers (soil etc.) allow high fluxes.
Clay capped	24	$5.02x10^{-2}$	$1.55x10^{-5}$	$4.77x10^{-3}$	Clay capped sites cover greater range than sand/LDPE sites (which may encourage methane oxidation).
Sand/LDPE	6	$3.00x10^{-4}$	$5.69x10^{-5}$	$1.56x10^{-4}$	
Soil/other material	15	$3.92x10^{-1}$	$2.38x10^{-5}$	$3.62x10^{-2}$	
Engineered	15	$3.32x10^{-4}$	$2.58x10^{-5}$	$1.39x10^{-5}$	Quality of cap is more important than material used.
Non-engineered	30	$3.92x10^{-1}$	$2.38x10^{-5}$	$2.14x10^{-2}$	
Age					
less than 5 years	22	$5.02x10^{-2}$	$1.55x10^{-5}$	$5.49x10^{-3}$	Other effects appear to control methane emissions more than age. Peak emissions during years 5 to 15
5-15 years	15	$3.92x10^{-1}$	$7.82x10^{-5}$	$2.54x10^{-2}$	
more than 15 years	8	$6.01x10^{-2}$	$2.38x10^{-5}$	$1.34x10^{-2}$	
Gas control					
None	20	$6.01x10^{-2}$	$7.82x10^{-5}$	$9.49x10^{-3}$	Only full site gas control appears to reduce average emissions from a site.
Limited cover	11	$3.92x10^{-1}$	$2.38x10^{-5}$	$3.66x10^{-2}$	
Full cover	14	$1.24x10^{-3}$	$1.55x10^{-5}$	$2.12x10^{-4}$	

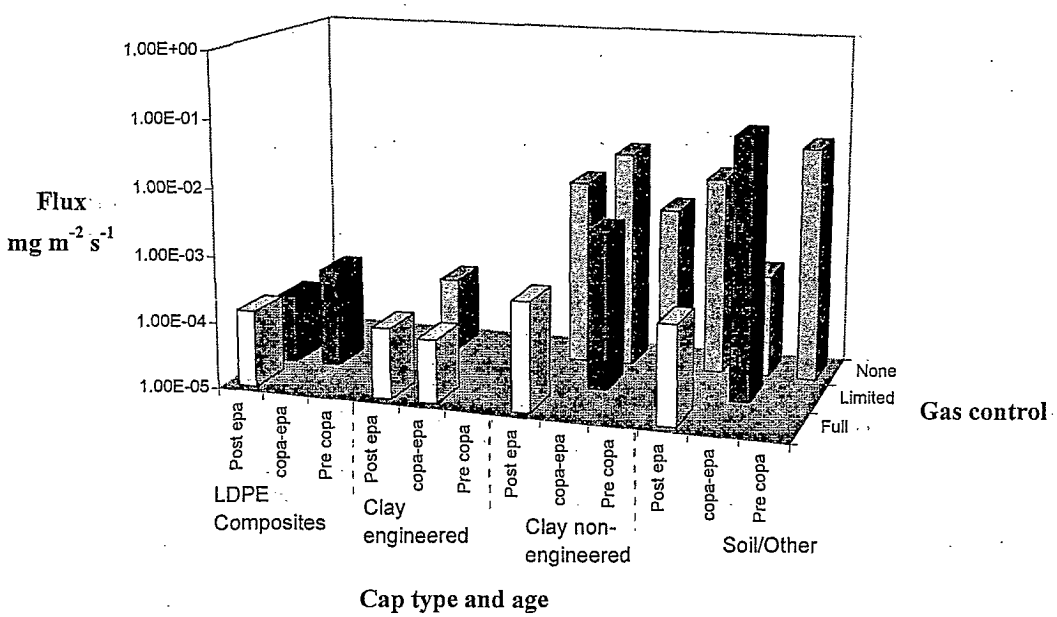

Figure 2.4a. Three way breakdown of variables

In the following sections a well-engineered site is defined as one of good construction that is well maintained and has an adequate thickness of cap made from a low permeability material.

2.4.1 Nature of cap

Generally, poor engineering equates with high methane emissions. It is possible for a site with a poorly engineered cap to have low methane emissions. This may be due to other methods of gas control such as active full-site gas abstraction. Sand/LDPE and other composite caps tend to be well engineered by the above definition.

There are four sites for which the variation in cap type or depth of waste is reasonably well known. At Site L the clay cap varies in thickness; it is 2m thick over the older areas and 1m thick over the newer areas. The mean fluxes from two sets of measurements on the thicker cap were 1.52×10^{-4} mg m^{-2} s^{-1} and 2.58×10^{-5} mg m^{-2} s^{-1}. From the thinner cap the mean flux was 3.32×10^{-4} mg m^{-2} s^{-1}. Figure 2.4b shows these fluxes. Some contribution to this difference may also come from the respective ages of the areas, as methane production rates may differ. The whole area connects to a gas collection and energy recovery system.

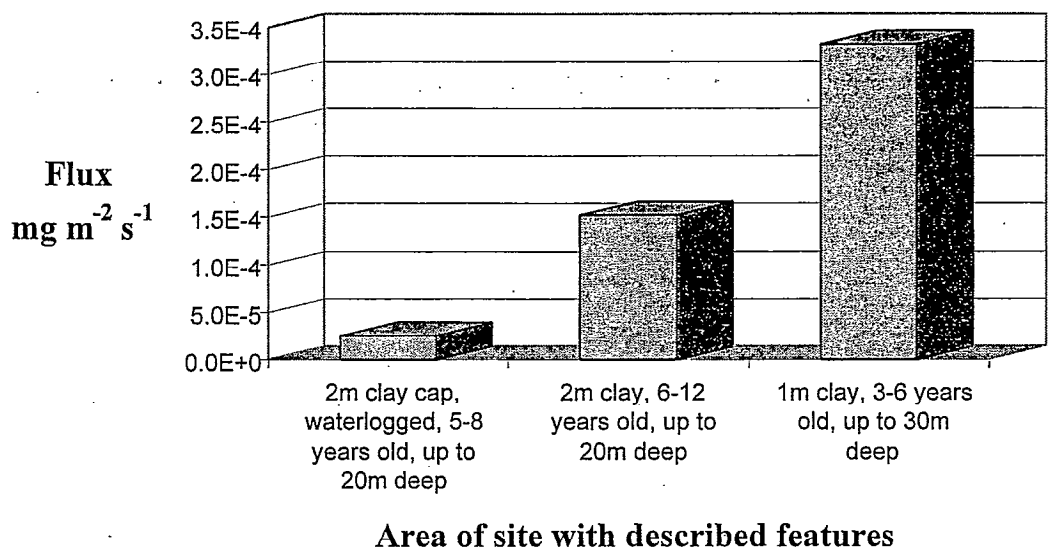

Figure 2.4b. Variation of flux with cap thickness, depth and age of waste, at Site L

At Site F there is a difference in capping material over the area. Approximately 1-2m of clay and pulverised fly ash (PFA) material covers some parts of the site whilst the remainder has up to half a metre of soil. The effect of having the clay cap is to bring mean fluxes down from 4.39×10^{-2} mg m^{-2} s^{-1} to 2.30×10^{-3} mg m^{-2} s^{-1} as illustrated on Figure 2.4c. It should be noted that these fluxes are for an area with a non-engineered cap, (i.e. of indeterminate quality).

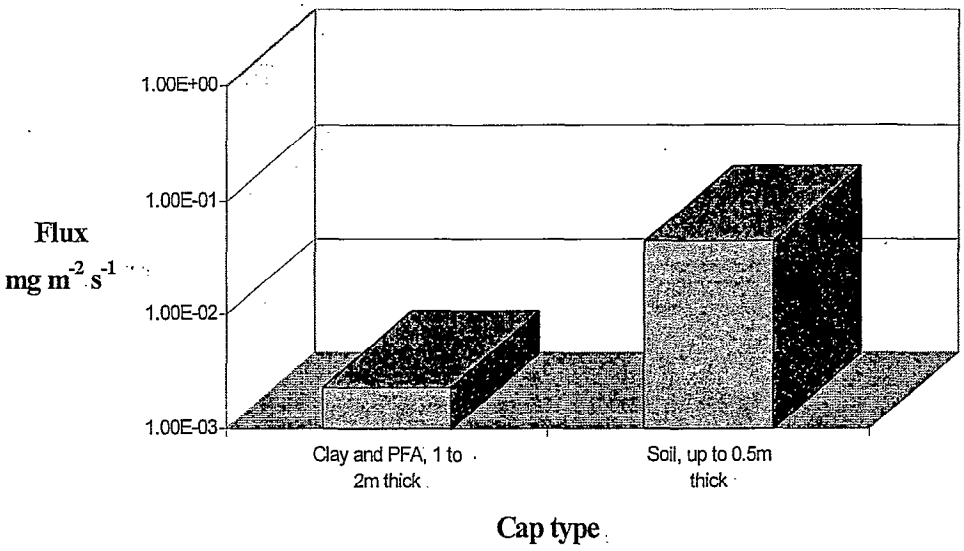

Figure 2.4c. Variation of flux with capping material at Site F

From the site S results it is possible to see the effectiveness of worked clay as a cap to prevent methane emissions (see Fig 2.4d). The three highest fluxes were measured from the deepest part of the waste and from an uncapped section. There is no gas control system at this site. Table 2.4c shows that the average flux from sites with soil/other material caps is up to two orders of magnitude higher than the results for clay and sand/LDPE caps.

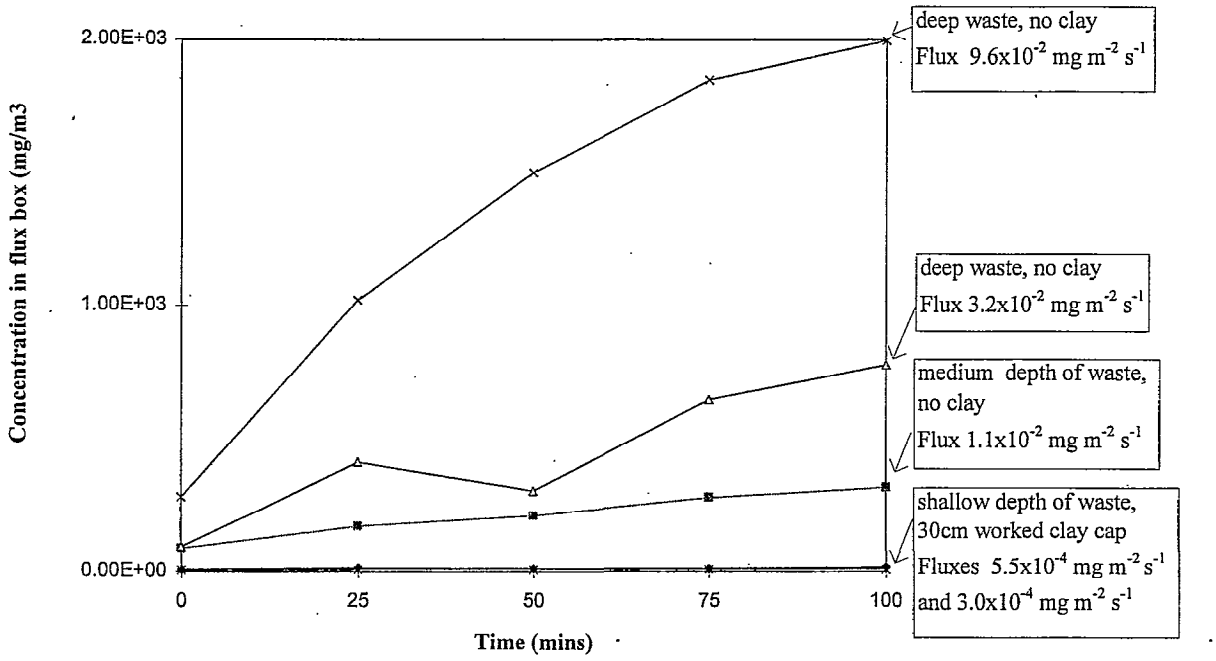

Figure 2.4d. Variation of methane concentrations and flux with cap type and waste thickness at Site S

2.4.2 Nature of gas control

Active gas abstraction can reduce methane by up to two orders of magnitude, in the optimum case, when combined with proper restoration measures (Figure 2.4e). Site E, though normally actively controlled, had one part of its area disconnected from the gas collection system during monitoring, whilst the remainder of the area remained connected. This venting of landfill gas to atmosphere is called passive gas control. Gas control reduces emissions by at least an order of magnitude for sites with other similar variables. Full cover gas control reduces average flux box results by two orders of magnitude in comparison with limited cover or no gas control sites. Table 2.4d shows this.

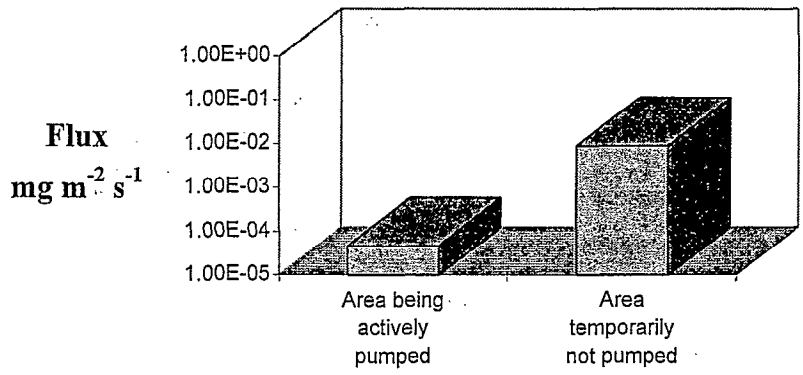

Figure 2.4e. Effect of gas control on Site E

Five study sites have full gas collection schemes for the purposes of energy recovery. We have for four sites compared surface methane emissions with collection rates (knowing the surface area from which the gas is collected). The surface emissions have been converted to units of CH_4 volume emitted to make them comparable with the flare flow rates, and are presented in Table 2.4d below.

It is assumed that the flux through the cap is the average of the measurements made on each site, and no allowance has been made for the effect of any undetected defects in the cap, which could increase emissions significantly.

Table 2.4d. Comparison of gas collection schemes and surface flux

Site	Collection scheme $m^3\ ha^{-1}\ h^{-1}$	Surface flux $m^3\ ha^{-1}\ h^{-1}$	Ratio of gas collected to surface flux
K	169	2.3×10^{-3}	73 000
L	67	8.5×10^{-3}	8 000
M	200	1.5×10^{-2}	13 000
W (phases 1 and 2)	6	6.2×10^{-2}	100
W (phases 3, 4 and 5)	46	1.7×10^{-3}	27 000

Full-site gas collection at these sites appears to divert almost all methane from the cap to a flare or utilisation scheme. In most cases, the diverted fraction is a factor greater than 8000 times that emitted through the surface. At Site W, however, phases 1 and 2 are attached to a flare drawing just 150 $m^3\ h^{-1}$ at 24% methane. The other phases are connected to a utilisation scheme drawing 1050 $m^3\ h^{-1}$ at 48%

methane. It appears, as might be expected intuitively, that when methane production is high, the collection efficiency is much greater than on sites with lower rates of gas production. This is probably because the gas collection system can be operated under a greater negative pressure without pulling air into the collected gas. Even so, there is still a clear benefit associated with the collection and flaring of gas at sites where gas generation rates and gas quality are low, providing the gas can be safely flared.

2.4.3 Effects of depth of waste

At site S there were higher fluxes on the deeper areas of waste. However, as described above, this effect is more likely to result from the nature of the cap in this area. At site L there is 20m of waste in the areas of lower mean flux and 30m of waste in areas with higher mean flux. Whilst depth of waste has some effect, this is not the sole difference to distinguish these areas.

The flux box results (by site area) have been plotted against depth in Figure 2.4f. The data show very little correlation. The largest uncertainty in the position of any data point is the limit of the knowledge on the depth, which is rarely known with any accuracy at any given location. In many cases, site personnel would estimate a range of depth, which may differ by as much as 10m or possibly up to 50% of the waste thickness. Furthermore the landfill gas will find the easiest route through the cap. This may mean that measured emissions are from sources other than those directly below the point of measurement, especially in instances of waterlogging of cap material.

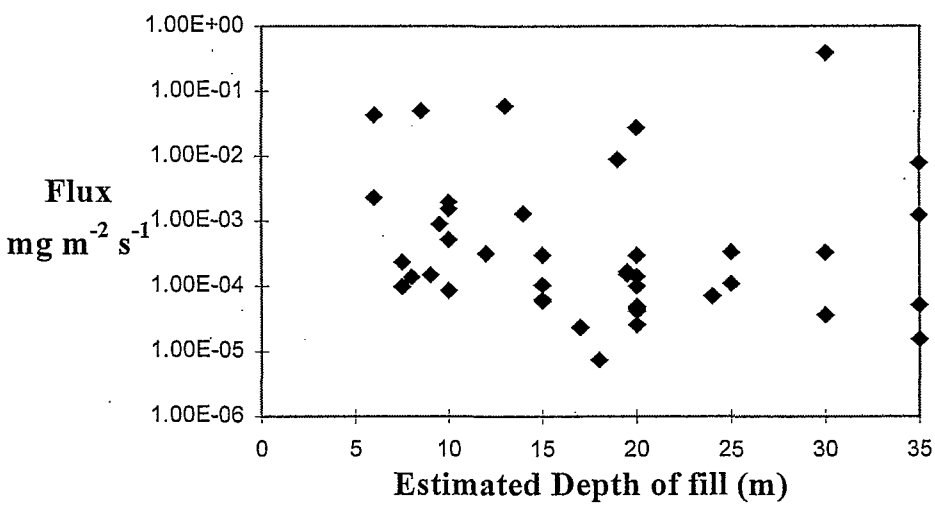

Figure 2.4f. Variation of flux with depth of waste

2.4.4 Spatial variability

Appendix 4 has a detailed statistical analysis of the flux data from this project, plus other case studies, undertaken by CRBE. CRBE found there is no statistically significant correlation between data points more than 40 to 70m apart. Flux boxes should therefore be placed at a spacing of no more than 40m for a thorough coverage of a site. There was order of magnitude flux variations at the high fluxing site, C_2, between flux boxes placed a metre apart. However this variation is within the range expected for the standard deviation of the sample. This emphasises the need to take as many measurements as time and resources will allow to characterise site emissions.

2.4.5 Effects of age

Figure 2.4g shows the effect of age of the waste. Mean methane fluxes measured on different areas of the same site are given for six sites: three of which are actively gas controlled (L, M and W); two are not controlled (C and J). The sixth, Site E, had variable gas control (see Section 2.4.2). The actual age difference varies between 1 year to 18 months at site M to more than a decade, possibly two, at J. The difference in age was about 3 years at L and up to a decade at E. In general lower methane fluxes were measured on the older areas. Site W was the exception. Here the flare on the older area is less effective at preventing emissions than the gas utilisation on the newer area (see Section 2.4.2). This means that gas control has a greater effect on methane emissions than age.

Site C had fluxes over a wide range. The measured methane fluxes varied between the older area and newer area by three orders of magnitude. The age difference is potentially up to fifteen years. However, although neither area is well capped, the area with the lower flux has as much as three times the amounts of soil cover as the area of higher flux. Thus differences in operating practices obscure the effects of age. In general, the older the site the lower the emissions. This compares sites or areas operated and completed in the same regulatory framework (i.e. pre-COPA (Control of Pollution Act, 1974), COPA to EPA (Environmental Protection Act, 1990), or post EPA). Figure 2.4a shows this to some extent.

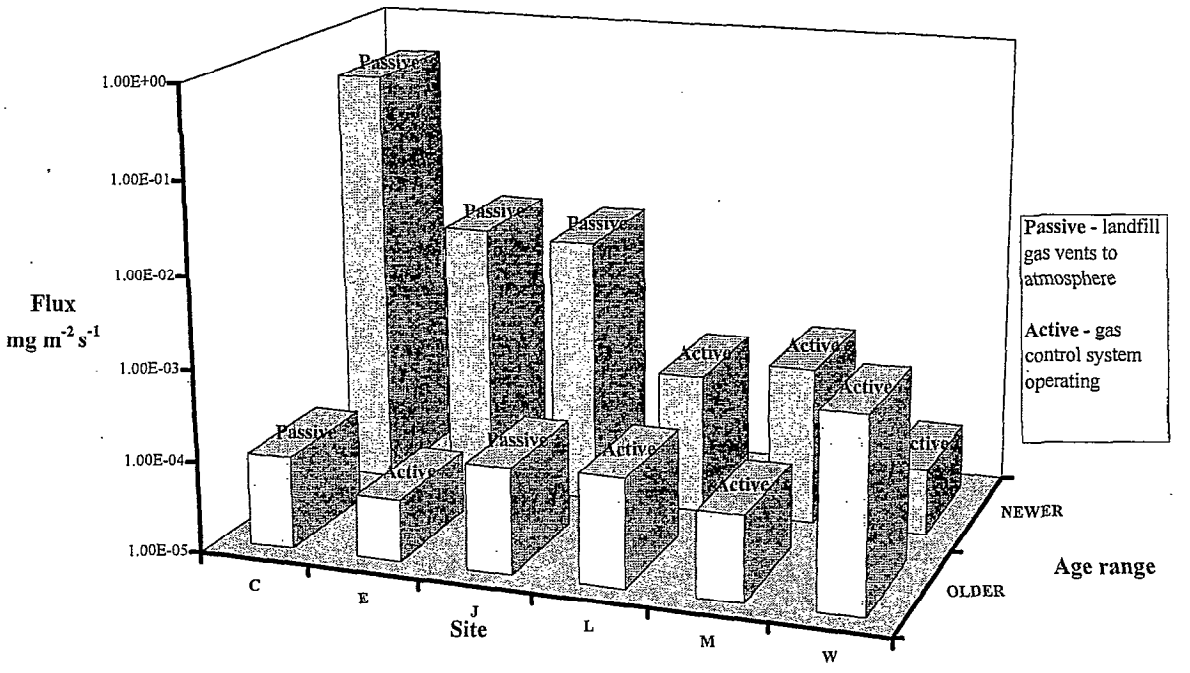

Figure 2.4g. Variation of flux with age of waste

2.4.6 Seasonal variation

There are wide variations and differences in the winter data despite apparently waterlogged caps. The reasons for this appear to be related to age, cover thickness and the presence of active gas abstraction.

Two sites have been visited twice, once at the end of summer 1995 and again during the winter of early 1996. Figure 2.4h presents the mean fluxes measured on these two visits and indicates the winter fluxes as a percentage of the higher summer fluxes.

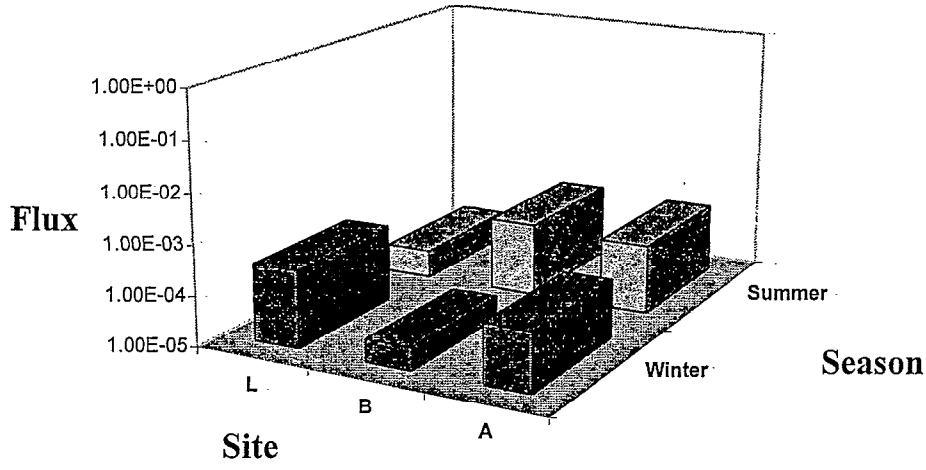

Figure 2.4h. Seasonal variation on Sites A, B and L

We made a second visit to site L with the intention of gaining summer results to complement the results obtained in January. Due to inclement weather the summer visit was abandoned. The fluxes were lower than the winter measurements for the same area. We feel that although the season has some effect on methane emissions there is likely to be more variation resulting from different weather patterns. The average of the aggregate summer fluxes is nearly an order of magnitude higher than the aggregate winter fluxes (Table 2.4c).

2.4.7 Short-term temporal variations

Short term temporal variations result from minor changes around the box such as temperature and pressure changes and alterations in moisture content, from rainfall or evaporation. Good sealing of the flux boxes to the landfill surface can reduce the effect of these variations on flux measurements. Painting boxes white or shielding reduces insolation. NPL examined this in detail, but found no discernible pattern in variations (Milton, 1996).

2.4.8 Effects of waste type

One site was defined as receiving only 'inert' wastes and this had a low methane flux of 2.4×10^{-5} mg m^{-2} s^{-1}. This flux is in the lowest 5% of all data measured and supports our view that 'inert' sites should be low contributors to the methane inventory. Very few sites receive only inert wastes so no further investigations were undertaken.

2.5 Comparison with other UK and International data

There are a number of reported methane studies in the literature. These are predominantly from the United States. The WSA results range from 10^{-5} to 10^{+1} mg m^{-2} s^{-1} (Table 2.5a). These are within the range of measurements from international studies. This suggests that:

- the flux box methodology is scientifically sound; and
- there are no significant differences in the broad behaviour of landfills in the UK compared with those summarised below.

Table 2.5a. Summary of flux box measurements reported from other studies.

References	Method	Lowest flux (mg m^{-2} s^{-1})	Highest flux (mg m^{-2} s^{-1})	Average flux (mg m^{-2} s^{-1})
Kunz & Lu, 1980	Flux Box	$4.3x10^{-3}$	$6.9x10^{-3}$	
Lytwynshyn *et al.*, 1982	Flux Box	$3.6x10^{-4}$	$1.6x10^{-1}$	
Bogner *et al.*, 1988	Flux Box Vertical Gradients			13 20
Bogner & Spokas, 1994	Flux Box	$4.1x10^{-5}$	$7.0x10^{-1}$	
Bogner *et al.*, 1993	Flux Box Vertical Gradients	$3.8x10^{-5}$ $2.3x10^{-4}$	$2.4x10^{-1}$ 3.8	
Reinhart and Paladugu, 1993	Dynamic Flux Box	1.0	1.3	

NPL also surveyed eleven sites monitored for this project. It used its gas flux survey technique. Nine site visits were co-ordinated to make NPL measurements simultaneously with our flux box technique so that all external environmental factors were the same.

The NPL gas flux survey method is based on a portable gas monitor carried along well defined measurement paths at a specific height above the surface of the site. Some of the paths are at the upwind or downwind edge of the site. The remainder traverse the site to locate the position and magnitude of particularly high or low emitting regions. Concentration measurements are then converted to an area

emission rate for the gas. This requires simultaneous measurements of wind speed and direction, together with a solar insolation factor from a meteorological model. NPL reported its methodology to the CH_4 Emissions from UK Landfill Sites Steering Committee (Milton *et al.*, 1997).

Table 2.5b and Figure 2.5a compare the NPL and corresponding WSA results. The WSA results spread over five orders of magnitude, in comparison with NPL results that spread over two orders of magnitude. Three sites show an almost equal correlation between NPL and WSA measurements (C_2, G and R). The characteristics of these sites are quite varied but no measurements were near to operational landfill areas. The remaining twelve data points show higher NPL fluxes compared to WSA fluxes by between one and three orders of magnitude.

Table 2.5b. WSA and NPL results for sites visited in common

Site	WSA result (mg m^{-2} s^{-1})	SD of WSA sample results	NPL result (mg m^{-2} s^{-1})
C_1	$1.01x10^{-4}$	$1.02x10^{-5}$	$1.5x10^{-2}$
C_2	$3.92x10^{-1}$	$6.05x10^{-1}$	$2.9x10^{-1}$
E	$4.53x10^{-3}$	$9.96x10^{-3}$	$1.8x10^{-2}$
F	$2.73x10^{-2}$	$4.13x10^{-2}$	$4.0x10^{-1}$
G	$5.02x10^{-2}$	$1.04x10^{-1}$	$1.8x10^{-2}$
K	$4.52x10^{-5}$	$8.74x10^{-6}$	$6.0x10^{-2}$
L_w	$1.70x10^{-4}$	$1.44x10^{-4}$	$1.4x10^{-1}$
L_s	$3.64x10^{-5}$	$1.62x10^{-5}$	$6.0x10^{-2}$
M	$3.03x10^{-4}$	$4.67x10^{-4}$	$2.1x10^{-1}$
R	$6.01x10^{-2}$	$1.89x10^{-1}$	$4.8x10^{-2}$
S	$1.48x10^{-2}$	$3.02x10^{-2}$	$8.0x10^{-1}$
T	$1.05x10^{-4}$	$2.80x10^{-5}$	$5.0x10^{-2}$
U	$1.06x10^{-4}$	$1.07x10^{-4}$	$1.0x10^{-1}$
V	$1.48x10^{-4}$	$2.18x10^{-4}$	$2.4x10^{-2}$
W	$4.36x10^{-4}$	$1.44x10^{-3}$	$2.0x10^{-2}$

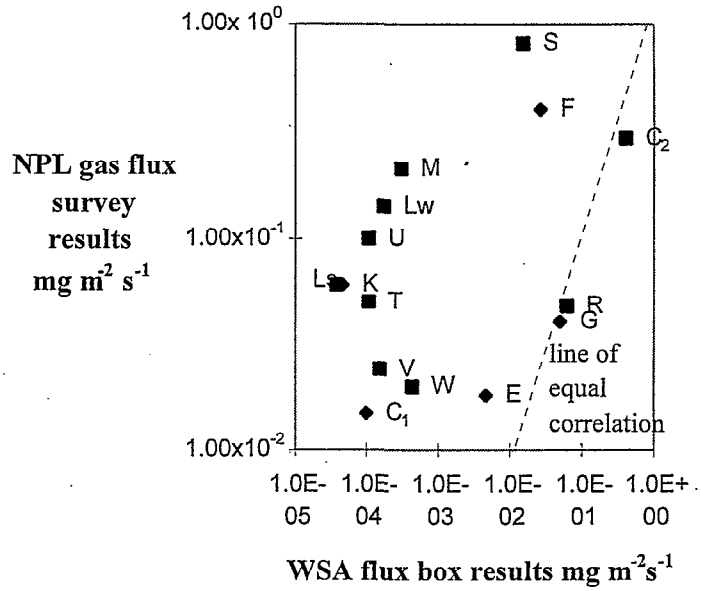

Figure 2.5a. Comparison of NPL and WSA results

The primary reasons for any differences observed are due to the nature of the two techniques. They do not measure the same parameters to derive the flux measurement and both rely on different modelling / mathematical assumptions. The salient differences are summarised thus:

- The WSA technique determines the true flux at the point of measurement. Fluxes vary spatially. The technique will not necessarily detect methane losses at the edge of the cap, and may well miss areas of high emissions from fractures not passing under a flux box;

- The NPL technique estimates total flux from the site from atmospheric concentration measurements, and attempts to correct for influx of atmospheric methane derived from operational areas. This may vary during monitoring the traverses, and there is a strong dependency on meteorologically stable conditions for calculation of the site flux.

The differences are similar in scale to the differences observed between different direct flux measurement techniques, e.g. flux boxes and vertical concentration gradient/spiker survey techniques, illustrated in Figure 2.5b.

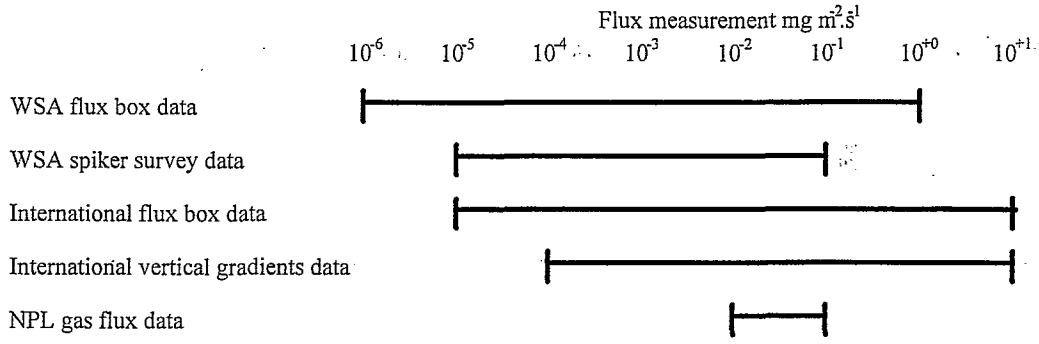

Figure 2.5b. Comparison of ranges of results for reported flux measurement results

We draw the following conclusions from the figure above:

- The WS Atkins data are extremely comparable in range and quality to other data sets reported (although these data represent a significant increase in the amount of available data published).

- The 50 percentile value of $1x10^{-4}$ mg m^{-2} s^{-1} methane for UK flux box data is towards the low end of other reported fluxes. By these data, the UK is not a high methane producer.

- The technique used has collected data at least one order of magnitude below the lower limit of detection reported from other methods. Fluxes below $1x10^{-5}$ mg m^{-2} s^{-1} are not significant.

- It is likely that the range of data collected by WS Atkins encompasses measurements from both high quality, well-maintained caps, and caps with poor engineering quality or discrete fractures present, although on the basis of emissions measured, most caps show a high level of performance against emissions.

- Differences observed between data from WS Atkins and NPL surveys *on some sites* may reflect the difference in emissions due to fractures in engineered caps.

3 LANDFILL METHANE EMISSION CATEGORIES

3.1 Introduction

The outputs from this project are expected to contribute to the following:

- Waste Regulation Policy Group's guidance to waste regulators and landfill operators on the most effective approach to reducing current methane emissions from individual landfill sites;
- assessing the scope for overall UK methane emissions reductions from landfills;
- reducing some uncertainties associated with estimating UK landfill methane emissions.

The aim of this part of the project is to characterise landfills by observable, measurable, or recorded data, into three major categories:

(1) Site types which are contributing *significantly* to UK methane emissions.

(2) Site types that contribute to UK methane emissions, but *to a lesser* (currently unquantified) *degree*.

(3) Site types which, because of their age and/or waste content, are *unlikely to be major contributors* to methane emissions.

This categorisation is to help prioritise policy for CH_4 reduction to sites that are significant contributors to the UK CH_4 inventory.

To determine the most appropriate measure(s) for a particular landfill site without the need for expensive and detailed monitoring, it is first necessary to examine the principal factors and practices that affect methane emissions, and the magnitude of these effects. Classifying a landfill by two or three easily distinguishable features makes it easier to recommend appropriate remedial measures, and to assess the probable cost-effectiveness of the suggested measures in reducing methane emissions. Methane emissions are site dependent and although a categorisation is of limited value it is still important as a tool to provide an overall picture of UK methane emissions.

Previous attempts at classification were examined. These included the *National Assessment Model of Landfill Gas Production* (NAMGAS) and more recent WRc classifications. Neither of these studies measured fluxes or correlated actual emissions with site features but they have formed a suitable starting point for this part of the project.

3.2 Factors affecting methane emissions

We identified the factors likely to affect methane emissions. We combined principal criteria from WRc with the preliminary categorisation scheme from NAMGAS (for which site information will be readily accessible from operators). The main factors are age, waste composition, hydrogeology and surface and management features, and are discussed below.

'Age' Factors

WRc considered three age categories for their classification:

(1) commencement of filling post 1984 (i.e. during the decade prior to the report), assumed to be sites with highest gas potential;
(2) closure pre 1974 (or pre Control of Pollution Act (COPA)), assumed to be of "low gas potential" by WRc; and
(3) operations not falling into either of the first two categories (the "middle ground").

The significance of categorising sites according to this age criterion is not only related to the rate of degradation of the waste, it is also closely related to improving standards.

'Waste Composition' Factors

All sites with any amount of degradable material, can emit landfill gas to a greater or lesser degree. The likelihood of knowing the initial average degradable fraction of waste entering any landfill site decreases significantly with age of the landfill, and detail of records kept. By adopting a pragmatic view on this, it is possible to limit the detailed classification to two categories:

- **Inert Waste Sites** with less than 5% degradable material; and
- **Degradable Waste Sites** with 5-100% degradable material.

Hydrology and Hydrogeology factors

Controls on methane emissions under this heading include the effect of moisture movement through the site (and cap). But perhaps the most significant control on the potential for methane to be lost through the cap is the complementary and competing potential for lateral migration. This will happen in a situation where lateral containment is not ensured either by natural geological containment, engineered containment, or the presence of a good perimeter gas control scheme. The NAMGAS classification treated this criterion by a threefold division into containment, slow dispersal, and rapid dispersal sites. Since the gas permeability of natural or synthetic liners is typically two or more orders of magnitude higher than the permeability to water, even a natural clay engineered barrier (to 10^{-9} m s^{-1}) will leak gas to some degree. The NAMGAS classification also showed that there were relatively few gas producing sites that behaved as rapid dispersal sites. The chosen classification is therefore a simplification of the NAMGAS criteria into two classes:

- **Containment** effected by natural clay, engineered clay, or liner; and
- **Dispersal** where the geology exhibits poor containment.

Surface Features and Active Management Techniques

Of all the criteria relating to loss of methane through the cap, those which appear to affect the potential for methane loss are as follows.

- The design of the cap. Proximity of the waste to the surface of the site, the type of material employed to cap the site, and the thickness of each capping layer all contribute to the capacity (or not) for methane to migrate through the cap.
- The presence or absence of any active gas control measures to control gas migration. Experience suggests that perimeter gas control will limit lateral emissions, and therefore control certain methane emissions in 'dispersal' or 'dilute and attenuate' landfills. Full site gas control schemes should also limit surface emissions by reducing the methane concentration gradient within the landfill cap.

The options for methane emissions control are therefore reduced to the two options below:

- **With Engineered Cap and/or Gas Control**
- **Without either of the above**

3.3 Applying measurement results

The key features described above, age, waste type, containment and control, were used as the basis for selecting a wide range of sites on which to undertake monitoring (Section 2.3.2). Some combinations of the above features were not readily available such as full gas control on old sites or zero controls on large post EPA sites. Section 2.4 presents results obtained from the measurement phase.

The S-shaped distribution of the results fits well with the broad WRc categorisation. The plateau at the top of the distribution being sites that significantly contribute to UK methane emissions, the middle slope being sites with a lesser contribution and the lower tail being sites that are unlikely to be major contributors.

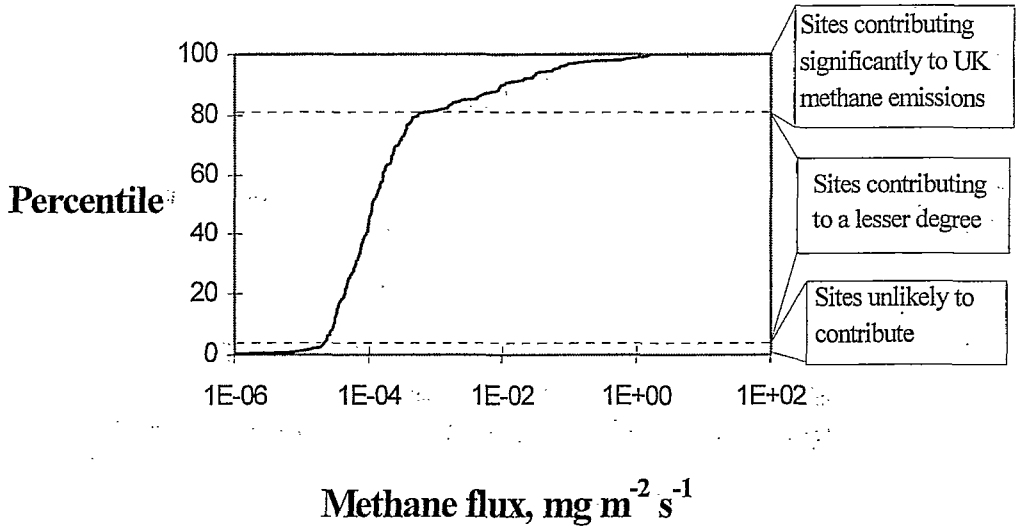

Figure 3.3a. Distribution of contributions to UK methane emissions

It is then necessary to distinguish the features of sites within each part of the distribution plot. On the whole, sites at the top of the distribution plot are uncapped or have a non-engineered cap and have no gas collection scheme or a very limited one. Table 3.3a lists sites with any individual flux box results over 10^{-3} mg m^{-2} s^{-1} and highlights the key features of those sites.

Table 3.3a. Table of sites with flux box results over 10^{-3} mg m^{-2} s^{-1}

Site	Percentage of results over threshold level	Standard of cap	Flaring or energy recovery	Age (years)
C_2	77%	Low	No	>5
F	60%	Low	No	15
G	40%	Low	No	>10
J	40%	Low	No	<5
S	40%	Low/medium	No	<5
E	30%	Medium	No	<5
N	30%	Low	No	>5
Z	20%	Low	No	<5
O	12%	Medium	Flare	>5
M	10%	Medium	Energy recovery	<5
R	10%	Low	No	>30
W	7%	Medium	Energy recovery	<15

From Table 3.3a, for the sites where over 20% of fluxes measured are greater than 10^{-3} mg m^{-2} s^{-1}, not only is there excellent correlation with a low to medium quality cap, none of the sites exhibit any permanent gas flaring or energy recovery. Sites that had gas abstraction had less than 12% of fluxes greater than 10^{-3} mg $m^{-2}s^{-1}$.

From the summary of results in Section 2 the relative effect of each variant can be assessed. This is calculated by setting the lowest mean flux in each class at unity. Table 3.3b shows the results. The most dominant variables are gas control and the quality of cap. Age, cap material and season are variables whose effects are much less significant although they do have a contributory effect. Although the highest relative value is for soil, compared with sand/LDPE caps, this is considered to be a reflection of the level of engineering of the cap. Soil capped sites are generally non-engineered whereas composite capped sites are extensively engineered. The clay caps studied comprised both well-engineered and poorly engineered clay caps.

Table 3.3b. Relative effect of landfill variables on methane fluxes

Variable		Relative value (rounded)
Season	Winter	1
	Summer	6
Cap material	Clay	31
	Sand/LDPE	1
	Soil	232
Cap engineering	Engineered	1
	Non-engineered	154
Age	less than 5 years	1
	5 to 15 years	5
	over 15 years	25
Gas control	None	45
	Limited	173
	Full	1

The relative value of the 'limited gas control' is greater than the relative value of the 'no gas control'. It is dominated by one site that has limited flaring for gas migration purposes but could be argued as having no gas control for surface emissions control. Having a flare on site is no assurance of emission reduction. Whichever category that site is put in, clearly full gas control is the best of the three options for its contribution to emissions reduction.

3.4 Landfill classification scheme

A basic requirement of any landfill classification scheme is simplicity through minimisation of the number of classes and applicability for regulatory control. With these considerations in mind the classification scheme in Table 3.4a has been devised, based on the results described previously.

From the perspective of regulatory control the onus would be expected to be on sites in Class I to retrofit remedial measures or to put forward a suitable case for no additional measures based on actual site measurements. Sites in Class II and III would need to be assessed on an individual basis. Sizeable emissions reductions

may be possible from optimisation of existing controls, such as provision of a suitably sized flare upgrade. There is not likely to be any requirement for sites in Classes IV and V to make any further improvements.

Table 3.4a. Landfill classification scheme

Class	Site description
I	Sites with neither full-site gas control scheme (includes 'no' or 'limited' gas control) nor engineered cap
II	Sites with either full-site gas control scheme or engineered cap but not both
III	Sites with engineered cap and gas abstraction with flare requiring some optimisation
IV	Sites with both engineered cap and full-site gas control (probably with energy recovery)
V	Sites with inert wastes only

4. EFFECTIVE LANDFILL MANAGEMENT TO REDUCE METHANE EMISSIONS

4.1 Introduction

This study has addressed the scale of methane emissions through the surface of various landfill types. It has not regarded lateral migration through the sides of the site. Such migration might in some cases be enhanced by a low permeability cover on the landfill, unless the potential is countered by some form of perimeter gas control. The exact effect of any such controls on the ultimate emissions of methane is not calculable, although some inferences can be drawn from the data acquired during this study.

Some form of gas migration control should be assumed on at least those sections of a landfill boundary that present a risk to the local environment. Current statutory requirements demand this. However, it is not within the scope of this study to assess how the effectiveness of such boundary controls might be compromised by an enhanced cover system aimed at minimising surface emissions. This is, therefore, seen as a further variable in the complex equation for measuring cost-effectiveness.

4.2 Emission Potential of Classes I to V

Table 4.2a gives the average flux values for the various classes of site identified. This shows clearly that Class I sites have emissions nearly two orders greater than the next worst class. There is generally less than one order of magnitude difference estimated in emissions between the remaining classes. Thus applying measures to a Class I site to convert it to a Class II site would be much more 'environmentally cost effective' than any other measures. That is provided there was a simple harmony between the respective cost bands. Moreover, when measured against compliance with the EC target reduction of 30% in emissions by 2005 (EC, 1996), then clearly the greatest benefits would arise from enhanced control measures to Class I sites. These comprise nearly a third of the waste in place in UK sites, according to data held in the Landfill GIS database (Milton, 1996). Fully abated methane emissions from this class could reduce emissions by over 90%. On the whole, although not exclusively, the Class I sites tend to have been run by the smaller independent companies or former local authorities. In these cases the available landfill site management experience may not be comparable with the larger independent operators.

Table 4.2a Fluxes associated with each class of landfill

Class	No. of observed results in class	Percentage of observed results	Average observed flux mg m^{-2} s^{-1}
I	56	25	$1.12x10^{-1}$
II	62	27	$5.43x10^{-3}$
III	16	7	$4.41x10^{-4}$
IV	82	36	$1.57x10^{-4}$
V	11	5	$2.67x10^{-5}$

4.3 Assumptions and Definitions Used in Cost Benefit Calculations

In estimating the costs and benefits of management practices, it would be ideal if costs and benefits were quantified in the same unit of measurement to allow direct comparison. However, at present there is insufficient information and consensus on either the financial benefit of reducing greenhouse gas emissions or on the financial cost of no abatement. In this section costs of remedial measures are calculated, based on a unit area of landfill, for a variety of size and depth combinations. Benefits are characterised, primarily, by quantity of CH_4 atmospheric emissions abated and, secondarily, on any coincidental benefits accruing (i.e. added value such as reducing leachate generation). This will allow comparison between schemes, applied to the different classes, to the potential impact on UK emissions as a whole.

4.3.1 Defining the unit area

The unit area is defined as an area of 100m by 100m (i.e. 1 hectare). Costing data has been collated for capping materials and gas control schemes. From Section 2.4 it is estimated that 300mm of clay reduces emissions by an order of magnitude. However, the capping costs have been based on a more rigorous cap that includes subsoil and topsoil for restoration activities and consequently achieves greater emissions reductions.

Emission potential during the earlier stages of sites is such that a high capacity system would be required for gas control. This is referred to as an 'active' system and is assumed to comprise four gas wells per hectare with interconnecting pipework and valves. In older sites with less methane potential, two wells per hectare are assumed. This is referred to as an 'intermediate' system. The additional

work required for the extra wells adds significantly to the gas control costs. Appendix 5 contains the layout and base costs of wells, pipework and capping.

4.3.2 Methane emission potential

An estimate of methane emission potential yield (assuming no control measures) has been made using a gas production model (WS Atkins, 1997) for comparison with costs of aversion, on the following assumptions:

- Site was filled with 100% domestic waste at time zero;
- emission rate halves every 10 years over the site life.

Each representative site will have a residual methane volume associated with it, and this can be calculated from the model. Figure 4.3a shows an example of the primary output. These values have been converted to units of methane emission per unit volume of waste per hour to allow flare capacity to be calculated. Thus it has been calculated that:

- a 3 year old site has a residual volume of 70.2 m^3 $tonne^{-1}$ of waste
- a 10 year old site has a residual volume of 34.8 m^3 $tonne^{-1}$ of waste; and
- a 30 year old site has a residual volume of 4.71 m^3 $tonne^{-1}$ of waste

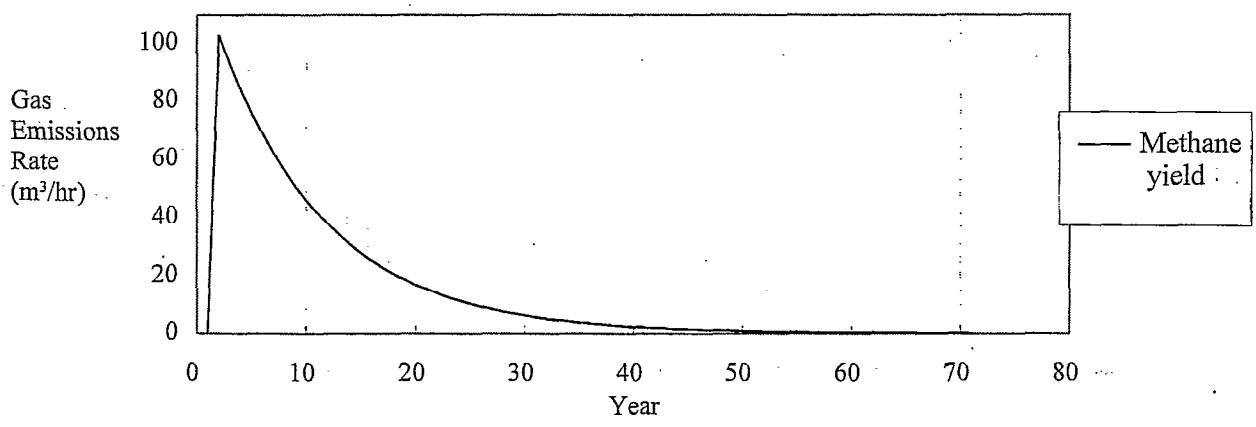

Figure 4.3a Gas emission model used for scenarios (1 hectare, 10m depth)

Thus for each combination of size and depth of site (i.e. volume) there is an estimated residual volume as shown in Table 4.3a.

Table 4.3a. Residual volume of methane (available for remediation)

Site Size	Depth of Waste (m)	Age of Waste (y)	Residual Volume (m^3 methane)
3 ha (30 000 m^2)	10	3	2.11×10^7
		10	1.04×10^7
		30	1.41×10^6
	20	3	4.21×10^7
		10	2.09×10^7
		30	2.83×10^6
10 ha (100 000 m^2)	10	3	7.02×10^7
		10	3.48×10^7
		30	4.71×10^6
	20	3	1.40×10^8
		10	6.96×10^7
		30	9.42×10^6
30 ha (300 000 m^2)	10	3	2.11×10^8
		10	1.04×10^8
		30	1.41×10^7
	20	3	4.21×10^8
		10	2.09×10^8
		30	2.83×10^7

4.3.3 Basis of Cost Benefit Calculations.

For this costing exercise it is assumed that conversion of a particular class of site to a class with a lower average emissions rate will result in the scale of methane emission reductions shown in Table 4.3b. These emission reduction factors have been judged to reflect the results described in Section 2 and the fluxes associated with each class of landfill summarised in Table 4.2a.

It should be noted that potentially detrimental effects such as lateral migration have not been quantified. The emission reduction factors developed for cap emplacement may not fully reflect the practical situation.

Table 4.3b. Scale of methane emission reduction

Initial class	Final class	Action taken	Emission reduction factor
I	II	Cap emplacement	20
I	II	Gas control and minimal cap installed	50
I	IV	Cap and gas control installed	1000
II	IV	Cap emplacement	25
II	IV	Gas control installed	25
III	IV	Optimisation of flare	<10

Appendix 5 details the various combinations of size of site, age of site and depth of waste. When performing the calculations for the cost benefit, undiscounted costs do not include the effects of emission abatement whilst examples with discounted costs include the most appropriate emissions reduction factors for the scenario considered.

Costs have been discounted over a period of n years to give net present value, assuming an average discount rate (r) of 5%, as follows:

$$\text{Net present value} = \frac{\text{Cost}}{(1+r)^n}$$

Discounting is applied to costs that would be incurred in the future life of a new site. For older sites the net present value of remediation is the undiscounted cost.

4.4 Results of Undiscounted Cost Scenarios

The undiscounted costs of methane emission control were calculated for each residual cubic metres of methane that could potentially be released for each age, size and depth of site combination. Table 4.4a shows that there is a strong depth and age dependence on the cost of control measures applied. Applying a capping system late in the life of a site provides lesser benefits for the same cost.

Table 4.4a Summary of Remedial Measures Costs

Site Depth	Cost to remediate full residual volume (£m^{-3} methane)		
	Capping and Flaring	Capping and Flaring	Capping (low quality)
	3 year old site	10 year old site	30 year old site
10m	~ 0.03	~ 0.05	~ 0.11
20m	~ 0.016	~ 0.03	~ 0.06

Data summarised from Table 4.4a, Appendix 5.

There are a number of key observations about the results of this analysis.

- Economies of scale come from deeper sites rather than sites with a larger surface area.
- Total costs of methane emission control decrease with age (gradually at first), but the costs per residual m^3 methane controlled increase.
- Any cost advantage in deferring costs to a later age is significantly offset by missed methane emission control.
- Most of the methane controlled comes from measures installed early in the site life.

Appendix 5 Table 4.4a presents the full set of data collected on costs for all combinations of site size, depth and age.

4.5 Results of Discounted Cost Benefit Studies

4.5.1 Abatement Data

The data presented in Tables 4.5a and 4.5b have been calculated for a 10 hectare site with waste depths of 10m and 20m respectively. The emission reduction factors given in Table 4.3b have been used to calculate the discounted cost and the cost of methane abatement per cubic metre of residual gas abated.

These data reinforce the observation that economies of scale are obtained for deeper sites, not sites of a larger surface area. The optimum time for installation of gas control measures is early in the site life when the methane available for abatement is greatest. For measure introduced at a later stage the costs are lower due to discounting but the methane available for abatement has dropped quite considerably.

It can be seen that capping costs dominate the total methane emissions control costs with flare installation costs typically being 10% of the total. For a Class I site the most cost effective method of methane emissions reduction is judged to be installation of a full site gas control scheme with (at least) a minimal cap. The key benefits of this approach are:

- methane converted to carbon dioxide;
- cap reduces air ingress and methane egress; and
- a minimal clay cap, at 25% of the cost of an engineered cap (see Appendix 5), would achieve 90% of the abatement of the engineered cap, if combined with full site gas control scheme.

Table 4.5a Discounted costs, methane abatement and added value of class conversion for 10 hectare site, 10m deep.

Year	Initial class	Final class	Action taken	Abatement volume (m3)	Discounted cost (£)	Cost of abatement (£m-3)	Added value
3	1	2	Cap emplacement	66690000	1.73E+06	0.026	Leachate control
	1	2	Gas control and minimal cap installed	68796000	5.47E+05	0.008	Energy recovery + leachate control
	1	4	Cap and gas control installed	70129800	1.84E+06	0.026	Energy recovery + leachate control
	2	4	Cap emplacement	3369600	1.73E+06	0.513	Leachate control
	2	4	Gas control installed	1347840	7.83E+04	0.058	
	3	4	Optimisation of flare	1263600	1.30E+04	0.010	
10	1	2	Cap emplacement	33060000	1.01E+06	0.031	Leachate control
	1	2	Gas control and minimal cap installed	34104000	3.66E+05	0.011	Energy recovery + leachate control
	1	4	Cap and gas control installed	34765200	1.07E+06	0.031	Energy recovery + leachate control
	2	4	Cap emplacement	1670400	1.01E+06	0.606	Leachate control
	2	4	Gas control installed	668160	5.57E+04	0.083	
	3	4	Optimisation of flare	626400	9.21E+03	0.015	
30	1	2	Cap emplacement	4474500	3.82E+05	0.085	Leachate control
	1	2	Gas control and minimal cap installed	4615800	1.37E+05	0.030	Leachate control
	1	4	Cap and gas control installed	4705290	4.03E+05	0.086	Leachate control
	2	4	Cap emplacement	226080	3.82E+05	1.689	Leachate control
	2	4	Gas control installed	90432	2.10E+04	0.232	
	3	4	Optimisation of flare	84780	3.47E+03	0.041	

Table 4.5b Discounted costs, methane abatement and added value of class conversion for 10 hectare site, 20m deep

Year	Initial class	Final class	Action taken	Abatement Volume (m3)	Discounted cost (£)	Cost of Abatement (£m-3)	Added value
3	1	2	Cap emplacement	133380000	1.73E+06	0.013	Leachate control
	1	2	Gas control and minimal cap installed	137592000	5.83E+05	0.004	Energy recovery + leachate control
	1	4	Cap and gas control installed	140259600	1.88E+06	0.013	Energy recovery + leachate control
	2	4	Cap emplacement	6739200	1.73E+06	0.256	Leachate control
	2	4	Gas control installed	2695680	8.69E+04	0.032	
	3	4	Optimisation of flare	2527200	1.30E+04	0.005	
10	1	2	Cap emplacement	66120000	1.01E+06	0.015	Leachate control
	1	2	Gas control and minimal cap installed	68208000	3.75E+05	0.005	Energy recovery + leachate control
	1	4	Cap and gas control installed	69530400	1.08E+06	0.016	Energy recovery + leachate control
	2	4	Cap emplacement	3340800	1.01E+06	0.303	Leachate control
	2	4	Gas control installed	1336320	6.18E+04	0.046	
	3	4	Optimisation of flare	1252800	9.21E+03	0.007	
30	1	2	Cap emplacement	8949000	3.82E+05	0.043	Leachate control
	1	2	Gas control and minimal cap installed	9231600	1.39E+05	0.015	Leachate control
	1	4	Cap and gas control installed	9410580	4.05E+05	0.043	Leachate control
	2	4	Cap emplacement	452160	3.82E+05	0.844	Leachate control
	2	4	Gas control installed	180864	2.33E+04	0.129	
	3	4	Optimisation of flare	169560	3.47E+03	0.020	

The costs and benefits of flare optimisation are highly site specific, resulting in a wide range of cost estimates (see Appendix 5). Sites requiring flare optimisation are not expected to comprise more than 10% of sites with limited gas control schemes. There is little scope for substantial reduction of national methane emissions by this route.

4.5.2 Costs to Achieve Target Reductions.

It is possible from these calculations to make a first order estimate of the cost to the UK of achieving the EC target reduction of 30% of 1990 landfill methane emissions by 2005. Table 4.5a compares the percentage of observed sites in each identified category with data obtained from the Landfill GIS database that has been fitted to the classification devised.

Table 4.5c Number and Mass of landfill waste associated with each class of landfill

Class	Average observed flux mg m^{-2} s^{-1}	Percentage of observed results	Percentage of UK sites[1]		Mass of waste in UK by category (Mt)[1]
			by mass	by no. of sites	
I	$1.12x10^{-1}$	25	32.3	25.6	525
II	$5.43x10^{-3}$	27	52.3	65.8	850
III	$4.41x10^{-4}$	7			
IV	$1.57x10^{-4}$	36	15.4	8.6	250
V	$2.67x10^{-5}$	5	-	-	-

[1] On the basis of data according to Landfill GIS database, excluding inert wastes, for sites closed post 1980.

The calculations assume 1 mol of methane weighs 16g and occupies 22.4 litres at STP, and the gas emissions model forecast that the total yield of methane from 1 tonne of domestic waste is 94.8 m^3, with a residual volume after 10 years of 34.8 m^3.

Since we are not considering individual sites, but a continuum whereby new waste maintains the status quo on methane emissions at the present time, we can assume that the average rate of gas production for a Class I site between 1-10 years old will be in the order of 6m^3 per tonne of waste per year. That is equivalent to 4.3 kg of methane. For the purposes of this calculation the mass of waste in Class I landfills should be assumed to be constant over the period of the calculation. That is as sites become Class II, then new Class I sites are brought on stream.

The EC emissions reduction requirement is 0.6Mt on a total yearly methane budget of 2.0Mt that has not changed significantly from 1990 to 1994. To abate 0.6Mt methane, control therefore needs to be exercised over 140Mt of waste. Class 1

landfills contribute over 90% of the methane emissions budget and some 30% by mass of the landfills in the UK. Moreover, achievement of abatement from Class 1 to Class II on one third of the mass believed to be present in Class I sites would achieve an abatement equivalent to the EC target. 33% of sites with 97% or 2 orders of methane emissions reduction is forecast by implementing full-site gas control with a minimal cap.

The undiscounted cost of abatement per cubic metre methane for a Class 1 site ranges from £0.02 to £0.05, depending on depth and age.

The 0.6Mt that needs to be abated has a volume of 8.4×10^8 m^3, which, from the above estimated range would cost the UK between £17 million and £42 million (averaging out at £34 million) to implement.

5. CONCLUSIONS

5.1 Emissions Characteristics

The data show that the principal classification of the sites vis-à-vis emission risks is based on the level of site cover and gas control. The normal parameters used to categorise sites (i.e. percentage biodegradable waste, waste age, site depth, water regime, and site geology), are of much less importance. This finding makes it easier to classify sites not only because there are fewer parameters to consider but also because information on the historical design and operational parameters may be more difficult to acquire.

The results of the site investigations fully confirmed the intuitive judgement that a good quality cap and the presence of full site gas control have a strong beneficial effect on controlling methane emissions. At one site where gas collection had been temporarily suspended on part of the area monitored, there was an increase of up to two orders of magnitude in methane emissions. This was in comparison with the area still being pumped.

Perhaps, paradoxically, emissions from a landfill with relatively low levels of gas production can be greater than from a landfill with higher gas production and gas management. At one capped landfill site studied, the average surface flux from an area with low gas production and flare control was 97% higher than from an area of high gas production with gas utilisation. This may reflect a difficulty of collecting landfill gas at combustible concentrations as the waste ages, and gas production tails off.

The lack of effectiveness of perimeter or partial gas control systems can probably be explained, to some extent, by the fact that such systems are most commonly designed to control lateral migration (possibly only in one direction from the site, depending on the relationship of the site with sensitive features). Equally such migration controls would be most unlikely to influence the gas regime in the central zone of the site where the greatest potential exists for emissions.

5.2 Cost Effectiveness of Management Options

Observation of fully controlled sites (as deemed appropriate under existing statute and 'best current practice') suggest that the average surface emission rate from a

well-maintained cap, of some $1x10^{-4}$ mg m^{-2} s^{-1}, could be considered as 'optimal'. This represents the reasonable practical limit of any emission control system, remembering that 'inert' sites are only one order of magnitude better. This value does not take into account any defects in the cap that, on the basis of the range of observations reported here, may increase emissions by at least one order of magnitude.

At first sight, this value would suggest that site Classes I and II, and possibly some of Class III, require some remediation measures. However, to achieve the proposed EC reduction in emissions by 2005 (Section 1.1), only approximately one third of the highest emitters (i.e. Class I landfills) would need to be remediated. For sites with total site emissions below 1×10^{-3} mg m^{-2} s^{-1} there would be no requirement for remediation.

There are a number of key observations about the results of the analysis.

- Economies of scale come from deeper sites rather than sites with a larger surface area.
- Total costs of methane emission control decrease with age (gradually at first), but the costs per residual m^3 methane controlled increase.
- Any cost advantage in deferring costs to a later age is significantly offset by missed methane emission control.
- Most of the methane controlled comes from measures installed early in the site life.

Capping costs dominate the total control costs with flare installation costs typically being 10% of the total. For a Class I site the most cost effective method of methane emissions reduction is judged to be installation of a gas control scheme with minimal cap. Sites requiring optimisation of the flare operation are not expected to comprise more than 10% of sites with limited gas control schemes. There is little scope for substantial reduction of national methane emissions by this route.

6. RECOMMENDED ASSESSMENT PROTOCOL

The protocol outlined below are those which are considered to be additional to requirements of such documents as WMP 26 and WMP 27, the latter dealing explicitly with landfill gas. In meeting the various needs for environmental control it will usually be inevitable that both on-site and off-site monitoring of gas regimes and ground conditions (including groundwater) will be carried out so as to:

a) a) assess the need for any measures; and
b) b) to prescribe the scale and extent of any such measures.

In effect the only protocols needed are those relating to Classes I and II, and possibly some of Class III.

* Class I: it is considered that the following is appropriate:

(i) Confirm the site classification.

(ii) Inspect the site generally for surface cracks and other explicit potential emission locations.

(iii) Set out flux boxes on an approximate 40m grid or such centres that will achieve, as a normal, 8-10 measurement positions per phase of site.

(iv) Use measurement protocols as set out in Appendix 1 to this report, with data collection periods that optimise the prospect of measuring worst emission conditions.

(v) Supplement the flux box data by measuring emissions from cracks and other potential emission locations.

(vi) Carry out selective corroboratory measurements by spiking the site surface (bearing in mind that it is a less efficient technique).

* Class II : (A) where the site does not have a site cover then the protocol should be as for Class I sites.

(B) where the site has a cover system the frequency of the flux boxes spacing can be reduced to some 60m centres (i.e. less than half the 'density') and the minimum number of locations reduced to 6-8 per site, all subject to the site cover design being considered 'reasonable' in the first instance.

* Class III : As for Class II

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APPENDIX 1: METHODS FOR FLUX ESTIMATION

Contents

APPENDIX 1: METHODS FOR FLUX ESTIMATION

1 INTRODUCTION

This section describes the flux measurement techniques which were considered at the beginning of the project and the three methods chosen for site trials (which are discussed in section 3). Table 1.1a, at the end of the section, summarises the advantages and disadvantages of the techniques described below.

1.1 Methods for methane emission rate measurement

Gas flux, or flow through unit area in unit time, can be assessed by measurement of gas velocity. Typical sensitivities of flowmeters, of the order of $0.05ms^{-1}$, are considered to be too high to be suitable for most landfill gas flux measurements. Change in gas concentration is a flux dependant variable. This can be measured with enough accuracy to allow an estimate of gas flux to be made on the basis that the change in concentration in a volume over a given time is proportional to the flux into that volume.

Methane emission rates from landfills can be measured by either direct or indirect techniques. Direct measurement techniques measure gas concentrations in, or in direct contact with, the ground and represent fluxes from a point source within the landfill. These measurements are then aggregated to produce *estimates* of whole site average gas fluxes. The measurements also give spatial variations across the area under investigation. Uncertainty in direct measurements arises from the fact that all of the gas generated is assumed to migrate through the surface and any lateral or basal migration pathways are therefore ignored. The following are examples of direct measurement techniques:

- flux boxes;
- sub-surface vertical methane gradients;
- sub-surface spiker surveys;
- permanent/semi-permanent sampling points.

Direct techniques are described in some detail in Section 2 below, including the mathematical assumptions and the associated errors. These techniques require detectors which sample the gas in order to determine the concentration. Samples may be analysed on site, or collected and stored for later analysis (Bogner and

Scott, 1995). Detectors suitable for direct measurement techniques are described in Section 3.

Indirect measurement techniques measure gas concentrations from all sources above the ground. These measurements are then related mathematically and statistically to the points of origin of the gas, to give an estimate of the average gas flux from the whole site. The following are examples of indirect measurement techniques:

- micro-meteorological methods
- tracer techniques
- long-path techniques

We decided that these techniques were not suitable for on-site trialling as they tend to be expensive, complex and require detailed analysis of the results. The project aimed to evaluate inexpensive, relatively simple, practical methods, to facilitate replication by operators and WRAs. A brief description and the key points associated with these techniques follow.

1.2 Indirect measurement techniques

i) Micrometeorological methods

An internal boundary layer develops when wind blows over an area of uniform surface characteristics. Vertical fluxes are constant with height and equal to the fluxes at the surface so that measurement of the vertical flux at any point within the boundary layer will be related to the flux at the surface. The strength of micrometeorological methods is the capability to estimate fluxes across a wide area with minimal disturbance to the underlying surface. The methods can be automated and are useful in measurements of diurnal and seasonal variations in gas fluxes. Weaknesses include the need for expensive, complex equipment, complex calculations and surface constraints that may limit the use to areas with an even surface *e.g.* wetlands (TIGER 1990-1992)

Experiments carried out using both micrometeorological methods and chamber techniques at one Tennessee (Meyers *et al.*, 1992) and three Dutch landfills (Verschut *et al.*, 1991) have shown that micrometeorological methods give comparable results to those obtained using flux boxes and seem to be less variable. However, for the micrometeorological gradient technique, a wind speed greater than 1 m s^{-1} is required and accuracy is limited to 20 - 30% (Oonk, 1994). Also, whilst the 'footprint' (the actual land surface area being observed

for the trace gas measurements) for flux boxes is accurately known, there is some difficulty in determining the footprint of micrometeorological techniques, in particular when there are areas of active landfill operation in the vicinity.

In summary the advantages of this survey method are that:

- it measure the total emissions from a site including contributions from all possible sources;
- it can cover large site areas and at low cost.

The disadvantages are:

- it may be difficult to apply in unfavourable meteorological conditions; and
- it requires very good monitor stability and accurate calibration to measure small changes in ambient concentrations.

ii) Tracer techniques

Tracer techniques use concurrent measurements of the concentration of methane and that of a tracer released at a known rate. The concentration ratio of these two gases is then related to the ratio of their fluxes (Bogner and Scott, 1995). Published results compare reasonably well with those obtained from the micrometeorological methods discussed above, but the method requires that the methane and the tracer gas be emitted in an identical fashion (Berne *et al.*, 1995).

iii) Long path techniques

An infra-red beam is reflected back (using mirrors) across a given transect to a spectrometer where spectral analysis determines the characteristic infra-red absorbencies of individual gases. These techniques can be applied over distances up to 1 km, and can provide gas-specific concentrations representative of the ambient atmosphere over that path (Bogner and Scott, 1995). For a given area source of methane, this method produces a series of path-based concentrations for the air above the source. These concentrations are then combined with a suitable dispersion model to calculate overall emissions.

The modelling stage is the weakness in this approach. The major sources of inaccuracies are errors arising in the windspeed measurement and the uncertainties in the flux of methane outside the area defined. It is an expensive technique, although cheaper than the DIAL technology described below, and is subject to interference from other atmospheric gases with similar absorption characteristics.

The Differential Absorption Lidar (DIAL) technique is used to perform range-resolved measurement of methane in the atmosphere, without the use of a retro-reflecting mirror, allowing three-dimensional measurements of the space surrounding a source (Bellingham *et al.*, 1994). A short, high powered pulse of radiation is fired into the atmosphere along a path. Measurements are made of the light back-scattered by particulates and aerosols in the atmosphere, to a telescope adjacent to the source. Two different wavelengths are used, only one of which is absorbed by the gas of interest. The concentration of gas at a point is determined by comparing the two amounts of back scattered light, allowing range-resolved measurements up to 3km with a resolution of 10m. Concentrations as low as a few parts in 10^8 can be detected, with uncertainties of around 15%. As above, accuracy is limited more by the wind speed measurement than the technique.

The advantages of integrated path techniques are:

- measurements represent average values along the measurement path, to 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 disadvantages of the optical integrated-path technique are that it can be complex to use and may not be feasible on sites with poor access or unusual topography.

2 DIRECT MEASUREMENT TECHNIQUES

The following sections describe in some detail the methods of methane measurement chosen as suitable for site trials, namely flux boxes, spiker surveys and vertical methane gradients. The description of these trials and the outcome are given in Section 2 of the main document.

2.1 Flux boxes

Flux boxes are used to determine the flux of gas to or from a known area of the landfill surface. The simplest form consists of a sealed enclosure of known dimensions, placed over a surface, allowing gas to migrate in through the base and accumulate within the enclosure. Inlet and outlet ports are fitted to the top of the enclosure to allow sampling of gases without disturbing the pressure within the box, thereby not encouraging flux into the box. The method of analysis is an unmodified flame ionisation detector with data logger which measures total hydrocarbon content. (In the case of landfill gas emissions higher alkanes and other gases are insignificant in terms of the composition, dominated by CH_4, detectable with the FID, (WMP 27)). The rate of change of concentration of gas within the box is related to the flux from the surface.

More sophisticated designs of flux box measure increasing concentration of methane in a sweep gas which is passed through the chamber. The low sensitivity of current field instruments results in the sweep gas technique not being recommended for landfill methane emissions. Chambers can be constructed of plastic, aluminium or steel. The design of flux boxes employed in this project is shown schematically (not to scale) in Figure 2.1a.

If the initial concentration is zero then the observed methane flux can be calculated from the general relationship:

$$Q = V/A\ (dC/dt) \qquad \textbf{[eqn 1]}$$

where: Q is the flux density of the gas (g m^{-2} s^{-1})
V is the volume of air within the chamber (m^3)
A is the area of soil surface enclosed by the chamber (m^2)
dC/dt is the rate of change of gas concentration in the chamber with time (g m^{-3} s^{-1})

- slower equilibration of the sampling point with the surrounding ground may take place; and/or
- dilution of the gases in the well leading to incorrect concentration measurements.

For ease of sampling, it is advisable to have an inlet and outlet probe permanently fixed at each point. These should all be fitted with isolating valves so that the sampling probe can be sealed between measurements, allowing easier equilibration between the sampling point and its surroundings.

The advantages of this technique are:

- in-situ measurements are possible;
- rapid installation;
- boreholes may also provide hydrogeological and geotechnical information about a site and are therefore multipurpose tools, useful in site investigations;

Disadvantages of the technique are:

- the need for specialist plant during installation;
- deeper probes may deviate from the vertical during the driving process and so the exact location of the measurement may be unknown;
- there is no way of accurately determining the precise source of measurements, or any variation with depth (Jones and Nedwell, 1989) unless multiple or nested probes are used;
- installation may be prevented by obstructions e.g. hard core, timber or tyres;
- costs may be high dependent on the number of probes installed;
- there is no visual indication of the nature of the ground penetrated, although the ease or difficulty of driving may provide some tentative indication of the materials involved;
- it is not known how representative conditions in the borehole are of the surrounding waste;
- there is no clear relationship between the concentration of methane in a borehole and the surface flux. This method can only give an indication of the potential for high rates of emission (as a function of methane concentration).

measurement situation, a negative flux is as equally indicative of low emissions as a low positive flux. Visual inspection of the data will show that the correction factor has little effect on the calculated flux, and need not be applied.

$$\left(\frac{dC}{dt}\right)_{t=0} = \left(\frac{zL}{V}\right)\left(1-\frac{C_0}{C_\infty}\right) = \left(\frac{zL}{V}-\frac{RC_0}{V}\right) \qquad \textbf{[eqn 2]}$$

where:- dC/dt is the methane concentration gradient (mg m^{-3} s^{-1})
z is the fraction (by volume) of methane in LFG
L is the flow rate (m^3 s^{-1}) of LFG into the box
V is the volume of the box (m^3)
R is the flow rate of methane gas into FID (m^3 s^{-1})
C_0 is the initial methane concentration (mg m^{-3})
C_∞ is the terminal methane concentration (mg m^{-3})

giving $$\frac{zL}{A} = \frac{RC_0}{A} + \frac{V}{A}\left(\frac{dC}{dt}\right)_{t=0} \qquad \textbf{[eqn 3]}$$

where: A is the surface area (m^2) of the cap covered by the flux box

and the other terms are as described above. This can be rearranged as: **[eqn 4]**

$$Actual\ flux = \frac{RC_0}{A} + Observed\ flux$$

By placing the flux box over the surface of the landfill it may inadvertently affect the nature of the gas diffusion from the surface. This is most noticeable when the ambient air concentration is greater than any increase in concentration that may have occurred during the period of monitoring. This trapped methane may, by pressure differentials, be forced out of the box through the surface to the surrounding area. Thus the above correction allows for the back diffusion where

the ambient air concentration is greater than the increase of concentration within the box over the measuring period.

A sampling port, at the top of the chamber is used to withdraw several gas samples at a uniform time interval. The resulting increasing gas concentrations are plotted against time, a straight line regression fitted to the data gives dC/dt in the above equation. Decreasing concentrations are also possible which may indicate methane consumption by soil methanotrophs in the soil overlying the landfill capping material. The sampling period cannot be too long because the build-up of gases in the chamber initiates back-diffusion of methane into the soil. This will cause the concentration to stabilise or decrease.

Flux boxes have a sensitivity of approximately 1 $\mu g\ m^{-2}\ min^{-1}$ (Bellingham *et al.*, 1994). This can be adjusted to site conditions by varying the chamber volume (Bogner and Scott, 1995). Typically obtainable accuracies are reported to be of the order of a few percent, depending on the flux density and the area of the soil surface. Flux boxes only measure the methane emissions at a particular point; site emissions are not homogeneous. Hence it is normally recommended that the average from a number of boxes is used to estimate the flux for a given area. The precision of this estimate depends on the number and size of random high emitting areas, 'hot spots', which may be missed.

Sealing the base of the chamber to the surface is required to minimise external effects (surface winds). This may be achieved by use of a collar or ballast.

When compared to other techniques, surface flux boxes are non-intrusive and have advantages of greater accuracy, simplicity, lower cost and flexibility, as well as a rapid turn-around time. They may however influence the nature of gas migration, temperature and concentrations at the soil / atmosphere interface (Bogner and Scott, 1995). It has recently been reported that approaching a static flux box may cause methane to bubble out of the soil and therefore, affect emission measurements (Ineson, 1995).

The areas of uncertainty, sensitivity and error likely to arise during the use of flux boxes are summarised below in Table 2.1a.

Table 2.1a. Areas of concern in flux box measurements

Area of concern	Likely effect on results
Number of boxes relative to surface area	typically 0.04% of area sampled - may not be representative: depends on inhomogeneity of surface flux
Sealing boxes	dependent on surface wind effects
Land surface	site dependent
Lack of mixing in box	flux dependent
Measuring time	+/- 2 mins on any reading
Detector	drift +/- 50%
	weather conditions
Measurement of flux box dimensions	less than one percent on V and A
Concentration conversion to flux	engineering judgement from graph
Pressure and temperature variations	few per cent if not corrected
Mean of X boxes	SD of sample - up to several times mean value

From this it can be seen that the uncertainty in the sample mean, represented by the standard deviation, dominates the measurement results making it very important to obtain as many results as possible, and increase the percentage of the surface area that has been sampled.

On the basis of the two completed case studies (Appendix 4), gas concentrations in landfills tend to show a degree of spatial correlation over short distances (40 m to 70 m). Coincidentally, this is also the range at which gas recovery wells are typically spaced on landfills with gas collection systems for subsequent flaring or energy utilisation. For the purposes of estimating methane emissions from landfill sites, it is recommended that measurements be carried out at a spacing of approximately 40 m. This is slightly less than the likely range and should result in good estimates of methane emission that adequately reflect the likely spatial correlation over the part of the site studied.

Experimental variograms may be calculated to confirm the spatial correlation on a site specific basis. If measurements are made at more widely spaced points, there is a significant possibility that the site's characteristics will not have been

adequately studied and estimates of methane emission will have larger uncertainties.

Errors arising in the detector, though still of concern, are less dominant as the technique provides a relative assessment of surface flux for different landfills and as such inherent errors are carried all the way through.

2.2 Sub-surface vertical methane gradients

Gases move through the sub-surface environment under the influence of both advection and diffusion. Usually, one process is dominant. Advection may dominate at depths near gas recovery wells or at the edges of surfaces of sites when rapid drops in atmospheric pressure cause pressure driven advective flow (Young, 1990). Diffusion is most important in near-surface soils in response to concentration gradients.

Sub-surface methane concentration gradients can be used to directly calculate methane emissions assuming diffusive transport only (Bogner and Scott, 1995). These calculations are often useful as an independent check on fluxes obtained from chamber techniques. Calculated fluxes are usually higher than those obtained from flux chamber experiments (Rolston, 1986).

Concentration gradients may be obtained by inserting a probe or probes to varying depths into the surface. This may be:

- hammered into the ground directly; or
- a pilot hole made with a metal rod prior to insertion of the probe; or
- a pilot hole made by an augering tool.

Single point sampling probes typically consist of a 1 m long, hollow tube. After insertion of the probe to the required depth, the hole is sealed at the surface to minimise ingress of air. Samples are then withdrawn from a sampling outlet near the head. Atmospheric mixing should be avoided. These probes come in various designs.

Another design comprises a solid probe with chambers at various depths, sealed by a semi permeable membrane. The chambers are allowed to equilibrate before samples are withdrawn, using a gas tight syringe, for subsequent analysis (Jones and Nedwell, 1989).

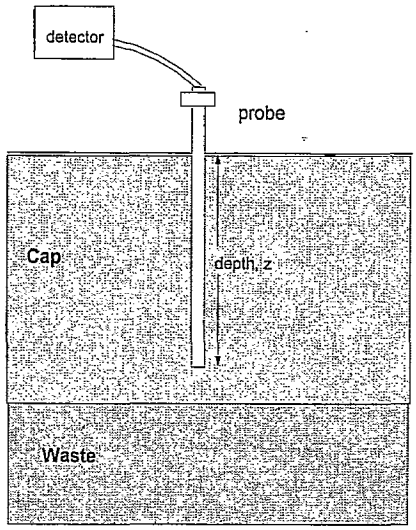


Figure 2.2a Schematic diagram of probe

Using a vertical gradient method to measure pressure and concentration gradients in the cover materials means that both advectional and diffusional flow can be studied separately and considered independently of soil constituents (Bogner, 1986). Sub-surface vertical gradients can be determined from anywhere in the soil profile. The latter is not possible when the flux is measured directly by area techniques such as flux boxes.

The relationship by which sub-surface vertical methane gradients can be used to calculate diffusive flux is effectively the same as that for sub-surface spiker surveys described below.

2.3 Sub-surface spiker surveys

Spiker surveys are analogous to measuring methane gradients with only one data point (other than an assumed zero at the surface). The technique assumes that there is a dynamic balance between gas generated within the waste and the rate of dispersion at the site surface. The surface flux is determined by assuming either advective (pressure) or diffusive flow. In the former case, overpressure is the driving force whilst in the latter, it is the concentration gradient. Flux is calculated using either of the following equations (Manley, 1994):

$$Q_p = k\, dp/dz \qquad \textbf{[eqn 5]}$$

$$Q_d = D\, dC/dz \qquad \textbf{[eqn 6]}$$

where: Q_p is the gas flow assuming pressure flow (m^3s^{-1})
k is the permeability coefficient ($m\ s^{-1}$)
dp/dz is the pressure gradient ($Pa\ m^{-1}$)
Q_d is the gas flow assuming diffusive flow (m^3s^{-1})
D is the diffusion coefficient ($m^2\ s^{-1}$)
dC/dz is the concentration gradient (Mole m^{-2}), where 1 Mole occupies 22.4L at STP

For diffusion in soils, the diffusion coefficient (D) can be approximated by:

$$\mathbf{D = 0.66\ D_1\ (1\text{-}S)} \qquad \textbf{[eqn 7]}$$

where: D_1 is the diffusion coefficient in air ($m^2\ s^{-1}$)
S is the soil saturation (dimensionless on a scale of 0-1.0)
(1-S) can be defined as the free air porosity of the soil.

It is clear from this relationship that a waterlogged soil overlying a cap will exhibit a very low specific diffusion coefficient.

Bogner *et al.,* (1993) used an alternative form of this equation for the calculation of instantaneous diffusive flux from shallow concentration gradients (0 - 1 m), based on Fick's first law (Lerman, 1979):

$$\mathbf{f = -(\phi/\theta)\ D\ dc/dz} \qquad \textbf{[eqn 8]}$$

where: f is the flux density of the gas ($g\ m^{-2}\ s^{-1}$)
ϕ is the gas filled porosity (fraction)
D is the free-air diffusion co-efficient for methane in air at a given temperature ($m^2\ s^{-1}$)
dc/dz is the concentration gradient ($g\ m^{-2}$)
θ^{-1} is the tortuosity (dimensionless), taken as:

$\phi^{1/3}$	for dry soils; and
$\phi^{1/3}[\phi/(\phi+\phi_w)]$	for wet soils (Millington, 1959),
where ϕ_w	is the volumetric moisture content (fraction)

The site to be assessed, or a representative part of it, is divided into a finite element grid and the flux for each element is assumed equal to the calculated flux for a measurement point at the centre of the element. All elements are then summed to produce an overall flux for the measurement grid. The conversion of

probe measurements to fluxes is more complex than for flux boxes and empirical in nature. In order to fully calculate flux, without the use of default values, samples are required to test for soil porosity and volumetric moisture content.

The benefits of shallow probing are:

- the equipment can be modified from similar geological surveys;
- specialist operators are not required;
- the technique is easy to use and has no safety implications.

The main disadvantages are:

- air diffusion into the probe can reduce measured gas concentrations, there is also a danger of over-pumping in narrow-bore tubes which results in air being drawn from the surface so diluting the sample;
- care must be taken not to insert the probe beyond the depth of the cap (especially when geomembrane liners are in use);
- small sample volumes can give misleading results and relatively high errors;
- probes can be easily blocked or damaged by debris and water, waterlogged soils will tend to render this technique ineffective;
- lateral and basal migration are assumed to be zero;
- soil porosity and tortuosity are not often accurately known.

Despite these disadvantages, this technique can be adequate for the initial scoping measurements for which it is intended.

2.4 Permanent and semi-permanent sampling points

For on-going measurements, more permanent sampling points or boreholes may need to be installed. A regular grid is often the best initial arrangement but there are no concrete rules on grid dimensions. Large numbers of sampling points will not necessarily give a clearer picture of site conditions, but meaningful interpretation of results based on too coarse a grid also proves difficult. As a starting point, grid locations should be within the range 30 - 60 m. Permanent sampling points should not be left open, otherwise, any of the following may result:

- ingress of atmospheric air into the ground, reducing any local anaerobic activity;
- large quantities of toxic and flammable gases may be released;

- slower equilibration of the sampling point with the surrounding ground may take place; and/or
- dilution of the gases in the well leading to incorrect concentration measurements.

For ease of sampling, it is advisable to have an inlet and outlet probe permanently fixed at each point. These should all be fitted with isolating valves so that the sampling probe can be sealed between measurements, allowing easier equilibration between the sampling point and its surroundings.

The advantages of this technique are:

- in-situ measurements are possible;
- rapid installation;
- boreholes may also provide hydrogeological and geotechnical information about a site and are therefore multipurpose tools, useful in site investigations;

Disadvantages of the technique are:

- the need for specialist plant during installation;
- deeper probes may deviate from the vertical during the driving process and so the exact location of the measurement may be unknown;
- there is no way of accurately determining the precise source of measurements, or any variation with depth (Jones and Nedwell, 1989) unless multiple or nested probes are used;
- installation may be prevented by obstructions e.g. hard core, timber or tyres;
- costs may be high dependent on the number of probes installed;
- there is no visual indication of the nature of the ground penetrated, although the ease or difficulty of driving may provide some tentative indication of the materials involved;
- it is not known how representative conditions in the borehole are of the surrounding waste;
- there is no clear relationship between the concentration of methane in a borehole and the surface flux. This method can only give an indication of the potential for high rates of emission (as a function of methane concentration).

This method was not trialled as part of this work as there was little requirement for ongoing measurements at a single site. This study required a large number of measurements at different sites.

3 DETECTION INSTRUMENTS

Flame ionisation detectors (FIDs) provide an accurate and sensitive method for concentration measurements of CH_4 within the range 0.5 - 10,000 ppm methane. They can be portable, robust and intrinsically safe. The measured CH_4 concentrations are then related to flux as described in Section 2.2.1. FID can be incorporated in gas chromatographs, in which individual gaseous species can be differentiated, or as direct detectors of total combustible gases in the stream. These consist of two electrodes placed immediately above a hydrogen / air flame. The sample is continuously introduced into this flame and ionised. The ions formed result in changes in the voltage between the electrodes proportional to the concentration of flammable gas.

Most instruments of this type use the air drawn in with the sample to provide the oxygen to support the flame in the detector. They therefore require a minimum amount of oxygen to be present to operate correctly. This oxygen requirement also puts an upper limit on the detection of methane although this has been overcome to some extent in instruments which add air to the sampled gas stream; usually in a ratio of 10:1 (Crowhurst and Manchester, 1993).

FIDs cannot detect hydrogen, carbon dioxide or water, but are sensitive to all hydrocarbons. If being used to measure methane only, the FID should be used in conjunction with a technique to separate out non-methane hydrocarbons (NMH). This can be achieved using a chemical converter which removes the NMH at the input to the detector (Bellingham *et al.*, 1994). In practice, for landfill environments, NMH concentrations are significantly lower than methane concentrations and so only minimal precautions are required.

The instrument contains a flame, and is therefore unsuitable for use in areas where there is a possibility of explosive gas mixtures being present. Under these circumstances, the instrument may be equipped with a limiter which automatically cuts out at a methane threshold of 1% by volume (i.e. one fifth of the lower explosive limit, LEL, of methane).

Table 1.1a. Summary table of flux measurement techniques

Technique	Advantages	Disadvantages
Direct methods		
Flux box (chamber techniques)	Relatively simple, accurate and robust. All variables easily measured, mathematically accurate.	May miss edge effects and areas of higher emissions.
Sub surface vertical methane gradients	Gradients can be determined from anywhere in the soil profile. Independent check on chamber techniques.	Need to measure many variables (inc. porosity and tortuosity) to be accurate. Need to know exact depth of probe in the vertical axis.
Sub surface spiker surveys	Adequate for initial scoping measurements.	Lateral or basal migration pathways ignored. Probes are easily blocked or damaged.
Permanent & semi-permanent sampling points	In-situ measurements are possible. Boreholes may provide hydrogeological and geotechnical information about a site.	Need specialist plant during installation. Costs may be high. No clear relationship between concentration of CH_4 in borehole and surface flux.
Indirect methods		
Micrometeorological methods	Measure fluxes across a wide area with minimal disturbance to underlying surface. Detects edge effects and surface emission anomalies.	Expensive, complex equipment, complicated modelling required. Windspeed greater than 1 ms^{-1} required. Difficulty in determining the exact source of atmospheric methane.
Tracer techniques	Results compare well with micrometeorological methods.	Methane and tracer gas must be emitted in an identical fashion.
Long path techniques	Can be applied over distances up to 1km. Provides gas specific concentrations representative of the ambient atmosphere over that path.	Dispersion model must be correct. Expensive technique. Subject to interference from other atmospheric gases with similar absorption characteristics.

APPENDIX 2: EMISSION FLUX PROTOCOL

APPENDIX 2: EMISSION FLUX PROTOCOL

1 USE OF FLUX BOXES

1.1 Introduction

1. Flux boxes are most suitable for use on completed areas of a landfill site. They will produce high flux measurements if used on waste which is not capped or covered by an intermediate layer of soil or other inert material. The technique can be used on unseeded or seeded caps, but it may be difficult to attain a good seal of the box to cap if there is long grass.

2. The flux box described here has been designed for simplicity of use. It is a passive design which can be built for minimal outlay. Other designs are available which employ either more complex designs or active flow through the flux chamber. These are alternatives which may be employed to similar effect.

3. The analyser is required to resolve small changes in part-per-million (ppm) concentrations of methane (v/v) over time intervals of between 20 minutes to 1 hour duration. A high sensitivity is therefore required and a portable flame ionisation detector (FID) instrument with a resolution over three decades from 0.1-100 ppm is the minimum requirement.

4. In general, the flux boxes are placed on the capped area, sealed to the ground surface and concentrations of methane within the box are measured over short time intervals for a period up to a couple of hours. These data are then processed to produce a graph of concentration versus time. The best fit slope of the graph is the value of the methane flux (in mg m^{-2} s^{-1}) for that flux box. The detail of this approach is described below.

1.2 Design of flux box and sampling equipment

This section highlights the fundamental points that need to be addressed when designing a flux box, and the purchasing of sampling equipment.

Flux box

Flux boxes can be easily constructed from readily available containers, designed primarily for other purposes. The flux boxes used for this project were adapted from

plasterers baths, which are relatively cheap and robust, and has a top edge which can be readily sealed to the cap. Inlet and outlet ports were added to the top of the box for pressure equilibration and sampling respectively. The boxes were painted white to reduce insolation effects.

The ratio of volume to area in contact with the surface should be about 1:5 to maximise sampling area, whilst preventing the sampling ports from being too far from the influx gas. Improvements to basic flux box designs include:

- a method of sealing the box to the landfill surface
- some form of paddle within the box to promote mixing.

Sampling equipment

The main concerns for the selection of sampling equipment are that it should be:

- portable
- weather resistant
- intrinsically safe
- able to detect very small changes in gas concentration.

1.3 Field work

1. Walk the area under investigation to gauge the surface area and shape with regard to the number of flux boxes available and hence their positions and the number of sets required. As a minimum boxes should be separated by no more than 40m.

2. Start the FID in an intrinsically safe area following the procedures described in the Operating Manual. Allow zero to stabilise whilst laying out the upturned boxes near the positions for analysis (do not seal down until ready to take measurements). Measure distance and direction between boxes. Span the FID with calibration gas.

3. Prepare the data logger (in this example a Psion Organiser II[1]) for use by the following:
   1) ensure sufficient battery reserve for the days data and clean datapak in place;
   2) press clear to switch datapak on, set up date and time;

[1] The use of a trade name is for purposes of identification only and does not imply endorsement by the Environment Agency.

3) enter logger and select 'New' and 'Datapak' (data stored internally will be lost in the event of battery failure);
4) set all four channels to mV
5) input Name of data file, e.g. SF11, SF21 etc.
6) set Records to 10
7) set Period to 00 mins 02 secs
8) select 'Start' and, when ready to take measurement, 'Now'.

4. Place the first box, with sampling T-bar insert fitted, on the cap and ensure a good seal between box edge and cap by use of pegs, or digging in/weighting down.

5. Take an initial reading, following the instructions in the analyser Operating Manual, after placing the first box. Switch pressure balance valve to ON whilst monitoring, return to OFF on completion. Ensure that all four channels are selected on the data logger (mV). Ten records at two second intervals should give an adequate span of results to reduce fluctuations.

6. Move on to the next box and repeat steps 4 and 5 and so on until all boxes are placed and the first set of results have been collected. (HINT: Place the boxes in the order in which they will be read. Thus the time lag between box 1 and subsequent boxes will be the same for each round of results.)

7. Repeat rounds of monitoring approximately every half an hour for at least 3 hours. If the gas concentrations do not change much over this time longer period should be allowed if possible. Experience shows that time intervals of 20 minutes for high fluxing sites, up to 40 minutes for low fluxing sites are suitable. Record the time for each sample.

8. Record weather, temperature and ground condition on site record sheet.

9. If results are stored on a data logger make back up paper copies in the field.

1.4 Data Analysis

1. A four channel data recorder is typically used to collect the data, where

   Channel 1 is a coarse measurement of channel 2 (not used)
   Channel 2 is proportional to the full scale deflection on the instrument
   Channels 3 and 4 determine on which scale range the instrument is set to and hence the multiplier for channel 2.

2. The data logger records the monitoring results in mV. This must first be converted to ppm by using the following calculation:

   10 to the power (channel 2 in mV x 3/2000) times factor y

   where factor y depends on the output to channels 3 and 4 as follows:

   if Chan 3 and Chan 4 > 667mV then y=0.1
   if Chan 3 < 667mV and Chan 4 > 667mV then y=1
   if Chan 3 > 667mV and Chan 4 < 667mV then y=10

2. Convert ppm to mg m^{-3} using the following equation:

   mg m^{-3} = ppm x molar mass / molar volume

   Correction to standard temperature and pressure can be carried out thus:

   $$mg\ m^{-3} = ppm \times (16{,}000 \times P_{obs} \times T_{stp}) / (22{,}400 \times T_{obs} \times P_{stp})$$

   where T_{obs} is the observed temperature (K);
   P_{obs} is the observed atmospheric pressure (mb);
   T_{stp} is the standard temperature (273 K); and
   P_{stp} is the standard atmospheric pressure (1000mb).

Note that if T_{obs} and P_{obs} are not readily available, this correction factor can be ignored, and the equation reduces to:

$$mg\ m^{-3} = ppm \times 16 / 22.4$$

This simplification introduces only very small errors, in the order ±1%, to the calculation of flux.

3. Flux is obtained from the following equation:

$$\mathbf{Q = V/A\ (dC/dt)}$$

where: Q is the flux density of the gas ($g\ m^{-2}\ s^{-1}$)
V is the volume of air within the chamber (m^3)
A is the area of soil surface enclosed by the chamber (m^2)
dC/dt is the rate of change of gas concentration in the chamber with time ($g\ m^{-3}\ s^{-1}$)

4. Plot concentration against time to obtain the flux profile for each box. On a hard copy of the plot determine, by visual inspection, the gradient of the slope. (Note that computer software packages which determine the slope will disregard the underlying phenomenon of back diffusion or methane oxidation, and are less suited to the task than visual inspection.)

5. The average flux for the site (or sub-site area) is the arithmetic mean of the flux derived from each box.

2 SPIKER SURVEYS

2.1 Introduction

1. Spiker surveys can be anything from the use of an iron bar, to make a temporary hole in the ground, from which to measure methane concentration, to a fixed array of piezometer sampling points. The approach selected for this work is midway between these approaches. A fully retrievable stainless steel probe with pounding hammer was used to achieve a measured depth of penetration into the cap.

2. The concentrations measured are in the ppm range and a portable flame ionisation detector (FID) instrument with a resolution over three decades from 0.1-100ppm, or possibly 1-1000ppm for high flux sites, is the minimum requirement.

3. In general, the probes are inserted to a known depth, methane concentration is measured, and the flux is calculated from an equation which includes soil moisture, tortuosity and porosity terms. Default values may be used to generate flux to a first approximation.

2.2 Design of Soil Probes

This section describes the design of soil probes, the design of sampling equipment is covered in Section 1.2 of this appendix.

Soil probes

The soil probes need to be strong, to survive the pounding during insertion. There needs to be an outlet port for sampling and a way of closing the port to prevent gas egress. Markings on the outside of the probe to indicate depth of insertion are also required

2.3 Field work

1. Choose a representative area of the site which measures at least 60m by 60m. Mark out a grid at 10m spacings using tent pegs or similar. Start the detector in an intrinsically safe area, as per the Operating Manual, and allow to settle.

2. Hammer in a probe to depth 500mm at position A1 on the grid and seal with valve fitting to prevent ingress of surface air.

3. Allow to equilibrate whilst hammering in available probes also to 500mm at succeeding interstices of grid.

4. To take a measurement attach detector sampling inlet to valve which should be opened as soon as the detector is attached to aid successful measurement and prevent the detector from pulling a vacuum.

5. After taking a measurement remove probe and use on next available position. Continue as above until flux at each interstice has been measured.

2.4 Data Analysis

1. A four channel data recorder is typically used to collect the data, where

   Channel 1 is a coarse measurement of channel 2 (not used)
   Channel 2 is proportional to the full scale deflection on the instrument
   Channels 3 and 4 determine on which scale range the instrument is set to and hence the multiplier for channel 2.

2. The data logger records the monitoring results in mV. This must first be converted to ppm by using the following calculation:

   10 to the power (channel 2 in mV x 3/2000) times factor y

   where factor y depends on the output to channels 3 and 4 as follows:

   if Chan 3 and Chan 4 > 667mV then y=0.1
   if Chan 3 < 667mV and Chan 4 > 667mV then y=1
   if Chan 3 > 667mV and Chan 4 < 667mV then y=10

3. Convert ppm to mg m^{-3} using the following equation:

   mg m^{-3} = ppm x molecular weight / molecular volume

   For methane this becomes

   mg m^{-3} = ppm x 16 / 22.4

   This is the simplified form of the equation. See the previous section for pressure correction factors.

4. Convert these values to flux using the following equation:

$$\mathbf{f = -(\phi/\theta)\, D\, dc/dz}$$

where: f is the flux density of the gas (g m^{-2} s^{-1})

ϕ is the gas filled porosity (fraction)

D is the free-air diffusion co-efficient for methane in air at a given temperature (m^2 s^{-1})

dc/dz is the concentration gradient (g m^{-2})

θ^{-1} is the tortuosity (dimensionless), taken as

$\phi^{1/3}$ for dry soils and

$\phi^{1/3}[\phi/(\phi+\phi_w)]$ for wet soils (Millington, 1959)

where ϕ_w is the volumetric moisture content (fraction)

4. The average flux for the area of the probes study is the arithmetic mean of the flux derived from each probe.

3 METHANE GRADIENT PROFILES

3.1 Introduction

1. The methane gradient profile method uses a similar approach to the spiker survey, but methane concentration is measured at various depths in the cap profile, producing a measure of methane concentration as a function of depth.

2. This method is more complex to sample than the spiker survey but can use the same analytical approach.

3. The design of the sampling probe, may at its simplest, be that specified in Section 1.2.2 above. More complex designs have been used and an example is shown in Section 1.3.2 below.

4. The method of analysis will depend on the design of the sampling probe used. The approach described in Section 1.2.4 is valid for the design of probe in Section 1.2.2.

3.2 Field work

Single Point Sampling Probe

1. Start the detector in an intrinsically safe area, as per the Operating Manual, and allow to settle.

2. Insert probe to initial depth of 100mm, allow to equilibrate then measure methane concentration.

3. Insert further to 300mm and repeat.

4. Insert to 600mm and repeat.

5. Repeat at as many locations as feasible, recording positions and distances apart on a diagram.

Multi-point Sampling Probe

1. A multi-point sampling probe is a stainless steel rod, of approximately 2.5cm diameter, into which chambers (1cm diameter x 1cm deep) have been drilled at 1.5 cm intervals for 36cm along the length of the rod.

2. A stainless steel cover plate, with small equilibration holes over the machined cavities, is used to hold a gas permeable polyethylene membrane in place over the machined cavities.

3. The stake is left in place for 48 hours to equilibrate with the soil gas atmosphere. The concentration of methane in each of the cavities is subsequently analysed by gas chromatography.

3.3 Data Analysis

1. For the single point sampling probe use the same method as for the spiker survey, noting different fluxes can be calculated for different combinations of dz, the vertical distance.

2. For the multi-point sampling probe a plot of depth of chamber against methane concentration will provide a profile of varying gas concentration through the cap.

APPENDIX 3: EMISSION FLUX DATA BY SITE/METHOD

Contents

APPENDIX 3: EMISSION FLUX DATA BY SITE/METHOD

SITE A

LOCATION: Surrey
PERIOD OF OPERATION: 1990-1995
WASTE COMPOSITION: Household & Industrial
GEOLOGY: River Terrace gravels over London Clay
CONTAINMENT: Natural
CAP TYPE: Clay
ENGINEERED FEATURES: No gas collection system

Site A is currently operational taking a mixture of household, industrial and commercial wastes. There is approximately 3 Mt of waste in place. This is a large and deep excavation lined with London clay worked up the sides of the site, to achieve containment. There is a level 1-2m clay cap forming a flat surface topography, over 5-10m of waste. There are currently no gas control measures in place. The first season flux box results, taken on 30th August 1995 are given in Table A1. The weather was very good, with stable atmospheric conditions,. The spiker survey and depth probe results obtained during the period 29th to 31st August 1995 are given in Tables A2 and A3 respectively. The second season flux box results, taken on 12th March 1996, in winter conditions, are given in Table A4. The spreads of results obtained with the flux boxes are shown in figures A1 and A3, and the cumulative flux for each shown in figures A2 and A4..

Table A1. Site A Flux Box results, 30/08/95

SITE/BOX	Observed Flux $mg\ m^{-2}\ s^{-1}$	Initial concentration C_o $mg\ m^{-3}$	Actual Flux $mg\ m^{-2}\ s^{-1}$
A1	$2.5x10^{-4}$	0	$2.5x10^{-4}$
A2	$2.4x10^{-4}$	0	$2.4x10^{-4}$
A3	$2.4x10^{-4}$	0	$2.4x10^{-4}$
A4	$2.3x10^{-4}$	0	$2.3x10^{-4}$
A5	$2.3x10^{-4}$	0	$2.3x10^{-4}$
A6	$2.2x10^{-4}$	0	$2.2x10^{-4}$

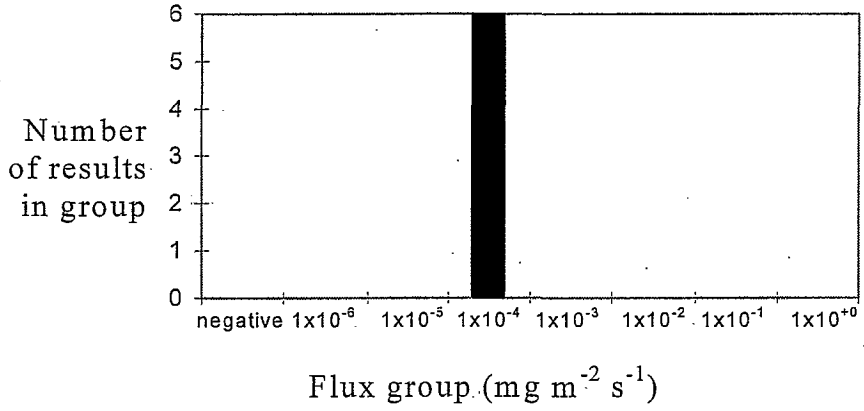


Figure A1. Distribution of flux box results (summer)

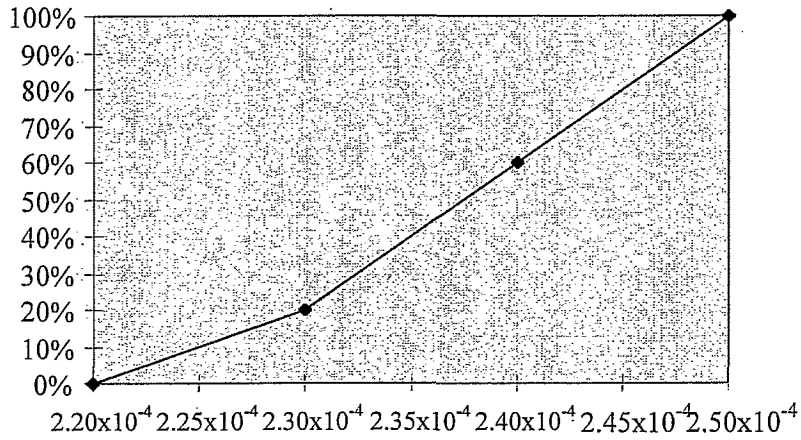


Figure A2. Cumulative plot of methane flux mg m^{-2} s^{-1} (summer)

Table A2. Site A Spiker Survey results (mg m^{-2} s^{-1}), 29/08/95

Grid position	A	B	C	D	E	F	G
1	$4.9x10^{-4}$	$3.2x10^{-3}$	$2.0x10^{-4}$	$2.5x10^{-4}$	$4.9x10^{-4}$	$3.4x10^{-4}$	$4.9x10^{-4}$
2	$2.0x10^{-4}$	$1.2x10^{-4}$	$6.7x10^{-4}$	$3.6x10^{-4}$	$4.8x10^{-4}$	$8.1x10^{-4}$	$7.1x10^{-4}$
3	$1.2x10^{-4}$	$8.2x10^{-4}$	$3.9x10^{-4}$	$4.9x10^{-3}$	$8.4x10^{-4}$	$5.4x10^{-4}$	$4.7x10^{-4}$
4	$9.4x10^{-3}$	$8.2x10^{-4}$	$4.4x10^{-4}$	$1.8x10^{-4}$	$1.3x10^{-4}$	$4.3x10^{-4}$	$1.6x10^{-3}$
5	$7.9x10^{-3}$	$2.8x10^{-3}$	$6.9x10^{-4}$	$4.5x10^{-4}$	$1.2x10^{-3}$	$1.0x10^{-3}$	$1.9x10^{-3}$
6	$9.6x10^{-4}$	$6.8x10^{-4}$	$7.6x10^{-4}$	$7.6x10^{-4}$	$1.8x10^{-3}$	$1.1x10^{-3}$	$7.0x10^{-4}$
7	$2.4x10^{-4}$	$3.3x10^{-4}$	$1.2x10^{-4}$	$6.3x10^{-4}$	$1.1x10^{-3}$	$2.2x10^{-3}$	$1.8x10^{-2}$

A-G and 1-7 relate to grid with positions, A1, A2...G6, G7

Table A3. Site A Methane Gradient Profile results (mg m^{-2} s^{-1}), 31/08/95

dz (mm)	I	II	III	IV	V	VI
600-300	$-2.3x10^{-2}$	$7.2x10^{-4}$	$3.0x10^{-4}$	$1.6x10^{-3}$	$3.1x10^{-5}$	$1.3x10^{-3}$
300-100	$3.5x10^{-2}$	$5.4x10^{-4}$	$2.6x10^{-5}$	$2.1x10^{-5}$	$1.4x10^{-4}$	$-3.5x10^{-4}$
600-100	$3.6x10^{-4}$	$6.5x10^{-4}$	$1.9x10^{-4}$	$9.5x10^{-4}$	$7.3x10^{-5}$	$6.1x10^{-4}$

Assumes Free air diffusion coefficient, D= $2.2x10^{-5}$ m^2 s^{-1} and porosity, ϕ=0.4

Table A4. Site A Flux Box results, 12/03/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
A1	0.0	5.8	$1.2x10^{-4}$
A2	$-6.3x10^{-5}$	6.7	$8.1x10^{-5}$
A3	$1.33x10^{-5}$	4.1	$1.0x10^{-4}$
A4	$-5.8x10^{-6}$	5.3	$1.1x10^{-4}$
A5	$-4.8x10^{-6}$	4.1	$8.3x10^{-5}$
A6	$8.5x10^{-7}$	5.1	$1.1x10^{-4}$
A7	$2.3x10^{-5}$	4.16	$1.1x10^{-4}$
A8	$-1.8x10^{-5}$	4.35	$7.5x10^{-5}$
A9	$-1.4x10^{-5}$	5.1	$9.6x10^{-5}$
A10	$-5.0x10^{-5}$	6.65	$9.3x10^{-5}$

A1-A10 are box references for this measurement set and do not relate to A1 to A6 in Table A1.

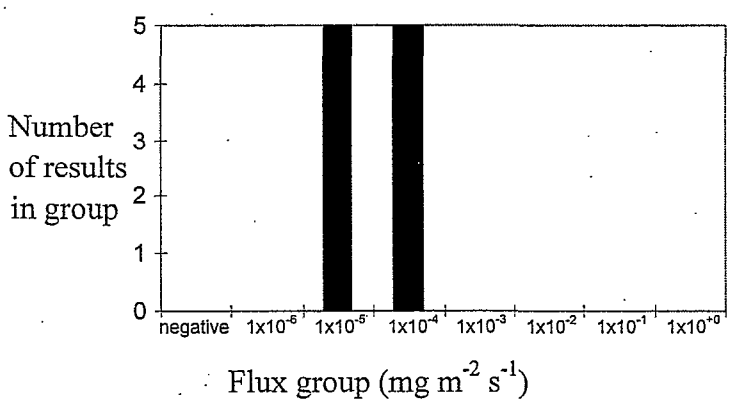


Figure A3. Distribution of flux box results (winter)

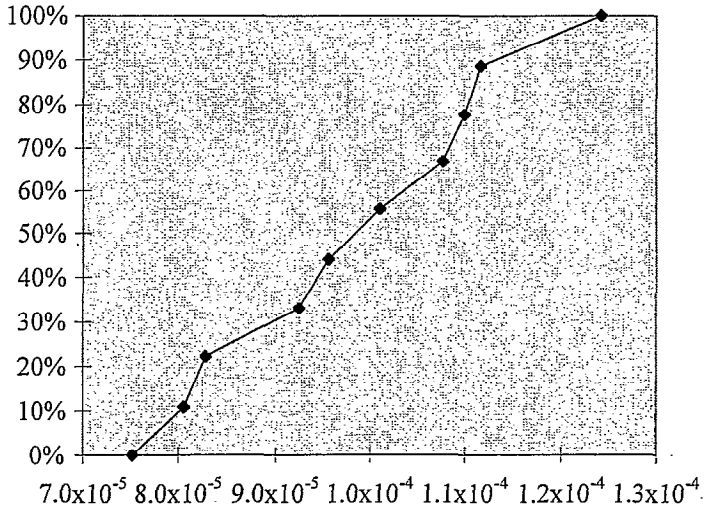


Figure A4. Cumulative plot of methane flux mg m^{-2} s^{-1} (winter)

Discussion of results

The range of flux box results for this site is very narrow, i.e. from $2.2x10^{-4}$ to $2.5x10^{-4}$ mg m^{-2} s^{-1} in summer and $7.5x10^{-4}$ to $1.2x10^{-4}$ mg m^{-2} s^{-1} methane in winter, implying a uniform cap quality. These ranges are at the lower end of that obtained for the spiker survey which varied from $1.2x10^{-4}$ to $1.8x10^{-2}$ mg m^{-2} s^{-1}. Individual methane gradient profile results span the range of flux box and spiker survey data, namely $2.6x10^{-5}$ to $3.5x10^{-2}$ mg m^{-2} s^{-1} , though in two probes the concentration was higher at either the 300 or 100mm point than at the point below it (giving negative results). Both the spiker survey and gradient methods rely on equations where default assumptions on soil moisture content, tortuosity and porosity parameters are made. These assumptions affect the calculation of methane flux, if these parameters varied through the cap it would affect the resulting fluxes.

The flux box results were low, even though it was late summer and the ground was dry, allowing the unimpeded progress of methane through the cap. The average flux box result was lower when the site was revisited during the winter. The first five boxes taken in March correspond to the same area as that monitored in August of the previous year. An additional area was monitored in the winter to provide a comparison within the site. Both areas are low flux.

The average flux box result for this site lies in the middle region of the S-distribution given in Section 2.4.

SITE B

LOCATION:	Surrey
PERIOD OF OPERATION:	July 1990 - Present
WASTE COMPOSITION:	50% Inert, 50% Dom/C&I, some contaminated waste
GEOLOGY:	Sandgate Beds
CONTAINMENT:	Unlined
CAP TYPE:	Sand/LDPE
ENGINEERED FEATURES:	Well engineered cap Gas collection scheme

This site, which is currently operational, has a geology of Sandgate Beds over Folkestone Beds. It is unlined but has a composite sand, HDPE lapped, sand cap. There is a gas control scheme in place, which combines flaring and utilisation for the site's needs, for the 2Mt of waste already covered. The monitored area, which is on the side of a hill with a 5 degree slope, was filled to an average depth of 15m during 1992 and capped immediately after. The flux box results for 7th September 1995, a wet summers day, are given in Table B1 below. The spiker survey results, which were accumulated on 6th September 1995 before mechanical failure of the probes, are given in Table B2. No methane gradient results were obtained from this site. This site was revisited on 13th March 1996, to obtain results in winter conditions. These are presented in Table B3. The spreads of results obtained with the flux boxes are shown in figures B1 and B3 with the cumulative flux results shown in figures B2 and B4.

Table B1. Site B, Flux Box results, 07/09/95

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
B1	$2.8x10^{-4}$	0	$2.8x10^{-4}$
B2	$3.6x10^{-4}$	0	$3.6x10^{-4}$
B3	$4.4x10^{-4}$	0	$4.4x10^{-4}$
B4	$3.9x10^{-4}$	0	$3.9x10^{-4}$
B5	$1.9x10^{-4}$	1.8	$2.3x10^{-4}$
B6	$7.4x10^{-5}$	1.3	$1.0x10^{-4}$

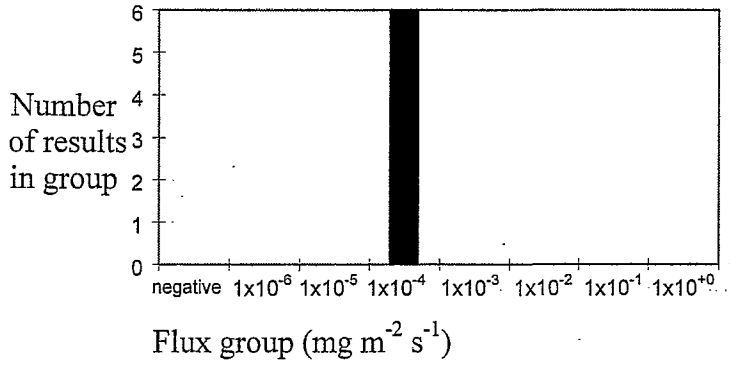


Figure B1. Distribution of flux box results (summer)

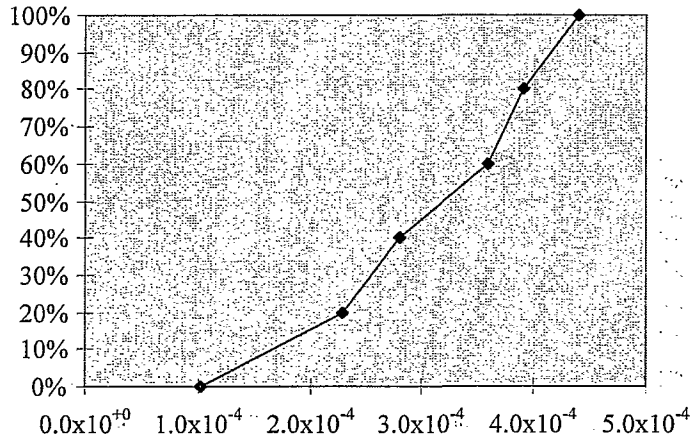


Figure B2. Cumulative plot of methane flux mg m^{-2} s^{-1} (summer)

Table B2. Site B, Spiker Survey results (mg m^{-2} s^{-1}), 06/09/95

	1	2	3	4	5	6	7
A	$1.8x10^{-3}$	$3.1x10^{-4}$	$2.5x10^{-4}$	$2.9x10^{-4}$	$1.7x10^{-4}$	$5.1x10^{-5}$	$3.4x10^{-5}$
B	$2.9x10^{-4}$	$2.7x10^{-4}$	$1.7x10^{-5}$	$2.1x10^{-4}$	$1.5x10^{-4}$	$6.4x10^{-4}$	$3.4x10^{-5}$
C	$2.3x10^{-4}$	N/A	N/A	N/A	N/A	N/A	N/A

Table B3. Site B Flux Box results, 13/03/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
B1	$3.0x10^{-5}$	1.625	$6.4x10^{-5}$
B2	$1.4x10^{-5}$	2.15	$6.0x10^{-5}$
B3	None observed	2.75	$5.9x10^{-5}$
B4	$4.4x10^{-5}$	0.94	$6.4x10^{-5}$
B5	$4.0x10^{-5}$	1	$6.2x10^{-5}$
B6	None observed	2.9	$6.2x10^{-5}$
B7	$3.9x10^{-5}$	0.95	$5.9x10^{-5}$
B8	$6.5x10^{-5}$	0.55	$7.7x10^{-5}$
B9	$6.4x10^{-5}$	0.05	$6.5x10^{-5}$
B10	$9.1x10^{-6}$	1.2	$3.5x10^{-5}$

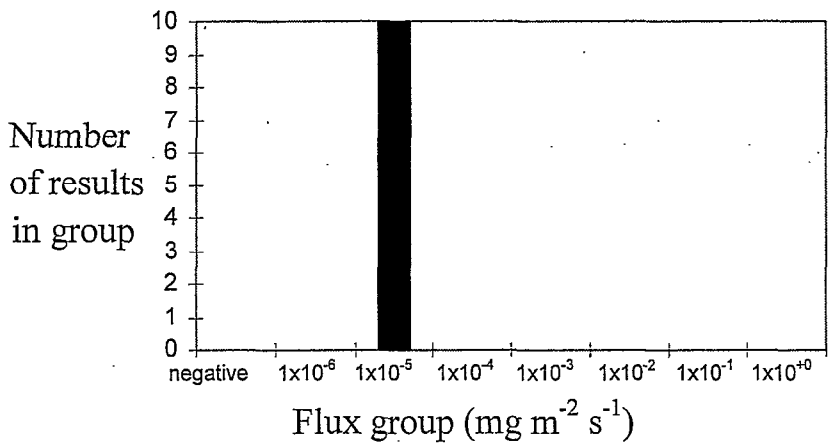


Figure B3. Distribution of flux box results (winter)

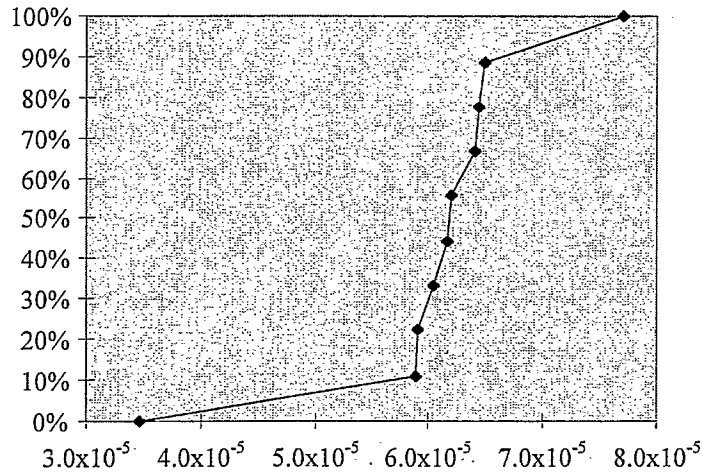


Figure B4. Cumulative plot of methane flux mg m^{-2} s^{-1} (winter)

Discussion of results

The range of flux box results for this site, in summer, spans less than half an order of magnitude, i.e. from $1.0x10^{-4}$ to $4.4x10^{-4}$ mg m^{-2} s^{-1}. The winter results range from $3.5x10^{-5}$ to $7.7x10^{-5}$ mg m^{-2} s^{-1} . These ranges are around the middle to lower end of that obtained for the spiker survey which varied from $1.7x10^{-5}$ to $1.8x10^{-3}$ mg m^{-2} s^{-1}, for the same reasons as discussed under site A. The average flux box result in winter, $6.1x10^{-5}$ mg m^{-2} s^{-1}, is a fifth of the average flux box result for summer, $3.0x10^{-4}$ mg m^{-2} s^{-1}.

The methane potential of the depth of waste at this site is reduced by the sizeable proportion of inert wastes present (50%). The flux box results were low even though it was late summer and the ground was dry (allowing the unimpeded progress of methane through the cap). This could suggest that methane oxidation in the cap is a viable mechanism at this site.

The narrowness of the results for this site implies a uniform quality of cap. This site has an average flux box result which falls on the middle section of the S-distribution presented in Section 2.4.

SITE C

LOCATION:	Surrey
PERIOD OF OPERATION:	Late 1970s
WASTE COMPOSITION:	50% Domestic, 50% Ind/Commercial
GEOLOGY:	Folkestone Beds
CONTAINMENT:	Minimal
CAP TYPE:	Soil
ENGINEERED FEATURES:	Gas collection system to flare

Site C was filled during the late 1970s and capped flat with a clay/sand mix soon after. It is an unlined site on Folkestone Beds, with a limited gas collection scheme in place to prevent gas migration to nearby residences. Waste in area C_1 is typically 1 to 3m below the surface which was heavily waterlogged during the monitoring period. The winter flux box results, given in Table C1 below, were taken on 26th September 1995. The spiker survey results, taken on the same day, are given in Table C2, zeros indicate either waterlogged soil preventing the detector from functioning correctly or impenetrable ground conditions. A second area (C_2) at this site was visited, in conjunction with NPL, on 30th May 1996, the results of which are given in Table C3. This area is larger than the first, with up to 10m deeper waste and a thinner cap. Gas wells in this area are not being pumped, except at the perimeter to prevent lateral migration. The spread of results obtained with the flux boxes are shown in figures C1 and C3, with the cumulative methane flux shown in figures C2 and C4.

Table C1. Site C Flux Box results, 26/09/95

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
C1	$9.1x10^{-5}$	1.1	$1.2x10^{-4}$
C2	$7.1x10^{-5}$	1.4	$1.0x10^{-4}$
C3	$5.0x10^{-5}$	1.65	$8.5x10^{-5}$
C4	$5.1x10^{-5}$	2.1	$9.6x10^{-5}$
C5	$6.5x10^{-5}$	2.04	$1.1x10^{-4}$
C6	$5.9x10^{-5}$	1.83	$9.8x10^{-5}$

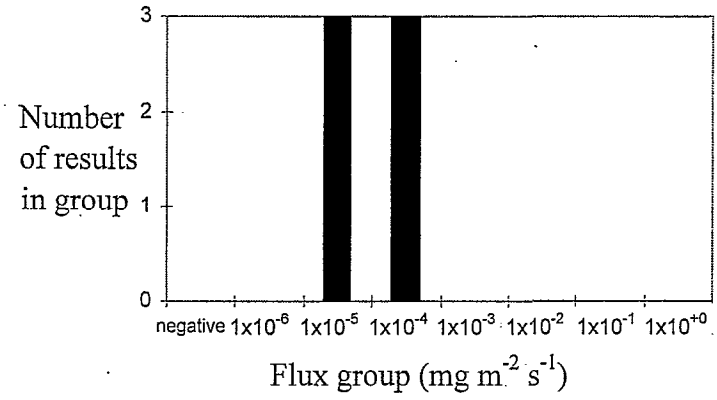


Figure C1. Distribution of flux box results (area C_1)

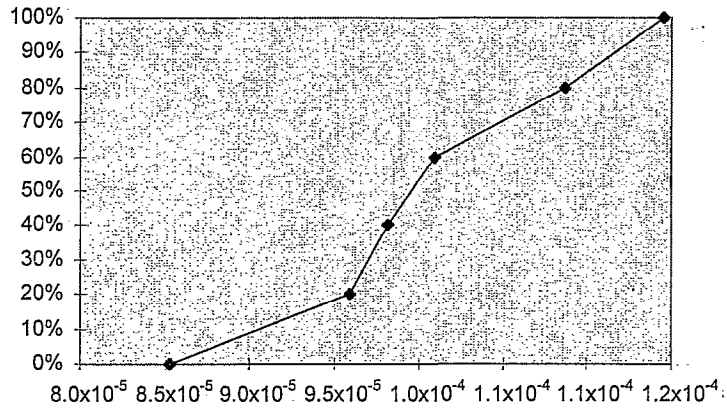


Figure C2 Cumulative plot of methane flux mg m^{-2} s^{-1} (area C_1)

Table C2. Site C Spiker Survey results (mg m^{-2} s^{-1}), 25/09/95

	A	B	C	D	E	F
1	$3.4x10^{-5}$	$1.0x10^{-4}$	$0.0x10^{+0}$	$9.5x10^{-5}$	$2.1x10^{-4}$	$2.9x10^{-4}$
2	$2.9x10^{-5}$	$1.2x10^{-2}$	$0.0x10^{+0}$	$8.1x10^{-4}$	$3.8x10^{-4}$	$7.1x10^{-5}$
3	1.3x10-1	$0.0x10^{+0}$	$6.8x10^{-4}$	$7.7x10^{-5}$	$1.7x10^{-4}$	$3.3x10^{-4}$
4	$5.8x10^{-4}$	$1.8x10^{-4}$	$6.5x10^{-4}$	$1.1x10^{-4}$	$8.6x10^{-5}$	$4.6x10^{-4}$
5	$3.6x10^{-4}$	$5.8x10^{-5}$	$1.2x10^{-4}$	$4.0x10^{-4}$	$1.1x10^{-3}$	$7.1x10^{-4}$
6	$1.1x10^{-4}$	$6.3x10^{-5}$	$7.7x10^{-4}$	$2.3x10^{-4}$	$1.6x10^{-3}$	$1.9x10^{-4}$
7	$4.8x10^{-4}$	$6.9x10^{-5}$	$8.6x10^{-5}$	$1.2x10^{-4}$	$5.2x10^{-5}$	$1.5x10^{-4}$

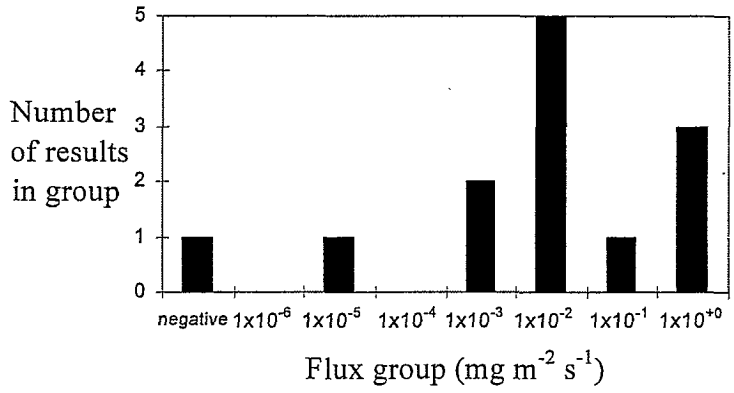


Figure C3. Distribution of flux box results (area C_2)

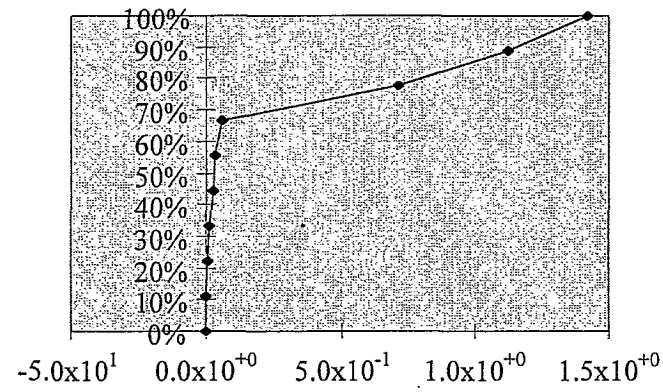


Figure C4. Cumulative plot of methane flux mg m^{-2} s^{-1} (area C_2)

Table C3. Site C Flux Box results, 30/05/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
C1	$2.3x10^{-2}$	249	$2.9x10^{-2}$
C2	$5.5x10^{-2}$	125	$5.7x10^{-2}$
C3	$2.2x10^{-3}$	11.8	$2.5x10^{-3}$
C4	$7.1x10^{-1}$	255	$7.1x10^{-1}$
C5	$1.1x10^{0}$	1540	$1.1x10^{0}$
C6	$-1.3x10^{-5}$	1.92	$2.8x10^{-5}$
C7	$3.4x10^{-2}$	76.9	$3.6x10^{-2}$
C8	$-5.7x10^{-5}$	2.49	$-3.9x10^{-6}$
C9	$1.4x10^{0}$	2870	$1.4x10^{0}$
C10	$9.2x10^{-3}$	76.7	$1.1x10^{-2}$

Discussion of results

Fluxes for area C_1 range from $8.5x10^{-5}$ to $1.2x10^{-4}$ mg m^{-2} s^{-1} measured with flux boxes, to $2.9x10^{-5}$ to $1.3x10^{-1}$ mg m^{-2} s^{-1} from the spiker survey. This latter result ranges over four orders of magnitude and emphasises the variability of results achieved with probes due to sampling difficulties and the use of default values in the equations converting concentration into flux. The quality of the cap, enhanced by the high moisture levels, is fairly uniform, as implied by figure C1. The average result for area C_1 lies close to the median of all results on the S-distribution.

Fluxes for area C_2 range from a negative result ($-3.9x10^{-6}$ mg m^{-2} s^{-1}) to the highest flux observed at any site, 1.4 mg m^{-2} s^{-1}. The spread of results implies a highly variable cap quality which is largely ineffective at preventing emissions. The implications of the negative readings are covered in Section 2.4, but may also reflect the uncertainty of fill boundaries. The average flux box result from this area lies on the topmost section of the S-distribution presented in Section 2.4.

SITE D

LOCATION: Kent
PERIOD OF OPERATION: Mid 1970s to 1981
WASTE COMPOSITION: Inert, slowly degradable
GEOLOGY: Ragstone
CONTAINMENT: Minimal
CAP TYPE: Soil
ENGINEERED FEATURES: Gas flaring across the bulk of the site

Site D was operated for a period of 12 years and finished between 1979 and 1983. A former Ragstone quarry, it is a flat site with waste depths in the region of 15-18m. It is freely draining and has a gas collection system and flare. During the monitoring period of 24th October 1995 the weather was fair but the presence of large pools of surface water indicated previous heavy rain and waterlogging of the soil. The flux box results are given in Table D1 below. Two sets of 6 results were taken. The spread of results obtained is shown in figure D1 and the cumulative flux is shown in figure D2.

Table D1. Site D Flux Box results, 24/10/95

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
D1	$8.5x10^{-6}$	1.12	$3.3x10^{-5}$
D2	$1.7x10^{-5}$	0.9	$3.6x10^{-5}$
D3	$8.7x10^{-6}$	1.05	$3.1x10^{-5}$
D4	$-9.9x10^{-6}$	1.9	$3.1x10^{-5}$
D5	$7.6x10^{-6}$	1.04	$3.0x10^{-5}$
D6	$2.2x10^{-6}$	1.11	$2.6x10^{-5}$
D7	$-5.9x10^{-5}$	2.4	$-7.6x10^{-6}$
D8	$-2.5x10^{-5}$	2.27	$2.4x10^{-5}$
D9	$-5.6x10^{-5}$	2.9	$6.1x10^{-6}$
D10	$-1.5x10^{-5}$	2.675	$4.2x10^{-5}$
D11	$-3.5x10^{-5}$	2.6	$2.1x10^{-5}$
D12	$-3.8x10^{-5}$	2.45	$1.4x10^{-5}$

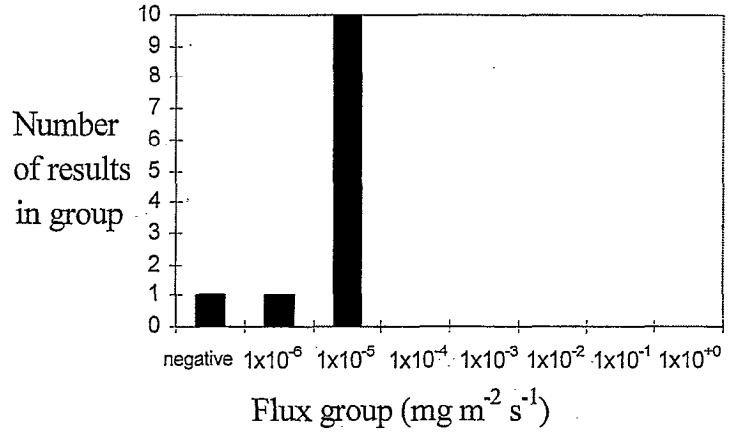


Figure D1. Distribution of flux box results

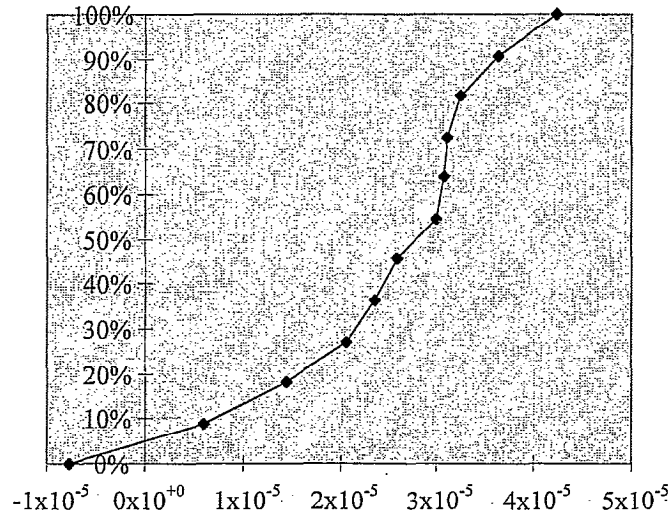


Figure D2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The flux box results from this site range from $6.1x10^{-6}$ to $4.2x10^{-5}$ mg m^{-2} s^{-1}, with one negative flux, even after adjustment for ambient levels, indicating the possibility of back diffusion. The heavily waterlogged soil prevented gas emission through the cap and the variation in concentration recorded may be linked to instrument drift or surface atmospheric effects, noticeable at very low fluxes, as the pattern of behaviour of the individual boxes was very similar.

It is worth noting that this site had a gas migration problem, for which a site-wide gas collection and flaring system was installed. Despite the cap being only comprised of a thin soil cover the active gas collection scheme, in combination with the slowly degradable nature of the waste, appears to have reduced flux to a minimum.

SITE E

LOCATION: Oxfordshire
PERIOD OF OPERATION: 1983-1994
WASTE COMPOSITION: Household & Industrial
GEOLOGY: Gravel pits
CONTAINMENT: Engineered cells
CAP TYPE: PFA
ENGINEERED FEATURES: Passive gas venting

This site was infilled over an 11 year period from 1983 to 1994. During this period site preparation works progressed from sidewall sealing by bulldozer placed clay to engineered works for the 'football pitch' cells. Depths of waste range from 10 to 25m in three cells which were fitted with a basal leachate collection system. The first two phases of gas collection were installed in 1991 and 1992 with Phase 3 installed in early 1994. Due to problems with the main flare the area was not being efficiently pulled so a lot of gas was passively vented. The first set of results E1 to E5 were in an area which has only been connected to the gas collection system since our visit. The flux box results obtained on 30th October 1995 are given in Table E1 below. The weather was fair, though windy. The current active area was upwind during the measurements of boxes E1 to E5. The spread of results obtained is shown in figure E1 and the cumulative flux is shown in figure E2.

Table E1. Site E Flux box results, 30/10/95

SITE/BOX	Observed Flux $mg\ m^{-2}\ s^{-1}$	Initial concentration C_0 $mg\ m^{-3}$	Actual Flux $mg\ m^{-2}\ s^{-1}$
E1	$1.9x10^{-4}$	9.8	$2.0x10^{-5}$
E2	$4.1x10^{-3}$	25	$4.6x10^{-3}$
E3	$2.5x10^{-3}$	300	$8.9x10^{-3}$
E4	$3.1x10^{-2}$	27	$3.2x10^{-2}$
E5	$-2.1x10^{-4}$	7	$-6.0x10^{-5}$
E6	$1.6x10^{-5}$	1.3	$4.4x10^{-5}$
E7	$2.1x10^{-5}$	0.8	$3.8x10^{-5}$
E8	$8.0x10^{-5}$	0.75	$9.6x10^{-5}$
E9	$1.8x10^{-6}$	1.59	$3.6x10^{-5}$
E10	$-2.6x10^{-5}$	2.2	$2.1x10^{-5}$

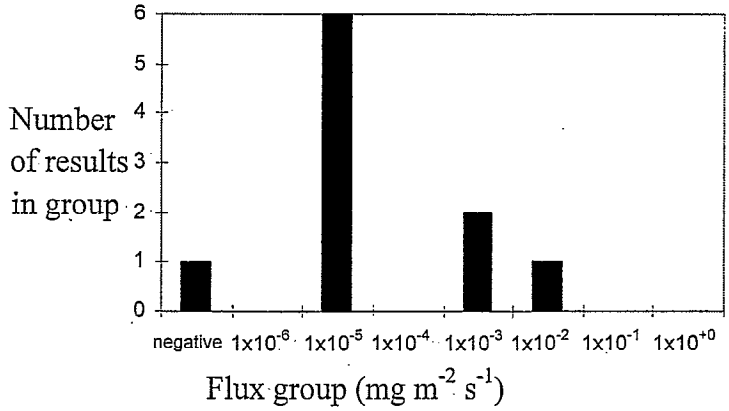


Figure E1. Distribution of flux box results

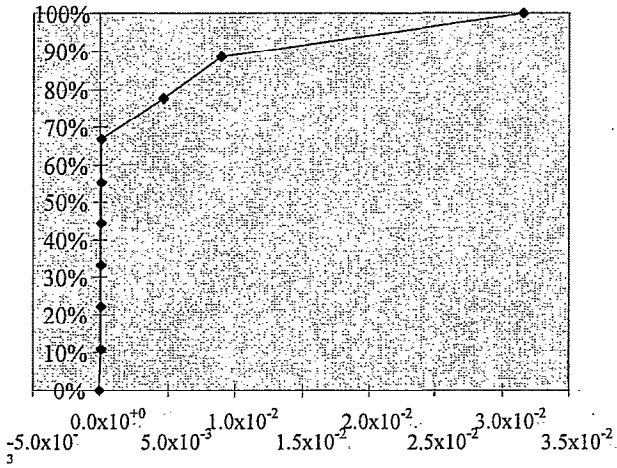


Figure E2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The range of fluxes measured over the whole of site E is $-6.0x10^{-5}$ to $3.2x10^{-2}$ mg m^{-2} s^{-1}. This can be separated into $-6.0x10^{-5}$ to $3.2x10^{-2}$ mg m^{-2} s^{-1} for the newer part of the site, which is not fully restored to grass and was not achieving full gas pumping on the day of monitoring, and $2.1x10^{-5}$ to $9.6x10^{-5}$ mg m^{-2} s^{-1} for the older part of the site which is restored to grassland and was being actively pumped. Additionally the gusts of wind, coming across the active area onto the first set of boxes, were noticeable by odour and the response of the detector when idling between measurements. In contrast no odour was detectable during the second set of measurements. This demonstrates how important it is to seal the flux boxes to the ground surface before measurements commence. It is possible that box E5 was close to the edge of a cell, the exact positions of which are difficult to identify, so there was no net methane flow into the box.

The average flux box result for this site, at $4.5x10^{-3}$ mg m^{-2} s^{-1}, is on the upper tail section of the S-distribution. With gas collection restored to the whole site the average result is likely to fall below 10^{-3} mg m^{-2} s^{-1}, i.e. below the 'knee' of the S-distribution.

SITE F

LOCATION: Oxfordshire
PERIOD OF OPERATION: 1977-1982
WASTE COMPOSITION: Household & Industrial
GEOLOGY: Gravel pit
CONTAINMENT: Clay/PFA lined
CAP TYPE: Clay and PFA
ENGINEERED FEATURES: Some gas recovery

Site F was used for the disposal of large quantities of domestic and inert waste and pulverised fuel ash (PFA) from 1977 to 1982, to a maximum depth of 6m. The clay base of the gravel pit provided containment to prevent downward migration of leachate whilst PFA bunds were built against the side slopes to provide a partial side wall seal. PFA was also used to provide intermediate cover and mixed with clay to cap over half of the site, the rest being minimally covered in soil. The site was restored flat, level with the surrounding low ground, although settlement has occurred.

Table F1. Site F Flux Box results, 31/10/95

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
F1(clay)	$-4.5x10^{-5}$	5.6	$7.5x10^{-5}$
F2(clay)	$-1.3x10^{-4}$	9.7	$7.8x10^{-5}$
F3	$-1.2x10^{-1}$	9000	$7.3x10^{-2}$
F4	$9.3x10^{-2}$	2340	$1.4x10^{-1}$
F5	$1.7x10^{-2}$	180	$2.1x10^{-2}$
F6	$3.4x10^{-3}$	3147	$7.1x10^{-2}$
F7	$-1.1x10^{-4}$	47.7	$9.1x10^{-4}$
F8	$1.4x10^{-4}$	1.6	$1.7x10^{-4}$
F9(clay)	$4.5x10^{-4}$	0	$4.5x10^{-4}$
F10(clay)	$2.9x10^{-3}$	60	$4.2x10^{-3}$
F11	$8.5x10^{-3}$	37.5	$9.3x10^{-3}$
F12	$1.9x10^{-2}$	105	$2.1x10^{-2}$
F13	$4.5x10^{-2}$	547	$5.7x10^{-2}$
F14(clay)	$1.1x10^{-4}$	6.1	$2.4x10^{-4}$
F15(clay)	$7.2x10^{-3}$	73	$8.8x10^{-3}$

No leachate collection system was installed at the site. There is a perimeter line of gas wells drawn by a small flare of circa 250m^3 hr^{-1} capacity. During the monitoring period of 31st October 1995 three sets of 5 flux box results were obtained and are shown in Table F1 above, boxes on the thick clay/PFA cap are indicated. The weather was fair and dry. The wide variation in results is shown in figure F1 below. Figure F2 shows the cumulative flux of methane.

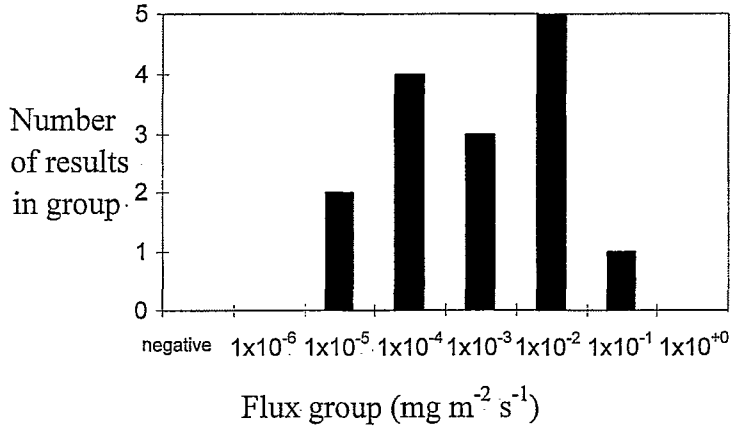


Figure F1. Distribution of flux box results

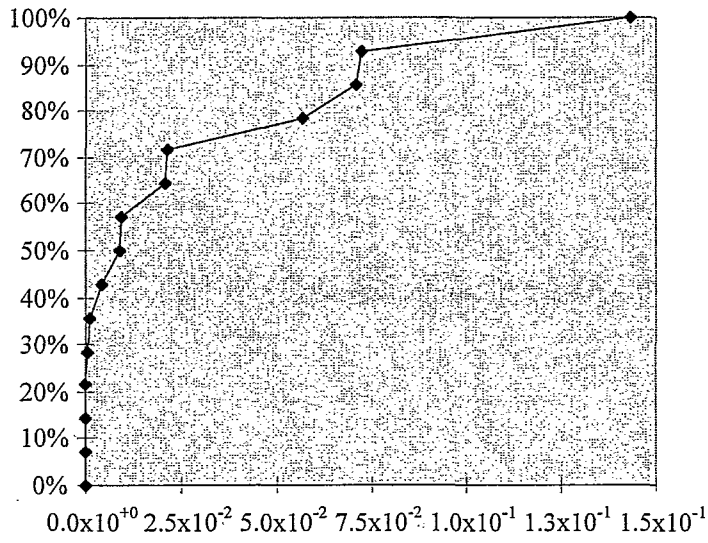


Figure F2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

Over the whole of site F, the fluxes ranged from 7.5x10^{-5} to 1.4x10^{-1} mg m^{-2} s^{-1}. However this site is divided into two key areas. An area, approximately half of the site, is covered with clay and PFA to a depth of 2 to 3m. The flux, here, ranged from 7.5x10^{-5} to 8.8x10^{-3} mg m^{-2} s^{-1}. The other half of the site is thinly covered by soil and had measured fluxes in the range 1.7x10^{-4} to 1.4x10^{-1} mg m^{-2} s^{-1}. Thus the average result with a clay/PFA cap was 2.3x10^{-3} mg m^{-2} s^{-1} and without it was 4.4x10^{-2} mg m^{-2} s^{-1}. The whole site average of 2.7x10^{-2} mg m^{-2} s^{-1} is on the upper section of the S-distribution given in Section 2.4.

SITE G

LOCATION:	Oxfordshire
PERIOD OF OPERATION:	1981/82 with surcharge in 1994
WASTE COMPOSITION:	Household & Industrial
GEOLOGY:	Non-engineered cell
CONTAINMENT:	Clay lined
CAP TYPE:	Clay
ENGINEERED FEATURES:	No collection scheme

This site which was originally filled in 1981/82 with domestic waste, was surcharged with further waste during March 1994 to give a final waste depth of 8-9m. The site was constructed as a non-engineered clay lined cell, capped in the summer of 1994, with 300mm of overburden placed on the cap later that year. There is no active gas collection system in place. Site G is awaiting final restoration. During the monitoring period of 1st November 1995 the weather was overcast with intermittent showers. The flux box results are given below in Table G1 and the spread of results is shown in figure G1. The cumulative methane flux is shown in figure G2.

Table G1. Site G Flux Box results, 01/11/95

SITE/BOX	Observed Flux $mg\ m^{-2}\ s^{-1}$	Initial concentration C_0 $mg\ m^{-3}$	Actual Flux $mg\ m^{-2}\ s^{-1}$
G1	$4.2x10^{-5}$	3.25	$1.1x10^{-4}$
G2	$9.0x10^{-6}$	7	$1.6x10^{-4}$
G3	$2.1x10^{-1}$	1200	$2.4x10^{-1}$
G4	$1.4x10^{-4}$	2.1	$1.8x10^{-4}$
G5	$8.6x10^{-3}$	282	$1.5x10^{-2}$

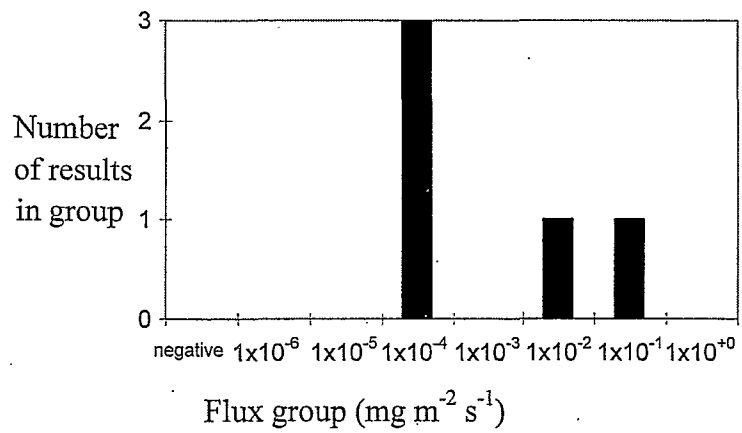


Figure G1. Distribution of flux box results

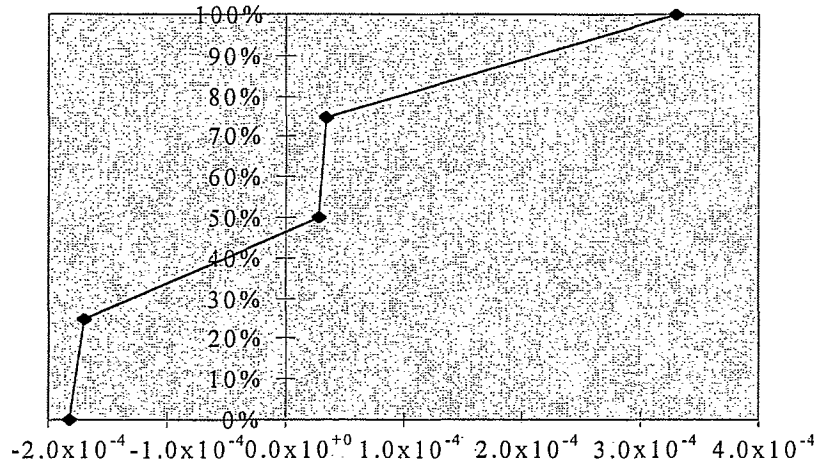


Figure G2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The range of fluxes measured for this site, of $1.1x10^{-4}$ to $2.6x10^{-1}$ mg m^{-2} s^{-1}, covers three orders of magnitude indicating the variability in cap quality. When the site was surcharged the existing monitoring wells were not closed over and have not subsequently been identified on the current surface. It is therefore possible that a box may have been randomly located over such a well and be directly above a 'window' to the waste. Alternatively it may be the relatively recent surcharge which is variable across the surface.

The average flux box result of $5.02x10^{-2}$ mg m^{-2} s^{-1} lies on the uppermost part of the S-distribution of all results.

SITE H

LOCATION: Oxfordshire
PERIOD OF OPERATION: 1986-1987
WASTE COMPOSITION: Household & Industrial
GEOLOGY: Clay
CONTAINMENT: Clay lined
CAP TYPE: PFA
ENGINEERED FEATURES: Passive gas venting

This site was filled during 1986-87 with a mixture of domestic waste and PFA to a maximum depth of 18m. The site was operated as a leachate containment landfill, with the clay base providing basal containment and placed clay forming the side walls. No leachate collection system has been installed. There are passive gas vents but no gas collection system. During the monitoring period of 1st November the weather was overcast and windy. The flux box results obtained are shown in Table H1 below. The spread of results obtained is shown in figure H1 and the cumulative flux in figure H2.

Table H1. Site H Flux Box results, 01/11/95

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
H1	$-3.7x10^{-4}$	9.3	$-1.7x10^{-4}$
H2	$5.7x10^{-6}$	1.06	$2.8x10^{-5}$
H3	$1.9x10^{-5}$	0.66	$3.3x10^{-5}$
H4	$3.3x10^{-4}$	0	$3.3x10^{-4}$
H5	$-7.5x10^{-4}$	26.5	$-1.8x10^{-4}$

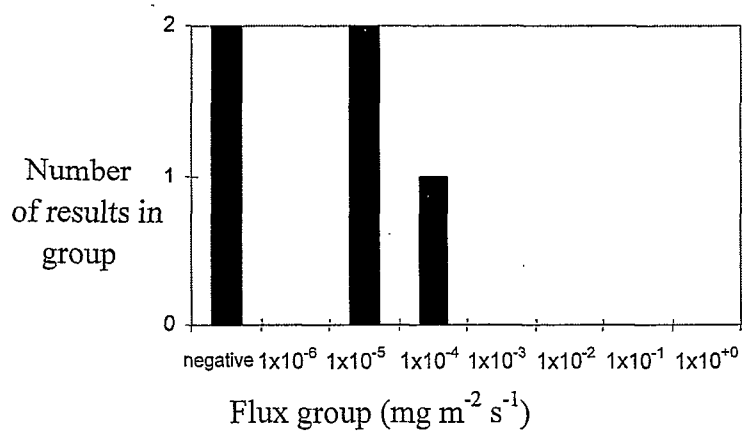


Figure H1. Distribution of flux box results

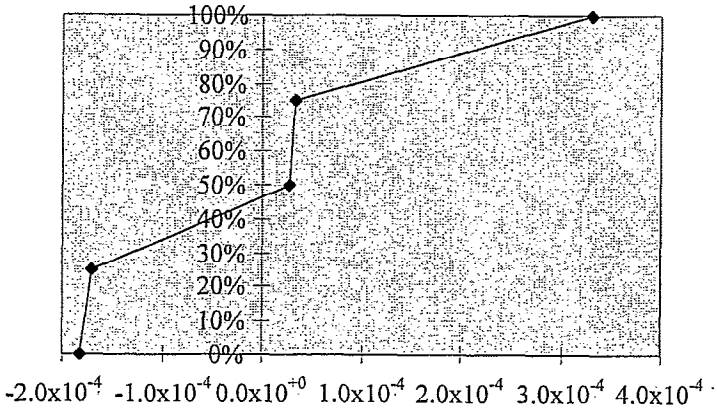


Figure H2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The measured methane fluxes at site H varied from $-1.8x10^{-4}$ to $3.3x10^{-4}$ mg m^{-2} s^{-1} and in general are at the lower end of the range encountered over all sites. Despite a sizeable depth of waste the fluxes are low, possibly due to the clay cap or the dilution of the waste by PFA.

The average flux box result for Site H, of $7.8x10^{-5}$ mg m^{-2} s^{-1} is at the lower end of the middle section of the S-distribution.

SITE I

LOCATION: Bedfordshire
PERIOD OF OPERATION: 1968-Present
WASTE COMPOSITION: Household & Industrial
GEOLOGY: Oxford Clay
CONTAINMENT: Clay lined
CAP TYPE: Clay engineered
ENGINEERED FEATURES: 5 Passive venting wells

This site is a former clay pit where infilling of hazardous wastes began in 1968. In the early 1970s it was acquired for disposing of household waste which was extended to include industrial and commercial wastes in 1977. Waste depths are up to 25m. In 1994 1m of clay was added to 2/3 of the site. It was previously covered with a soil layer but was effectively uncapped. During the monitoring period of 15th November 1995 the weather was fair and breezy, but the clay cap was substantially waterlogged. Flux box results are shown below in Table I1, the spread of results and the cumulative flux are presented in figures I1 and I2 respectively.

Table I1. Site I Flux Box results, 15/11/95

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
I1	$-3.5x10^{-3}$	171	$1.6x10^{-4}$
I2	$-6.2x10^{-6}$	1.85	$3.3x10^{-5}$
I3	$-1.6x10^{-6}$	2.5	$5.3x10^{-5}$
I4	$-5.8x10^{-5}$	1.7	$-2.1x10^{-5}$
I5	$7.9x10^{-5}$	2.3	$1.3x10^{-4}$

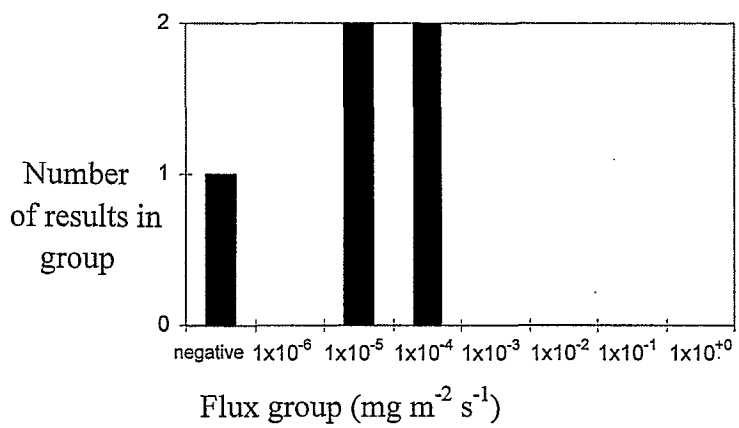


Figure I1. Distribution of flux box results

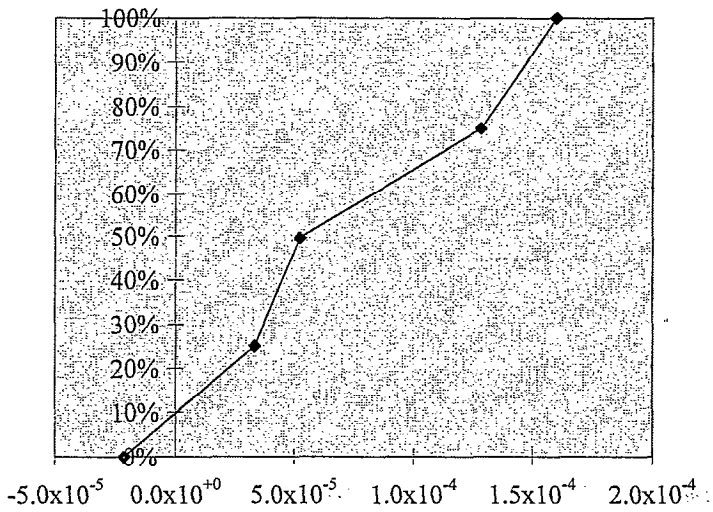


Figure I2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

This site has only recently been capped in the area that was monitored so substantial passive venting had already occurred and there was insufficient time for a build up of gas. In addition the clay cap was waterlogged, and this is probably the main cause of the observed fluxes being very low or negative.

The average flux box result for this site was 7.1×10^{-5} mg m^{-2} s^{-1} which lies at the lower half of the middle section of the S-distribution shown in Section 2.4.

SITE J

LOCATION: Bedfordshire
PERIOD OF OPERATION: 1922-Present
WASTE COMPOSITION: 40% Inert, 35% Domestic, 25% Ind/Comm
GEOLOGY: Chalk
CONTAINMENT: Dense layer of grate ash over base
CAP TYPE: Minimal soil/chalk
ENGINEERED FEATURES: No engineering of cap, no gas collection scheme

Waste has been brought to this former chalk quarry since 1922 but only on a small user basis. It was acquired by the local County Council in 1977 from which time inputs have increased considerably. The site is up to 35m in depth and there is no cap except a thin layer of soil/chalk mix, though the older areas have soil supporting vegetation. There is currently no gas collection. During the monitoring period of 16th November 1995 the weather was wet and overcast, the two sets of flux box results are given below (1-5 and 6-10) in Table J1. Set J1-5 were collected nearer to the fresh waste in the operational phase. Set J6-10 were collected from the much older, vegetated soil-covered waste. The spread of results obtained with the flux boxes is shown in Figure J1 and the cumulative flux is shown in Figure J2.

Table J1. Site J Flux Box results, 16/11/95

SITE/BOX	Observed Flux $mg\ m^{-2}\ s^{-1}$	Initial concentration C_0 $mg\ m^{-3}$	Actual Flux $mg\ m^{-2}\ s^{-1}$
J1	$1.4x10^{-3}$	3.2	$1.5x10^{-3}$
J2	$3.8x10^{-4}$	8.3	$5.6x10^{-4}$
J3	$3.5x10^{-3}$	73.2	$5.1x10^{-3}$
J4	$4.1x10^{-3}$	2	$4.1x10^{-3}$
J5	$2.9x10^{-2}$	0	$2.9x10^{-2}$
J6	$-3.5x10^{-5}$	9.2	$1.6x10^{-4}$
J7	$3.2x10^{-5}$	2.2	$7.9x10^{-5}$
J8	$-1.1x10^{-5}$	2.7	$4.7x10^{-5}$
J9	$1.9x10^{-5}$	2.4	$7.0x10^{-5}$
J10	$-2.6x10^{-5}$	17.7	$3.5x10^{-4}$

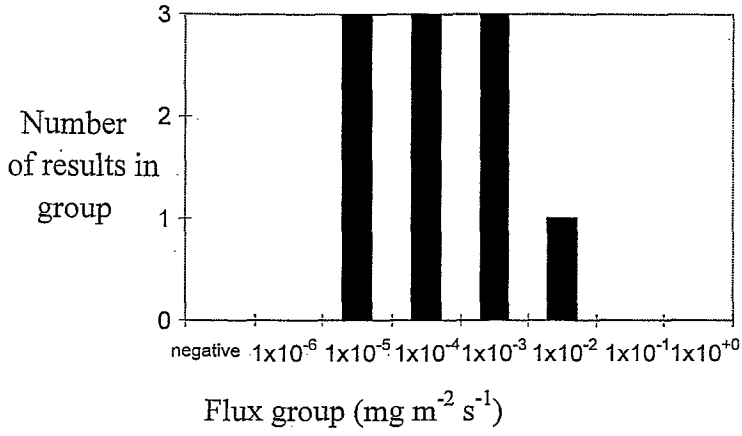


Figure J1. Distribution of flux box results

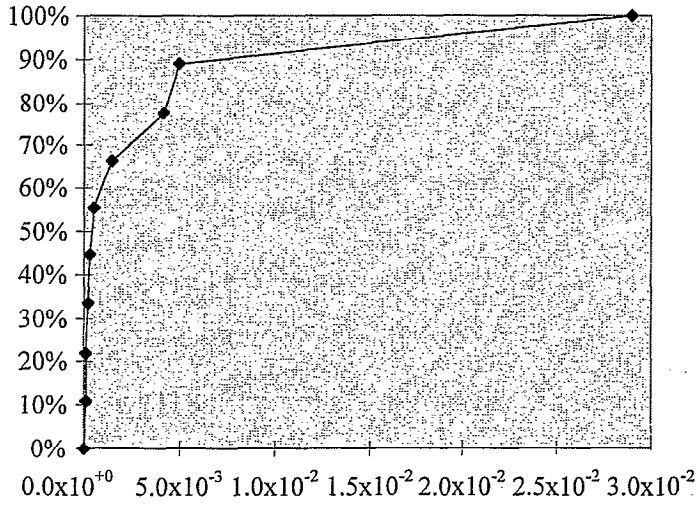


Figure J2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The results for this site are clearly divided between the first set (J1 to J5), from $5.6x10^{-4}$ to $2.9x10^{-2}$ mg m^{-2} s^{-1} and the second set (J6-J10), from $4.7x10^{-5}$ to $3.5x10^{-4}$ mg m^{-2} s^{-1}. As none of the site has an engineered cap on it the principal difference between the two areas is age, the first set of data being of much more recent origin. Thus there is a difference in flux between $8.05x10^{-3}$ mg m^{-2} s^{-1} and $1.42x10^{-4}$ mg m^{-2} s^{-1} as a result of about twenty years.

The average flux for the whole site, of $4.1x10^{-3}$ mg m^{-2} s^{-1}, lies on the uppermost section of the S-distribution, however, it is clear that the average flux for the older subset is on the middle section of the S-distribution and would benefit less from remedial actions. The spread of results shows the non-uniformity of age of waste.

SITE K

LOCATION: Bedfordshire
PERIOD OF OPERATION: Late 1980s to Present
WASTE COMPOSITION: Household & Industrial
GEOLOGY: Oxford Clay
CONTAINMENT: Natural attenuation
CAP TYPE: Clay
ENGINEERED FEATURES: Well engineered cap, active gas extraction and energy recovery

This is a very extensive site operated from the late 1980s to the present time. The monitoring was conducted on an area which had been infilled with household and industrial wastes during 1991/92. Previous bad weather and rain on the day of monitoring made the clay cap, as yet unseeded, very waterlogged. This site has a full gas collection scheme which serves an energy recovery unit. The flux box results obtained are shown in Table K1 and the narrow range is shown on Figure K1. The cumulative methane flux is shown in figure K2.

Table K1. Site K Flux Box results, 17/11/95

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
K1	$1.4x10^{-5}$	0.86	$3.2x10^{-5}$
K2	$3.2x10^{-5}$	0.13	$3.5x10^{-5}$
K3	$4.4x10^{-5}$	0	$4.4x10^{-5}$
K4	$4.7x10^{-5}$	0	$4.7x10^{-5}$
K5	$5.0x10^{-5}$	0	$5.0x10^{-5}$
K6	$1.0x10^{-5}$	1.11	$3.4x10^{-5}$
K7	$3.9x10^{-5}$	0.43	$4.8x10^{-5}$
K8	$5.3x10^{-5}$	0.09	$5.5x10^{-5}$
K9	$5.5x10^{-5}$	0	$5.5x10^{-5}$
K10	$5.2x10^{-5}$	0	$5.2x10^{-5}$

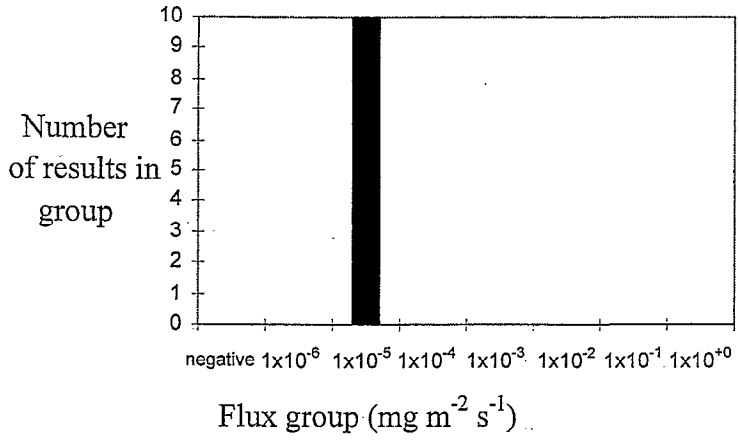


Figure K1. Distribution of flux box results

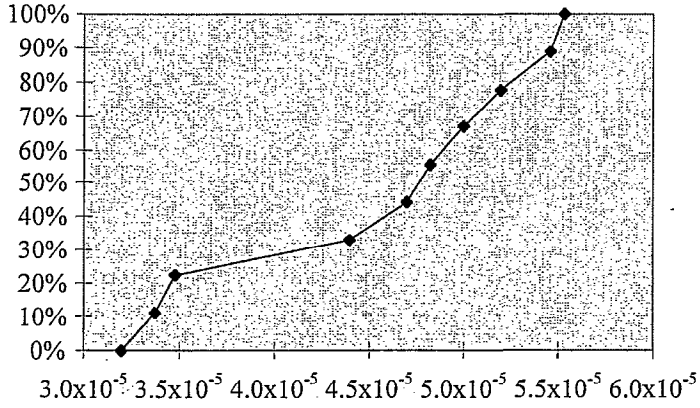


Figure K2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The measured fluxes for this site are in the range $3.2x10^{-5}$ to $5.5x10^{-5}$ mg m^{-2} s^{-1} showing no spread in the results and implying a high uniformity of quality of cap. The well engineered clay cap, which was heavily moisture bound, appeared to prevent any significant methane emissions. The lower average flux, $4.16x10^{-5}$ mg m^{-2} s^{-1} came from the older phase of the two that were monitored. However, as the second phase followed the first by about a year that average flux is not much higher at $4.88x10^{-5}$ mg m^{-2} s^{-1}.

SITE L

LOCATION: Lancashire
PERIOD OF OPERATION: 1980 - present
WASTE COMPOSITION: Domestic, some commercial
GEOLOGY: Shales
CONTAINMENT: Unlined
CAP TYPE: Clay
ENGINEERED FEATURES: Gas collection and utilisation

This is an operational domestic waste site authorised to take up to 2.5 million tonnes total emplacement. The natural geology of the site, shales overlain with Haslingden flagstone and rough rock, is the method of containment. The cap is a composite of up to one metre of crushed rock, and half a metre each of clay and shale. Methane is collected and fed into the on-site power station. During the monitoring period (16/1/96) the weather was fair. The clay cap was substantially waterlogged, at the lowest point of the monitored area, but the rest was much drier than normal for that time of year according to site personnel. Winter flux box results are shown in Table L1, the results spread is shown in Figure L1. Cumulative flux is shown in figure L2.

Table L1. Site L Flux Box results, 16/01/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
L1	$4.0x10^{-4}$	1.08	$4.3x10^{-4}$
L2	$7.1x10^{-5}$	13	$3.5x10^{-4}$
L3	$-1.6x10^{-5}$	15	$3.1x10^{-4}$
L4	$3.0x10^{-4}$	3	$3.6x10^{-4}$
L5	$1.5x10^{-4}$	3.09	$2.2x10^{-4}$
L6	$3.0x10^{-5}$	4.66	$1.3x10^{-4}$
L7	$2.3x10^{-5}$	6.1	$1.6x10^{-4}$
L8	$2.3x10^{-5}$	8.96	$2.2x10^{-4}$
L9	0	10.05	$2.2x10^{-4}$
L10	$6.4x10^{-6}$	1.116	$3.0x10^{-5}$
L11	$-1.1x10^{-5}$	3.96	$7.4x10^{-5}$
L12	$-4.9x10^{-5}$	2.9	$1.3x10^{-5}$
L13	$-1.5x10^{-5}$	1.6	$1.9x10^{-5}$
L14	$-4.8x10^{-5}$	2.3	$1.0x10^{-6}$
L15	$-3.4x10^{-5}$	2.63	$2.2x10^{-5}$

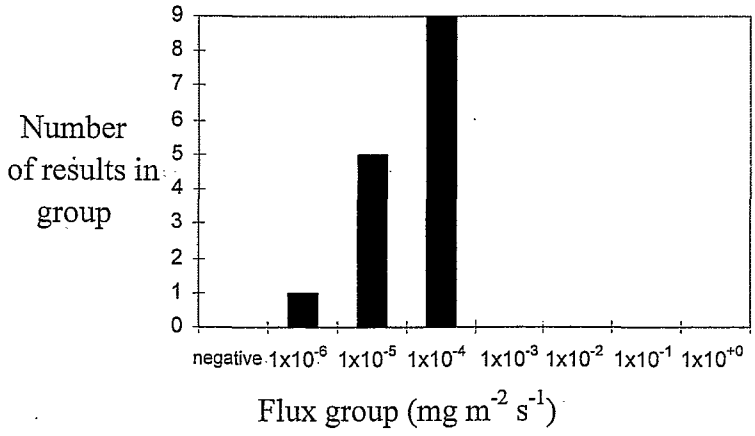


Figure L1. Distribution of flux box results (winter)

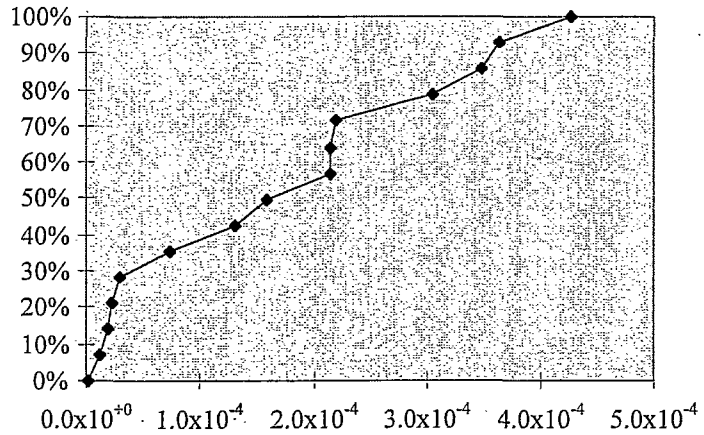


Figure L2. Cumulative plot of methane flux mg m^{-2} s^{-1} (winter)

A second visit was made to this site on 11 June 1996 in order to consider the effect of seasonal variation. However, on the day of the site visit, continuous rain prevented a full set of measurements and the visit was aborted. The results obtained, shown below in Table L2, are from the area corresponding with L1 to L5 of the winter visits. The spread of results obtained in the summer is shown in Figure L3 and the cumulative flux is shown in figure L4.

Table L2. Site L Flux Box results, 11/06/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
L1	$9.9x10^{-6}$	1.69	$4.6x10^{-5}$
L2	$9.0x10^{-6}$	1.13	$3.3x10^{-5}$
L3	$4.7x10^{-5}$	1.03	$6.9x10^{-5}$
L4	$4.2x10^{-5}$	0.0855	$4.4x10^{-5}$
L5	$2.4x10^{-5}$	0.0926	$2.6x10^{-5}$

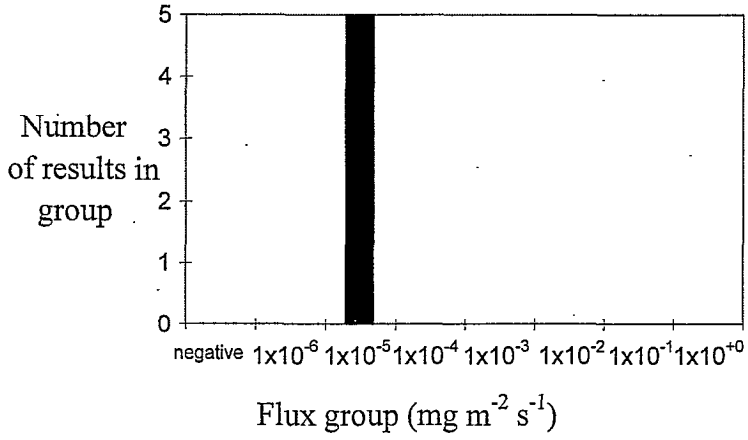


Figure L3. Distribution of flux box results (summer)

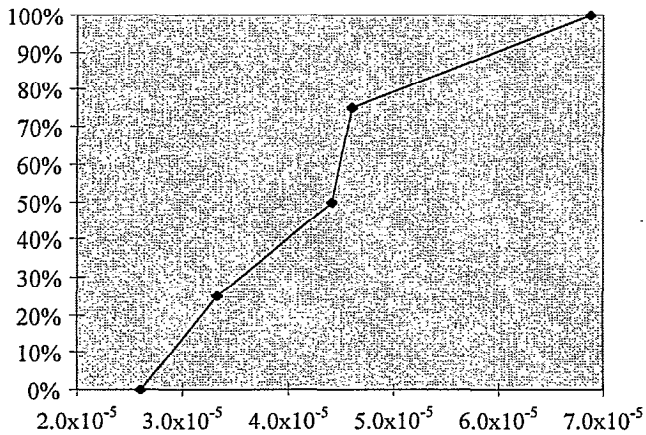


Figure L4. Cumulative plot of methane flux mg m^{-2} s^{-1} (summer)

Discussion of results

The average flux at this site was $1.7x10^{-4}$ mg m^{-2} s^{-1}, in winter, and $3.6x10^{-5}$ mg m^{-2} s^{-1} in summer which was aborted due to wet weather. The area under investigation at this site has variations in cap thickness and age of waste, thereby allowing consideration of intrasite variables. The area with the older waste and thicker cap (L6-L10) had half the methane emission flux of the newer waste with half the depth of clay for a cap, (L1-L5). The area that was water-logged on the first visit had a flux which was an order of magnitude lower than the other areas, (L11-L15).

The average flux for this site, $1.37x10^{-4}$ mg m^{-2} s^{-1}, lies on the middle section of the S-distribution.

SITE M

LOCATION: Lanarkshire
PERIOD OF OPERATION: 1990 - present
WASTE COMPOSITION: Domestic / Commercial
GEOLOGY: Clay
CONTAINMENT: Unlined
CAP TYPE: 1m "material" predominantly peat
ENGINEERED FEATURES: Gas collection and utilisation

This is a large operational site which is infilling the voids created by ongoing clay extraction. The waste is principally domestic with some commercial streams to a depth of about 10m. The cap is specified as 1m of "material" which is generally peat, as it is locally available. The restored areas are actively pumped for gas utilisation. Two sets of boxes were monitored, the first set being on the earlier phase, 1A, the second being phase 2A. The vegetation was better established on the earlier phase. The flux box results for 18th January 1996, an overcast and gusty day, are given in Table M1 below. The spread of flux box results obtained are shown in figure M1 and the cumulative flux is shown in figure M2.

Table M1. Site M Flux Box results, 18/01/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
M1	-8.2×10^{-5}	6.1	4.9×10^{-5}
M2	2.7×10^{-5}	1.06	4.9×10^{-5}
M3	5.9×10^{-5}	1.925	1.0×10^{-4}
M4	5.7×10^{-5}	1.85	9.6×10^{-5}
M5	1.1×10^{-4}	0.96	1.3×10^{-4}
M6	1.1×10^{-3}	23	1.6×10^{-3}
M7	-1.1×10^{-4}	22	3.7×10^{-4}
M8	2.3×10^{-4}	10.5	4.5×10^{-4}
M9	-5.0×10^{-4}	23	-3.8×10^{-6}
M10	-1.7×10^{-4}	15.7	1.7×10^{-4}

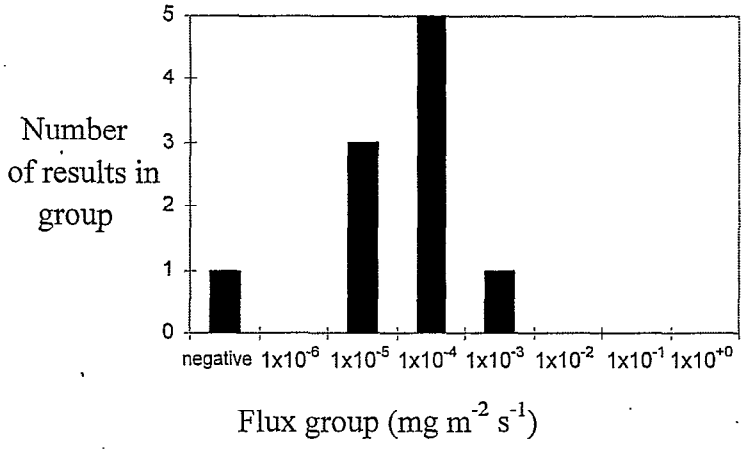


Figure M1. Distribution of flux box results

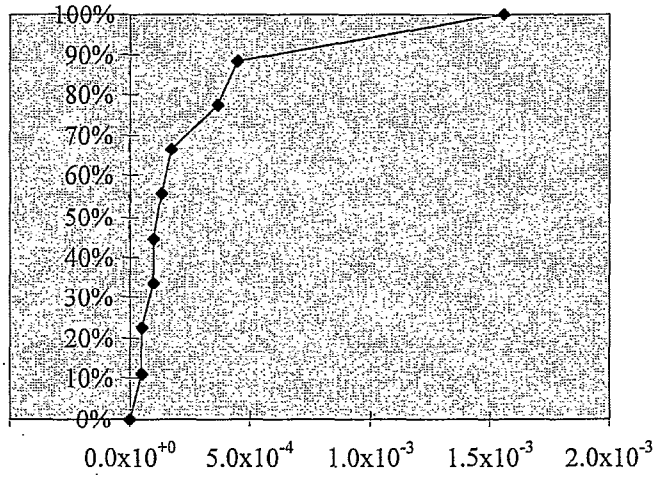


Figure M2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The average flux box result for this site was $3.0x10^{-4}$ mg m^{-2} s^{-1}, which can be separated into $8.5x10^{-5}$ mg m^{-2} s^{-1} and $5.2x10^{-4}$ mg m^{-2} s^{-1} for Phases 1A and 2A respectively. The upper age of Phase 1A is 6 years and the upper age of Phase 2A is 3 years. Thus a three year period of decay and gas collection has resulted in a factor six reduction in methane emissions, assuming the cap is of the same quality on both phases.

SITE N

LOCATION: Essex
PERIOD OF OPERATION: During 1980s
WASTE COMPOSITION: Domestic, commercial and industrial
GEOLOGY:
CONTAINMENT:
CAP TYPE: Soil and 0.5m clay
ENGINEERED FEATURES: Passive venting

This is a local authority site operated during the 1980s taking household waste. The first phase was completed in 1985 and a second phase was built up on the middle of the first from 1985 to 1987. The cap is built up of a half metre of clay with soil on top. The whole site is extensively vegetated. There is no gas collection scheme but there are passive venting pipes at wide intervals across the area. During the monitoring period of 10th September 1996 the weather was overcast and windy. The two sets of flux box results are given in Table N1 and the spread of results is shown in figure N1. Cumulative flux is shown in figure N2.

Table N1. Site N Flux Box results, 10/09/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
N1	$2.2x10^{-3}$	3.23	$2.3x10^{-3}$
N2	$1.1x10^{-5}$	1.56	$4.4x10^{-5}$
N3	$6.4x10^{-5}$	0.499	$7.4x10^{-5}$
N4	$1.2x10^{-3}$	3.27	$1.2x10^{-3}$
N5	$2.9x10^{-4}$	1.04	$3.1x10^{-4}$
N6	$6.5x10^{-3}$	144	$9.5x10^{-3}$
N7	$1.0x10^{-4}$	5.22	$2.2x10^{-4}$
N8	$-9.0x10^{-5}$	5.31	$2.4x10^{-5}$
N9	$-6.6x10^{-5}$	4.31	$2.7x10^{-5}$
N10	$-1.3x10^{-4}$	5.84	$-5.0x10^{-6}$

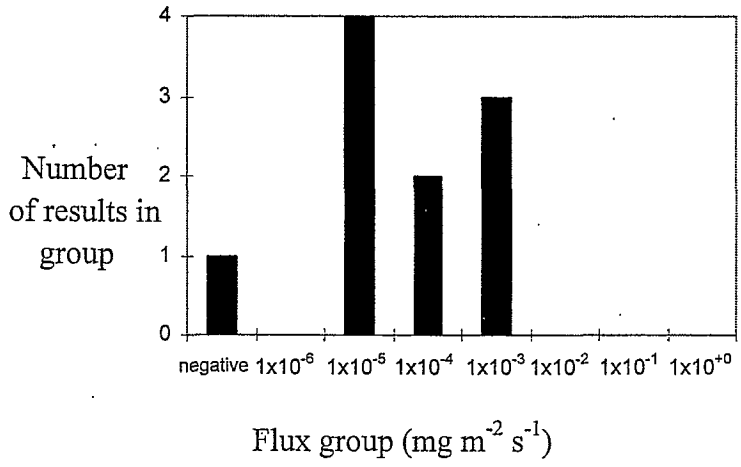


Figure N1. Distribution of flux box results

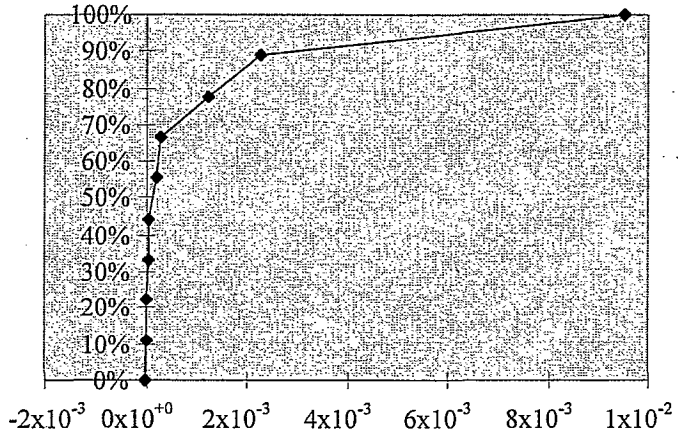


Figure N2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The average result at this site is $1.37x10^{-3}$ mg m^{-2} s^{-1} which just lies on the uppermost section of the S-distribution. This result can be separated into $7.87x10^{-4}$ mg m^{-2} s^{-1} for set one and $1.96x10^{-3}$ mg m^{-2} s^{-1} for set two (older waste), the age difference being about two to three years between the sets. Additional work has been done to the cap on the top-most section (later phase) of cap and this may be the explanation of the lower emissions on the more recent phase. The spread of results shown in Figure N1 is indicative of the variability of cap quality.

SITE O

LOCATION: Suffolk
PERIOD OF OPERATION: 1980 to 1992
WASTE COMPOSITION: Domestic, commercial and industrial
GEOLOGY: Chalk
CONTAINMENT:
CAP TYPE: Geotextile/LDPE/sand composite
ENGINEERED FEATURES: Small flare

This site has resulted from the infilling of a chalk quarry, the containment on two sides being the quarry walls. There is a small flare burning gas drawn from the waste, which is of domestic, commercial and industrial origin. The cap is made of a composite sand/LDPE layer. The results obtained on 22 January 1996, an overcast and gusty day, are shown in Table O1. The spread of results is shown in figure O1 and the cumulative results are in figure O2.

Table O1. Site O Flux Box results, 22/01/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
O1	$7.5x10^{-6}$	1.105	$3.1x10^{-5}$
O2	$-3.8x10^{-4}$	90	$1.6x10^{-3}$
O3	$-2.3x10^{-5}$	2.975	$4.1x10^{-5}$
O4	$2.8x10^{-5}$	2.3	$7.7x10^{-5}$
O5	$-2.1x10^{-6}$	1.46	$2.9x10^{-5}$
O6	$7.3x10^{-6}$	1.61	$4.2x10^{-5}$
O7	$-2.0x10^{-4}$	19.2	$2.1x10^{-4}$
O8	$-1.0x10^{-3}$	68	$4.2x10^{-4}$

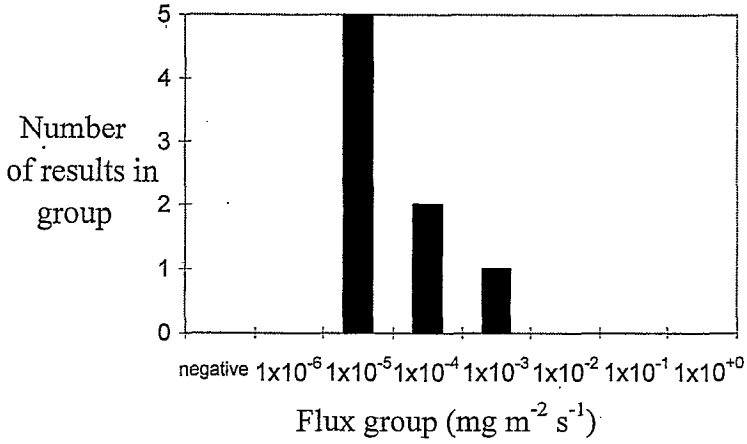


Figure O1. Distribution of flux box results

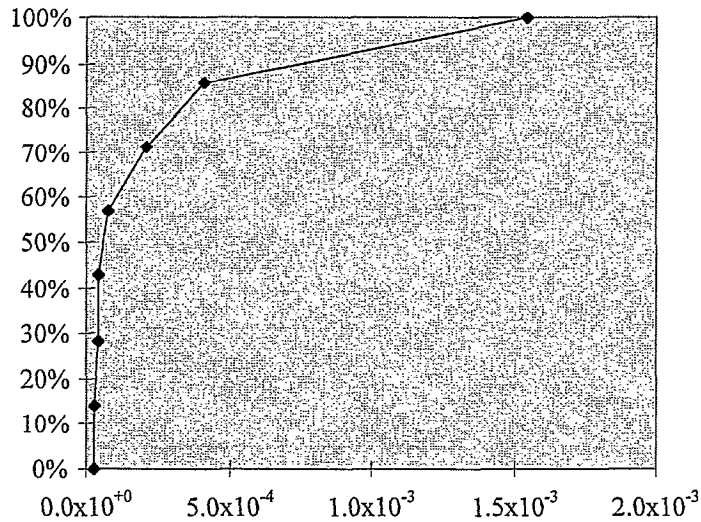


Figure O2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The average result for this site is 3.06×10^{-4} mg m^{-2} s^{-1} which lies on the middle section of the S-distribution. There is some spread in the results which is indicative of the non-uniformity in the cap which is known to suffer from faults and cracks. The measurement can be divided into two sets O1-O4 and O5-O8. Set one has an average value of 4.37×10^{-4} mg m^{-2} s^{-1} dominated by a single value (O2) and set two has an average value of 1.75×10^{-4} mg m^{-2} s^{-1}. Set one is believed to be older waste than set two by up to fifteen years. However, for box 2 there was a high initial concentration which may indicate a local source or fault in the cap.

SITE P

LOCATION: Suffolk
PERIOD OF OPERATION: 1969 to 1980
WASTE COMPOSITION: At least 50% domestic
GEOLOGY: Earth and gravel works
CONTAINMENT:
CAP TYPE: No engineered cap
ENGINEERED FEATURES: Flare

This site is formed on two sides by the walls of the gravel extraction area with two banked sides to the existing operations. Operated by the local authority, from 1969 to 1980, it contains at least 50% domestic wastes. There is no engineered cap but there is a flare. The flux box results obtained on 23rd January 1996, a damp and windy day, are presented in Table P1. The spread of results is shown in Figure P1.

Table P1. Site P Flux Box results, 23/01/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
P3	$-7.7x10^{-4}$	52.4	$3.5x10^{-4}$
P6	$-2.2x10^{-4}$	23.9	$2.9x10^{-4}$

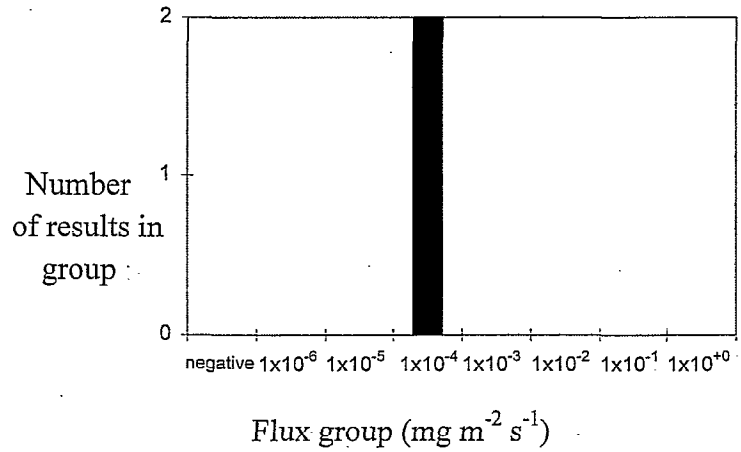


Figure P1. Distribution of flux box results

Discussion of results

Of the eight boxes measured on this site only two boxes recorded any values above the minimum detectable limit (lld). An lld of $7.9x10^{-5}$ mg m^{-2} s^{-1} has been calculated for this site based on the maximum concentration of gas which could have accrued within a box during the monitoring period but not be detected due to the concentration of hydrocarbons in a faulty zero gas (3.5ppm). The bottle was new and subsequently replaced with a higher specification gas.

SITE Q

LOCATION: Suffolk
PERIOD OF OPERATION: 1983 to 1992
WASTE COMPOSITION: Predominantly domestic
GEOLOGY: Chalk/clay
CONTAINMENT:
CAP TYPE: Boulder clay
ENGINEERED FEATURES: Gas collected and flared

This is a local authority site which took predominantly (64%) domestic waste from 1983 to 1992. The local geology is chalk and clay which has been used to form a natural containment. This site is largely above ground. The waste is capped with boulder clay and the methane encapsulated is collected and flared. The result of monitoring on 24th January 1996 is presented in Table Q1.

Table Q1. Site Q Flux Box results, 24/01/96

SITE/BOX	Observed Flux $mg\ m^{-2}\ s^{-1}$	Initial concentration C_0 $mg\ m^{-3}$	Actual Flux $mg\ m^{-2}\ s^{-1}$
Q4	$-5.8x10^{-4}$	42.7	$3.34x10^{-4}$

Discussion of results

Of the four boxes measured on this site only one box recorded any values above the lower limit of detection (lld). An lld of $6.8x10^{-5}$ $mg\ m^{-2}\ s^{-1}$ has been calculated for this site based on the maximum concentration of gas which could have accrued within a box during the monitoring period but not be detected due to the concentration of hydrocarbons in a faulty zero gas (3.5ppm). The bottle was new and subsequently replaced with a higher specification gas.

SITE R

LOCATION: Warwickshire
PERIOD OF OPERATION: Early 1960s to 1967
WASTE COMPOSITION: Mixed
GEOLOGY: Sand and gravel pits
CONTAINMENT: None
CAP TYPE: Approx 1m material
ENGINEERED FEATURES: None

This is a privately owned area of land, which was previously a sand and gravel pit, and infilled during the 1960s with a mixture of waste to a depth of 13m. Being pre-CoPA there are no detailed records available. It is believed to have been capped with approximately a metre of material but there has been up to 2m settlement at the centre of the site. There are also signs of vegetation distress over a small area. There is no gas control scheme at this site. The results of flux box monitoring on 10th June 1996 are shown in Table R1 and the spread of results encountered are illustrated in Figure R1. Cumulative flux is shown in figure R2.

Table R1. Site R Flux Box results, 10/06/96

SITE/BOX	Observed Flux $mg\ m^{-2}\ s^{-1}$	Initial concentration C_0 $mg\ m^{-3}$	Actual Flux $mg\ m^{-2}\ s^{-1}$
R1	$8.1x10^{-5}$	0.948	$1.0x10^{-4}$
R2	$3.9x10^{-4}$	13.1	$6.7x10^{-4}$
R3	$1.5x10^{-4}$	1.19	$1.8x10^{-4}$
R4	$1.5x10^{-4}$	0	$1.5x10^{-4}$
R5	$1.6x10^{-4}$	0.135	$1.6x10^{-4}$
R6	$-9.1x10^{-6}$	2.59	$4.6x10^{-5}$
R7	$-1.5x10^{-4}$	8.12	$2.6x10^{-5}$
R8	$5.8x10^{-1}$	901	$6.0x10^{-1}$
R9	$-5.5x10^{-5}$	3.01	$9.9x10^{-6}$
R10	$9.8x10^{-5}$	3.01	$1.6x10^{-4}$

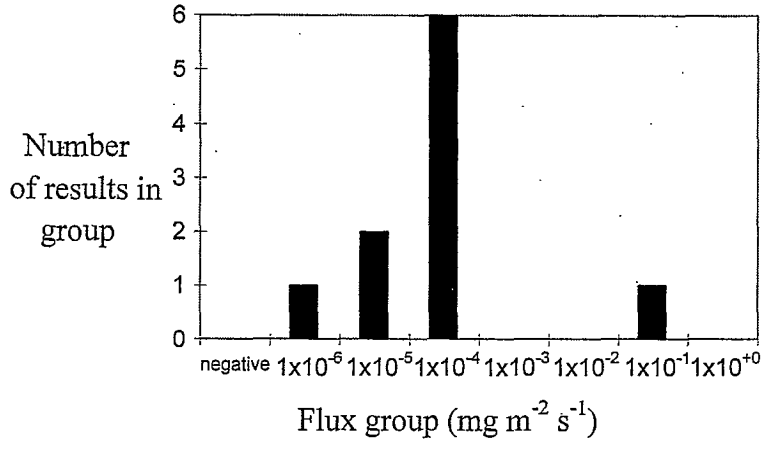


Figure R1. Distribution of flux box results

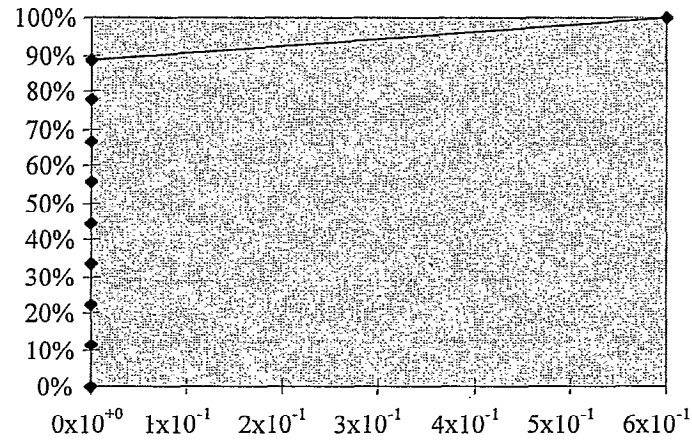


Figure R2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The average flux box result at this site is 6.01×10^{-2} mg m^{-2} s^{-1}, predominantly due to the result from a single box, R8, which was placed in the area of settlement and vegetation distress. The majority of the boxes at this site had fluxes of the order of 10^{-4} mg m^{-2} s^{-1} or lower. The spread of results encountered is indicative of the non-uniformity of cap quality, and could be due to the variability of the waste for which there is no information.

SITE S

LOCATION:	Lancashire
PERIOD OF OPERATION:	Dec 1989 to Summer 1993 (Phase 2)
WASTE COMPOSITION:	Sewage Sludge and dry waste
GEOLOGY:	Alluvium on Boulder Clay on Sherwood Sandstone
CONTAINMENT:	Clay perimeter embankment, no basal liner
CAP TYPE:	300mm temporary clay cap, compacted to Dtp spec
ENGINEERED FEATURES:	Passive venting

Due to its position next to an estuary this is effectively a 'landraise' site with depths of waste ranging from 4 to 11.5m. Of the 5.08 tonnes authorised waste emplacement there is currently 3.7m tonnes in three phases. There is a 300mm worked clay cap over the majority of Phase 2 which was monitored on 12th June 1996. However, a small area had no cap in place, the waste being visible through the thin soil layer. There is no gas collection system at this site. The flux box results, obtained on a cool and windy summer's day, are given in Table S1 and the spread of results is shown in Figure S1. Cumulative flux is shown in Figure S2.

Table S1. Site S Flux Box results, 12/06/96

SITE/BOX	Observed Flux $mg\ m^{-2}\ s^{-1}$	Initial concentration C_0 $mg\ m^{-3}$	Actual Flux $mg\ m^{-2}\ s^{-1}$
S1	$3.5x10^{-4}$	9.28	$5.5x10^{-4}$
S2	$9.5x10^{-3}$	88.9	$1.1x10^{-2}$
S3	$3.0x10^{-2}$	95	$3.2x10^{-2}$
S4	$9.0x10^{-2}$	286	$9.6x10^{-2}$
S5	$1.5x10^{-4}$	7.1	$3.0x10^{-4}$
S6	$4.2x10^{-3}$	129	$6.9x10^{-3}$
S7	$8.7x10^{-5}$	2.69	$1.4x10^{-4}$
S8	$8.0x10^{-5}$	2.73	$1.4x10^{-4}$
S9	$5.7x10^{-5}$	3.76	$1.4x10^{-4}$
S10	$2.9x10^{-4}$	4	$3.7x10^{-4}$

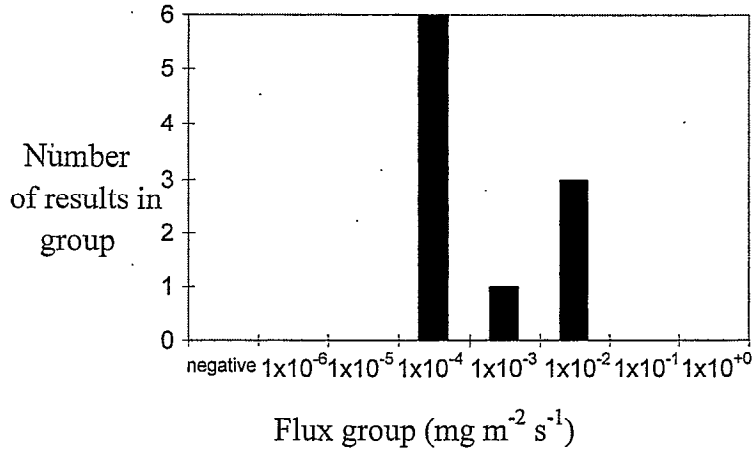


Figure S1. Distribution of flux box results

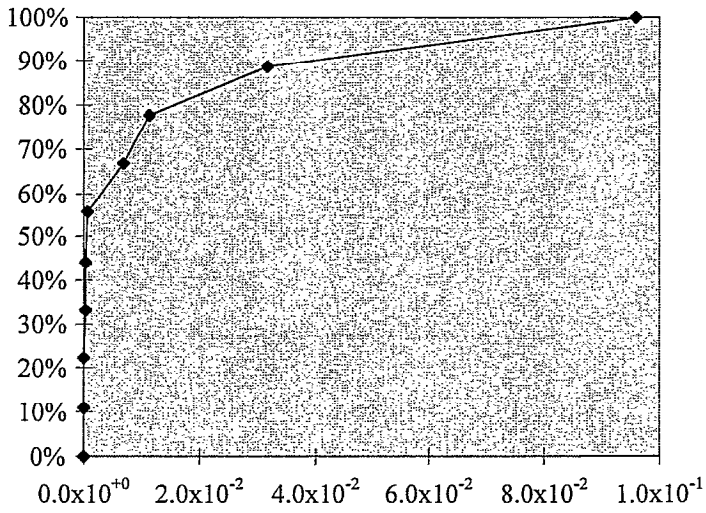


Figure S2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

Boxes S2 to S4 were placed on the area with minimal cap and measured emissions which were nearly a factor 40 higher than those on the clay covered area. These figures are enhanced by the greater depth of waste under the area with no cap. The spread of results shown in Figure S1 illustrates the non-uniformity of cap, all other variables being the same across the site. The average flux for the whole site (Phase 2) of 1.47×10^{-2} mg m^{-2} s^{-1} lies on the top section of the S-distribution.

SITE T

LOCATION:	East Riding
PERIOD OF OPERATION:	- present
WASTE COMPOSITION:	Baled MSW
GEOLOGY:	Chalk
CONTAINMENT:	No basal lining, some rubble and liner to sides
CAP TYPE:	1m clay plus half metre of subsoil
ENGINEERED FEATURES:	Flare

This former chalk quarry is being filled with baled municipal solid waste (MSW) by the local authority waste disposal company (LAWDC). There is a flare to burn gas collected from the area which is capped by a metre of clay and approximately half a metre of sub-soil. The flux box results obtained on 3rd July 1996 are given in Table T1 and the spread of results are shown in Figure T1. Cumulative flux is shown in Figure T2.

Table T1. Site T Flux Box results, 03/07/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
T1	$1.2x10^{-5}$	2.81	$7.2x10^{-5}$
T2	$3.5x10^{-5}$	2.64	$9.2x10^{-5}$
T3	$4.9x10^{-5}$	2.37	$1.0x10^{-4}$
T4	$9.7x10^{-5}$	2.32	$1.5x10^{-4}$
T5	$6.5x10^{-5}$	2.25	$1.1x10^{-4}$

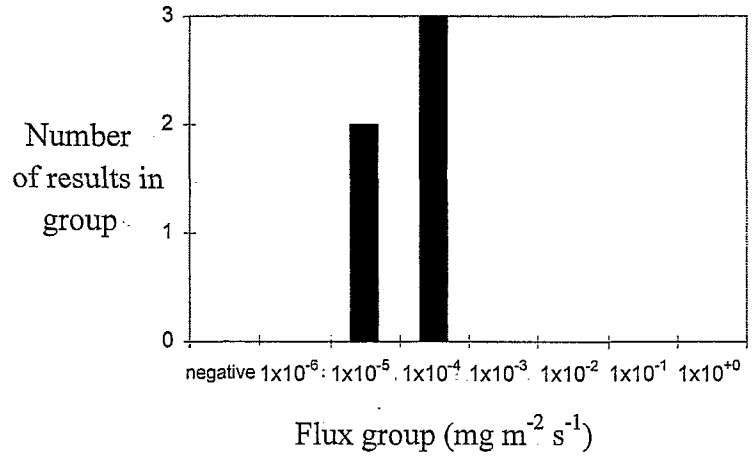


Figure T1. Distribution of flux box results

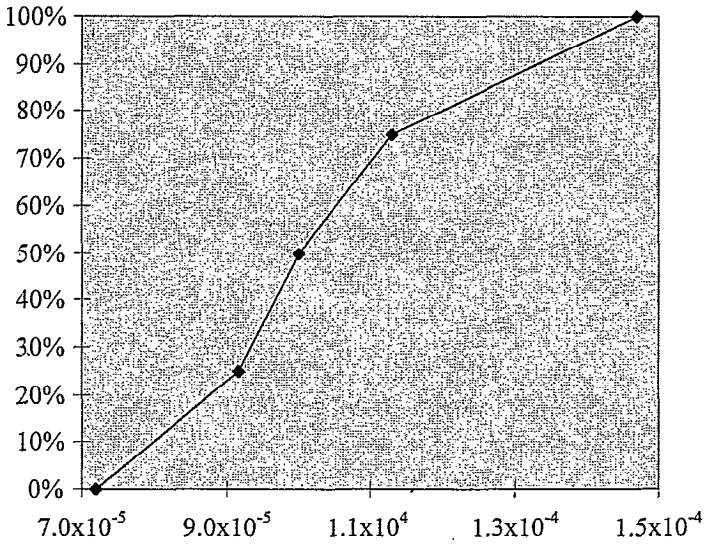


Figure T2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The average result from this site is $1.05x10^{-4}$ mg m^{-2} s^{-1} which is close to the median result for all measurements. The combination of a flare and a metre of clay has resulted in low emissions despite the waste having a high methane potential. It is possible that any higher emitting areas were missed by the flux boxes.

SITE U

LOCATION: Lincolnshire
PERIOD OF OPERATION: 1988 - present
WASTE COMPOSITION: MSW, commercial and industrial
GEOLOGY:
CONTAINMENT: Clay lined cells
CAP TYPE: HDPE and restoration material
ENGINEERED FEATURES: Flare

This is a local authority waste disposal site operated since 1988, taking domestic, commercial and industrial wastes. There is a clay liner and an HDPE and restoration material cap. Methane generated and collected is flared. The flux box results for monitoring on 3rd and 5th July 1996 are given in Table U1. The spread of results are shown in Figure U1 and cumulative flux in Figure U2.

Table U1. Site U Flux Box results, 03 and 05/07/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
U1	$-3.9x10^{-4}$	14.4	$-8.7x10^{-5}$
U2	$-1.5x10^{-4}$	10.5	$7.6x10^{-5}$
U3	$-2.4x10^{-4}$	12.5	$3.2x10^{-5}$
U4	$-2.2x10^{-4}$	15.8	$1.2x10^{-4}$
U5	$-2.4x10^{-4}$	9.15	$-4.5x10^{-5}$
U6	$9.1x10^{-5}$	3.11	$1.6x10^{-4}$
U7	$2.2x10^{-4}$	2.8	$2.8x10^{-4}$
U8	$9.2x10^{-5}$	3.25	$1.6x10^{-4}$
U9	$4.5x10^{-5}$	3.69	$1.2x10^{-4}$
U10	$8.7x10^{-6}$	4.87	$1.1x10^{-4}$

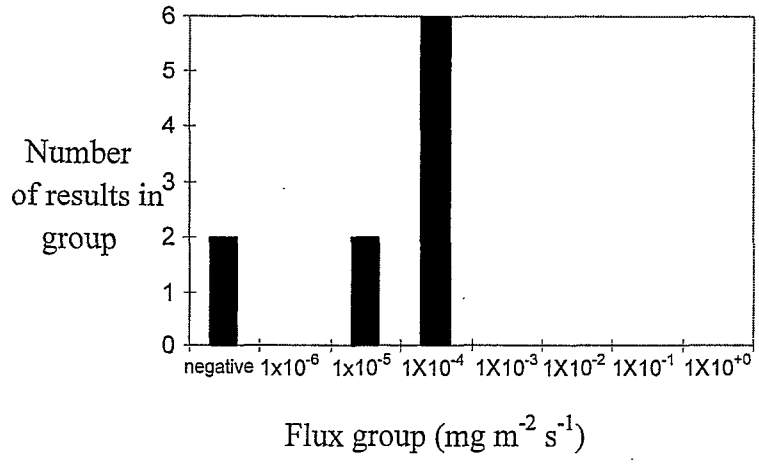


Figure U1. Distribution of flux box results

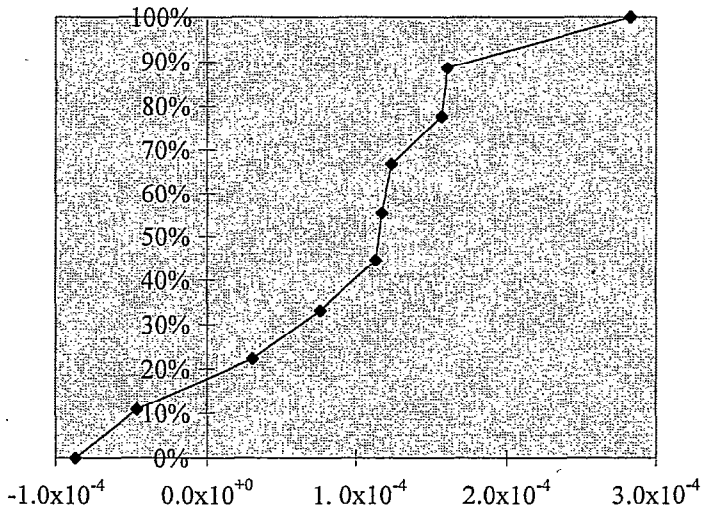


Figure U2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The average flux box result is $1.06x10^{-4}$ mg m^{-2} s^{-1} which lies on the middle section of the S-distribution. From Figure U1 it can be seen that the quality of cap is largely uniform, in so far as the flux box technique has characterised the area and not missed any high emitting areas.

SITE V

LOCATION: East Riding
PERIOD OF OPERATION: 1963-1995
WASTE COMPOSITION: Municipal and commercial waste
GEOLOGY:
CONTAINMENT: Clay liner
CAP TYPE: Clay and plastic
ENGINEERED FEATURES: Passive venting

This is a local authority site operated from 1963 to 1995 which accepted MSW and commercial wastes. The site is lined with clay and capped with a composite of clay and plastic. The flux box results obtained on 2nd July 1996 are given in Table V1 and the spread of results is shown in Figure V1. Cumulative results are shown in Figure V2.

Table V1. Site V Flux Box results, 02/07/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
V1	$9.7x10^{-6}$	2.82	$7.0x10^{-5}$
V2	$6.2x10^{-6}$	2.48	$5.9x10^{-5}$
V3	$5.3x10^{-4}$	0.349	$5.4x10^{-4}$
V4	$3.5x10^{-6}$	1.85	$4.3x10^{-5}$
V5	$-1.0x10^{-5}$	1.83	$2.9x10^{-5}$

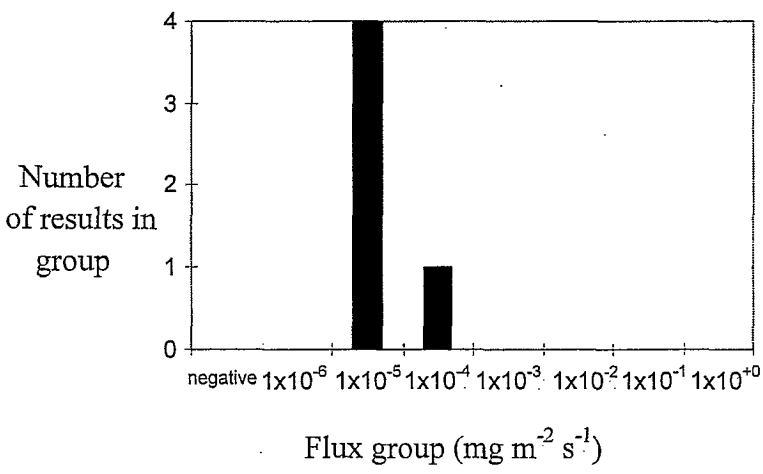


Figure V1. Distribution of flux box results

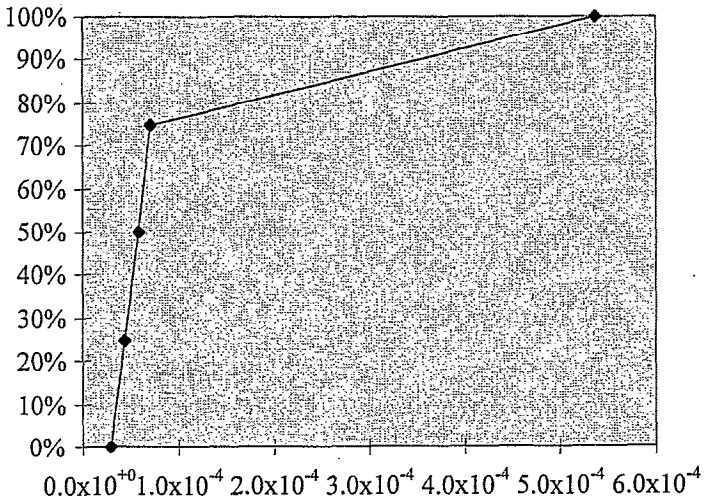


Figure V2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The average flux box result from this site is $1.48x10^{-4}$ mg m^{-2} s^{-1}, dominated by a single box. This result lies on the middle section of the S-distribution. It appears that the clay and liner cap has been effective at reducing emissions associated with municipal and commercial wastes (within the limits associated with the flux box technique).

SITE W

LOCATION: Lincolnshire
PERIOD OF OPERATION: 1981 - present
WASTE COMPOSITION: MSW and commercial
GEOLOGY:
CONTAINMENT:
CAP TYPE: Clay and soils
ENGINEERED FEATURES: Full gas collection and energy recovery

This is a local authority waste disposal company site operated from 1981 to the present day, accepting municipal solid waste (MSW) and commercial wastes. There is full gas collection from the site with three phases out of five supplying an energy recovery unit. The other two phases are flared. The flux box results obtained on 4th July 1996 are given in Table W1 and the spread of results shown in Figure W1. Cumulative flux results are shown in Figure W2.

Table W1. Site W Flux Box results, 04/07/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
W1	$6.4x10^{-5}$	1.52	$9.7x10^{-5}$
W2	$5.4x10^{-3}$	8.62	$5.6x10^{-3}$
W3	$7.3x10^{-5}$	2.46	$1.3x10^{-4}$
W4	$5.4x10^{-5}$	2.62	$1.1x10^{-4}$
W5	$1.8x10^{-4}$	4.6	$2.8x10^{-4}$
W6	$-1.3x10^{-4}$	5.89	$-3.9x10^{-6}$
W7	$-1.7x10^{-4}$	6.85	$-2.4x10^{-5}$
W8	$-9.1x10^{-5}$	5.68	$3.1x10^{-5}$
W9	$-1.3x10^{-4}$	7.03	$2.3x10^{-5}$
W10	$-1.2x10^{-4}$	6.79	$2.3x10^{-5}$
W11	$3.1x10^{-5}$	4.92	$1.4x10^{-4}$
W12	$-1.9x10^{-4}$	6.83	$-4.0x10^{-5}$
W13	$-3.2x10^{-5}$	5.49	$8.6x10^{-5}$
W14	$-3.2x10^{-5}$	4.52	$6.5x10^{-5}$
W15	$-1.4x10^{-4}$	4.42	$-4.6x10^{-5}$

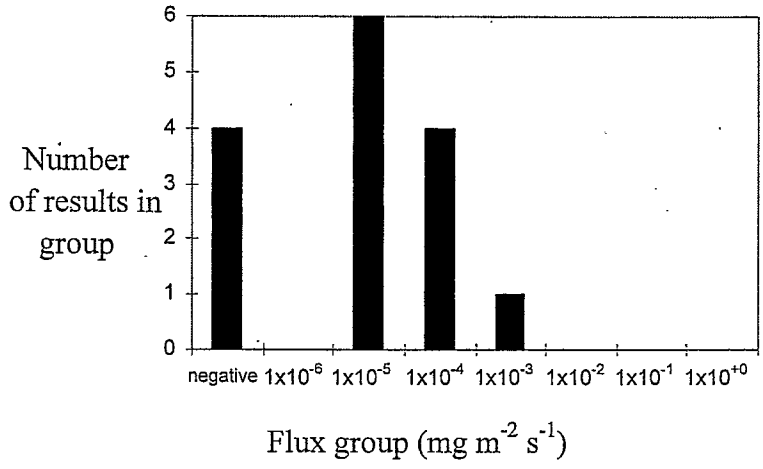


Figure W1. Distribution of flux box results

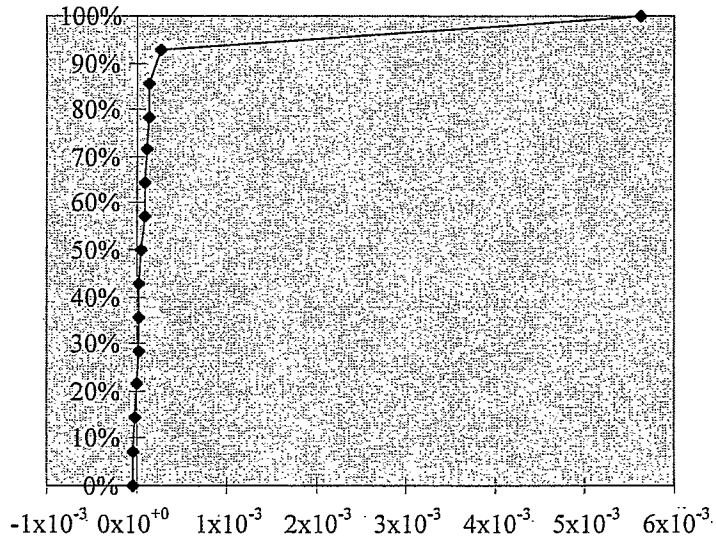


Figure W2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

Boxes W1 to W5 were on the oldest phase of waste which is served by the flare. Boxes W6 to W15 measured fluxes on two of the newer areas supplying the energy recovery unit. The average flux is noticeably higher on the flared area at $1.24x10^{-3}$ mg m^{-2} s^{-1}, compared to $1.55x10^{-5}$ and $5.17x10^{-5}$ mg m^{-2} s^{-1}. The spread of results shown in Figure W1 reflects the two different operating practices in use at this site.

SITE X

LOCATION: Surrey
PERIOD OF OPERATION: Finished over 20 years ago
WASTE COMPOSITION: Household
GEOLOGY: Weald Clay
CONTAINMENT: Natural geology
CAP TYPE: No cap likely
ENGINEERED FEATURES: None

This is a small site operated by the local authority, for household waste, during the early 1970s. There is no cap or gas control in place, though historical information is scarce. The flux box results obtained on 22nd August 1996 are given in Table X1. The spread of results is shown in Figure X1. Cumulative flux results are shown in Figure X2.

Table X1. Site X Flux Box results, 22/08/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
X1	$1.7x10^{-4}$	1.75	$2.0x10^{-4}$
X2	$1.2x10^{-4}$	2.52	$1.8x10^{-4}$
X3	$7.6x10^{-5}$	3.21	$1.5x10^{-4}$
X4	$2.4x10^{-5}$	3.66	$1.0x10^{-4}$
X5	$-1.7x10^{-5}$	3.97	$6.8x10^{-5}$

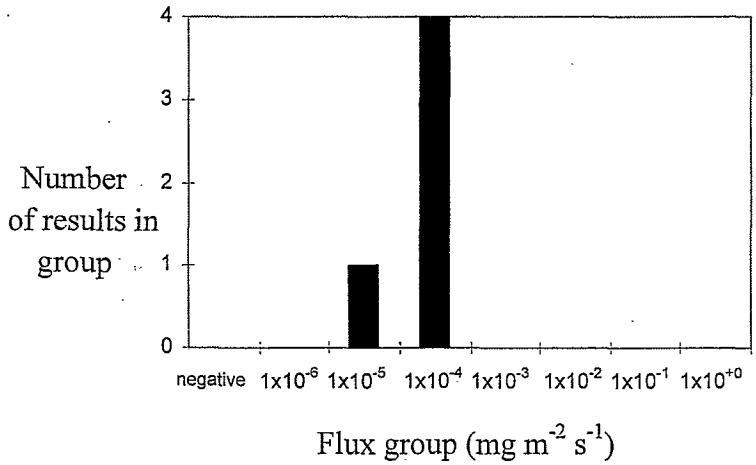


Figure X1. Distribution of flux box results

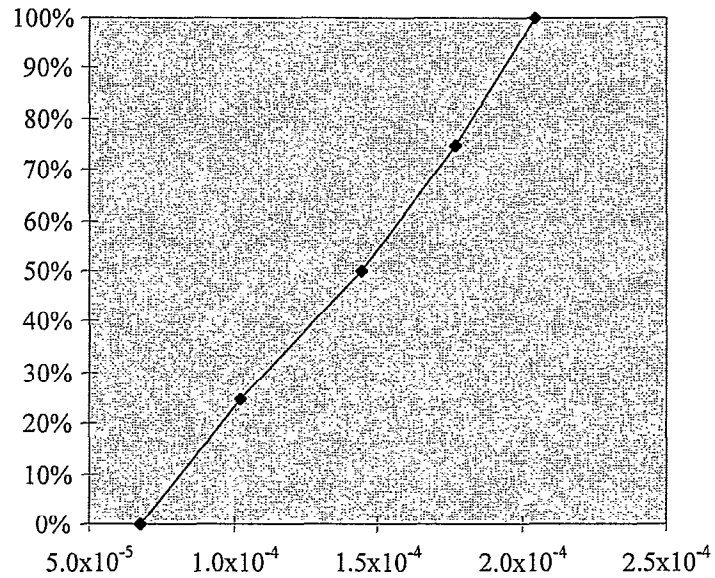


Figure X2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The range of results from this site is narrow, from $6.8x10^{-5}$ to $2.0x10^{-4}$ mg m^{-2} s^{-1}, with the average flux, $1.39x10^{-4}$ mg m^{-2} s^{-1} being around the median of the S-distribution. Due to the age of the site and the passive venting that has occurred the current emissions are low.

SITE Y

LOCATION: Surrey
PERIOD OF OPERATION: Completed 10 years ago
WASTE COMPOSITION: Household
GEOLOGY: Chalk pit
CONTAINMENT: Natural geology
CAP TYPE: Soil
ENGINEERED FEATURES: None

This is an old local authority household waste site completed ten years ago. It is up to 25m deep, formed from a valley feature which was previously a chalk pit. The monitoring was conducted on 22nd August 1996, the results are shown below in Table Y1. The spread of results is shown in Figure Y1. Cumulative flux results are shown in Figure Y2.

Table Y1. Site Y Flux Box results, 22/08/96

SITE/BOX	Observed Flux mg m^{-2} s^{-1}	Initial concentration C_0 mg m^{-3}	Actual Flux mg m^{-2} s^{-1}
Y1	$8.0x10^{-5}$	0.499	$9.1x10^{-5}$
Y2	$1.1x10^{-4}$	0.249	$1.1x10^{-4}$
Y3	$1.1x10^{-4}$	0.221	$1.1x10^{-4}$
Y4	$1.2x10^{-4}$	0	$1.2x10^{-4}$
Y5	$8.1x10^{-5}$	0	$8.1x10^{-5}$

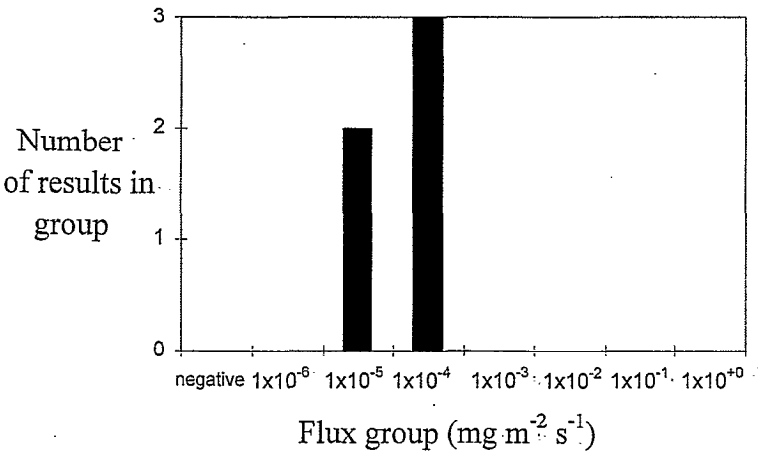


Figure Y1. Distribution of flux box results

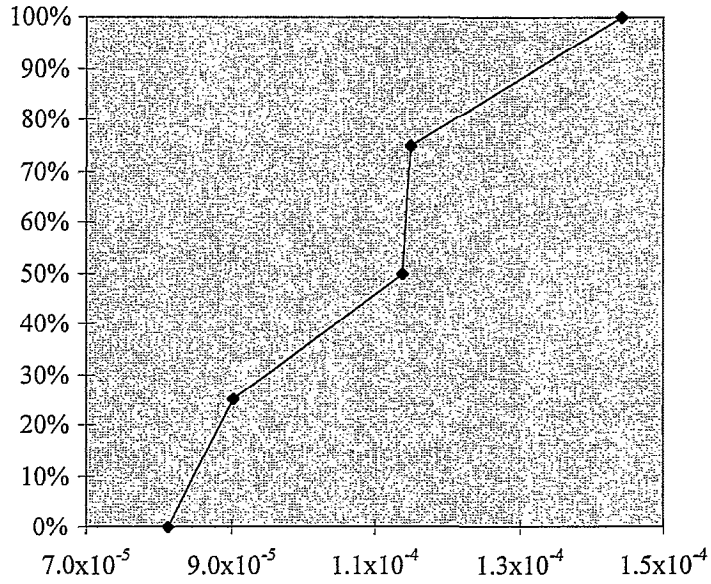


Figure Y2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The average flux box result from this site is $1.09x10^{-4}$ mg m^{-2} s^{-1}, any methane generated has been passively vented over the years. The spread of results is very narrow, at about plus or minus 10% of the average value. Over the area monitored the quality of the cap is uniform, assuming the technique has not missed any high emitting areas.

SITE Z

LOCATION: Surrey
PERIOD OF OPERATION: 1960s to 1990s
WASTE COMPOSITION: Commercial / industrial
GEOLOGY: Gravel extraction
CONTAINMENT: Natural geology
CAP TYPE: No cap, soil cover for agriculture
ENGINEERED FEATURES: Vent trenches

This site, which was privately operated from the 1960s to the 1990s, has a fill of commercial and industrial waste which is less than 10m deep. There is a well known age profile for the site so two comparative areas were chosen, one approximately fourteen years old, the other about two, (sets Z2 to Z5 and Z6 to Z9 respectively). A light rain shower during the setting out of flux boxes resulted in water getting in to the sampling valve of box one rendering it temporarily unusable. The flux box results are given below in Table Z1 and the spread of results is shown in Figure Z1. Cumulative flux results are shown in Figure Z2.

Table Z1. Site Z Flux Box results, 23/08/96

SITE/BOX	Observed Flux $mg\ m^{-2}\ s^{-1}$	Initial concentration C_0 $mg\ m^{-3}$	Actual Flux $mg\ m^{-2}\ s^{-1}$
Z2	$-1.3x10^{-4}$	5.2	$-1.5x10^{-5}$
Z3	$-2.2x10^{-4}$	6.63	$-8.2x10^{-5}$
Z4	$-2.3x10^{-4}$	6.74	$-8.4x10^{-5}$
Z5	$-4.5x10^{-4}$	9.14	$-2.5x10^{-4}$
Z6	$-3.6x10^{-4}$	11.6	$-1.1x10^{-4}$
Z7	$1.3x10^{-3}$	24	$1.8x10^{-3}$
Z8	$-5.3x10^{-4}$	21.4	$-7.6x10^{-5}$
Z9	$-1.2x10^{-3}$	139	$1.8x10^{-3}$

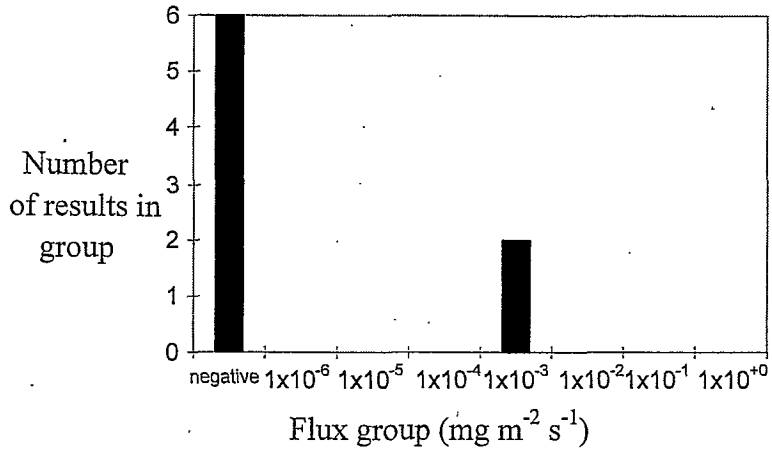


Figure Z1. Distribution of flux box results

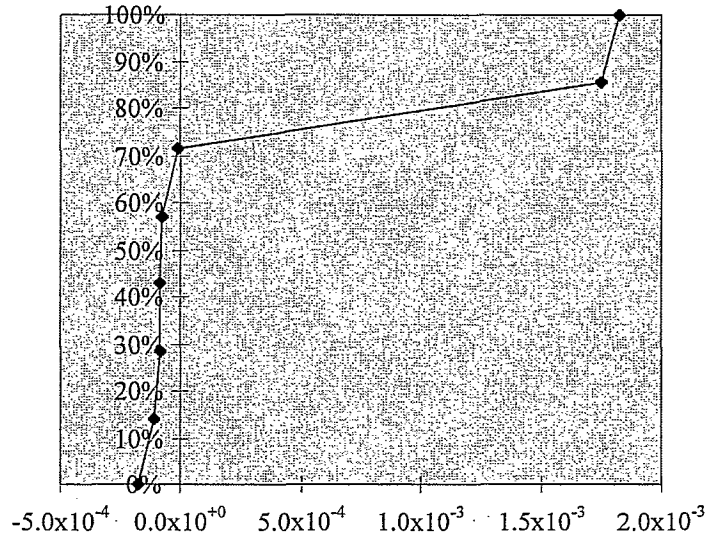


Figure Z2. Cumulative plot of methane flux mg m^{-2} s^{-1}

Discussion of results

The flux box results for this site range from negative values to $1.8x10^{-3}$ mg m^{-2} s^{-1}. The two positive results came from the younger phase of landfilling with the results from the older phase all being negative, even after correction for ambient concentrations. The average for the site is $3.7x10^{-4}$ mg m^{-2} s^{-1}, however, this can be split into all negative fluxes for the boxes on the oldest area giving a $9.0x10^{-4}$ mg m^{-2} s^{-1} average for the four boxes on the most recent area. The difference in age is around 10 to 12 years. As there is no operational area at this site there is no obvious explanation for the raised ambient concentration and negative fluxes. There may have been cracks which allowed methane to escape which were not picked up with this technique.

APPENDIX 4: STATISTICAL ANALYSIS OF SPATIAL VARIABILITY

Contents

APPENDIX 4: STATISTICAL ANALYSIS OF SPATIAL VARIABILITY

1. MEASUREMENT STRATEGIES

Methane emissions were measured at point locations using spiker surveys, borehole installations and flux boxes. In order to estimate the total emission from a landfill site, enough measurements are needed to ensure that the spatial variability in methane emission is adequately represented.

Variations in emissions with time have been considered by taking measurements at some sites during both winter and summer periods. However a detailed study of temporal variability was outside the scope of this project. The principal aim of the geostatistical analysis was to determine the optimal spacing for measurements of methane flux.

2. GEOSTATISTICS

Geostatistics is *'a branch of statistics dealing with spatial phenomena'* (Journel 1986). It allows geologists and others to incorporate their understanding of a parameter into an interpolation exercise (Matheron, 1989; Journel & Huijbregts, 1978). Measurements of properties at locations close together tend to be more similar than measurements at locations that are a long way apart (e.g. La Pointe, 1980; Rosenbaum, 1987; Hoerger & Young, 1987). This intuitive understanding of spatial correlation was formalised in the Theory of Regionalised Random Variables (Matheron, 1971) and is applied to modelling spatial data using the geostatistical tool kit:

- The *variogram*; used to observe and model spatial correlation between sample locations.
- *Kriging* techniques; used to make interpolations from both observed values and their spatial relationships as deduced from the variogram.
- *Cokriging* and *external drift;* which enable observations of variables other than the one being estimated to be used in the estimation process.
- *Conditional simulations* and *indicator kriging*; used to estimate probability of exceeding threshold values.

In this study, the variogram and associated tools have been used to study the spatial correlation of gas concentrations above gassing landfill sites.

2.1 Spatial correlation

'Tobler's law' states that measurements at points closely spaced are more similar than those made at points further apart. If this is true, then the measurements can be said to be spatially correlated and can be used to make predictions at points other than those at which measurements have been made. Several tools have been developed to analyse the degree of spatial correlation between observation points in a study area. The one that has received widest use and acceptance is the variogram. The value of the variogram, $g(h)$, at a given control point separation or lag distance, h, is defined as the average squared difference between the values, $z(x)$, of control points a given distance h apart (Equation 1) (Journel & Huijbregts, 1978). The variogram is displayed as a plot of sample separation h against the semi-variance of pairs of samples h units apart:

$$\text{variogram, } \gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\{z(x_i) - z(x_i + h)\}^2 \qquad \textit{equation 1}$$

Experimental variograms may be calculated from regularly or irregularly spaced data points.

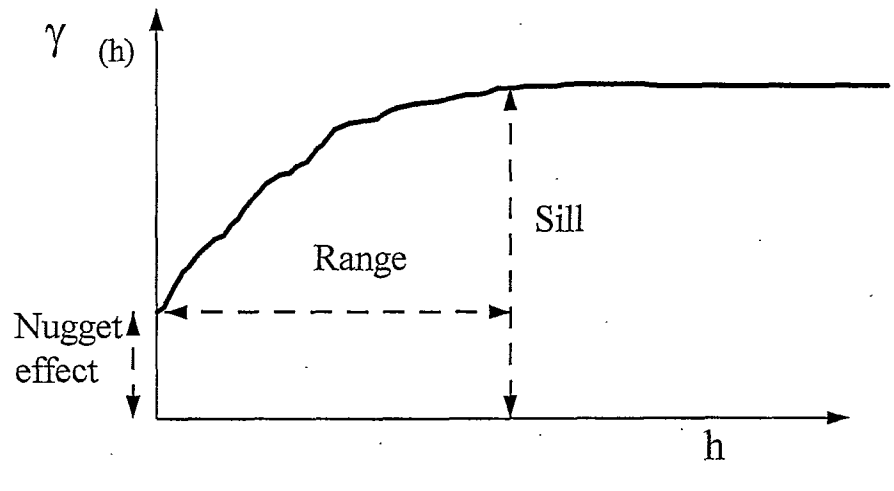
2.2 The experimental variogram

The *true variogram* of the landfill gas emissions is never known because the site is never fully sampled. Information obtained from point measurements is used to construct the *experimental variogram,* which can then be modelled for use in estimation or simulation. The experimental variogram can be used to:

- Study spatial correlation;
- Look for directional anisotropy;
- Guide spacing and extent of future sampling campaigns;
- Detect scales at which different processes are operating;
- Provide a basis for a model variogram for use in kriging.

The four essential features of an experimental variogram (Box 1) are:

- Maximum variogram value (sill).
- Variogram value at zero lag distance (nugget effect).
- Lag distance at which sill is reached (range).
- General shape of plot.



Box 1 Anatomy of a variogram

The *sill* is the variogram value at which an experimental variogram tends no longer to increase with increasing lag distance. It represents the sum of the spatially dependent and non-spatial components of the variance in a model variogram. If a variogram reaches a sill and the value of the sill is equal to the value of the variance of the data set, then the data set can be considered to be a random variable which is intrinsically stationary.

The *nugget effect* is a discontinuity at the origin of the variogram and is generally due to short range variability or non-spatial effects such as fabric or measurement errors.

The *range* is the distance at which the variogram reaches its maximum value, or sill. For variograms which approach the sill asymptotically, the 'practical', or 'effective' range is defined as the value where the function reaches approximately 95 per cent of the maximum.

Periodicity, although occasionally encountered with time series, is rather unusual in the applied earth sciences and should be treated with suspicion. Erratic data are more likely to be the cause. Possible periodicity could be present with fracture data, repetitive geological facies or folded strata. In the case of landfill sites, the history of waste deposition could give rise to periodicity.

The *hole effect* is generally caused by too few pairs of points having been used for calculation at that lag distance. The effect may also be due to a geological process at the corresponding range or to the presence of a trend (i.e. non-stationary behaviour).

2.2.1 Scatter plots

The variogram cloud and the *h*-scattergram are two further tools for analysing spatial continuity in a data set. The *variogram cloud* is a scatter plot of squared difference against separation distance for all pairs of values in a data set (the variogram cloud may be thought of as a summary of the variogram) (Chauvet, 1982). Data points responsible for extreme values in the cloud can be investigated for possible errors, or signs of mixed populations. The *h*-scattergram (Journel, 1983) or *h*-scatter plot (Isaaks & Srivastava, 1989) is a plot of all pairs of points separated by a given lag distance in a given direction. The shape of the scatter is related to the value of the variogram at that lag distance.

2.2.2 Anisotropy

Spatial correlation in the earth sciences often displays a pronounced directional anisotropy. By treating the separation of control points as a vector quantity, *directional variograms* may be constructed to investigate spatial correlation in different directions (Journel & Huijbregts, 1978). The degree of anisotropy can be calculated by plotting a rose diagram of the ranges and recording the ratio of major to minor axes and the direction of the major axis (Kuchta, 1989).

The *anisotropy ratio* is just as important as the *direction of anisotropy*. Qualitative knowledge of directional influences such as waste deposition history, direction of leachate flow or prevailing wind direction can be incorporated into the variogram model through the anisotropy. Local fluctuations in the direction of anisotropy may produce an isotropic effect if the whole data set is handled without regard to setting realistic maximum cut-off distances.

The *variogram surface* allows anisotropy to be studied in all directions without recourse to several directional variograms (Isaaks & Srivastava, 1989). It is produced by calculating the variogram in a variety of directions and for a variety of lag intervals and then displaying the results as a contour map. The axes of the variogram surface are separation in an east-west direction and north-south direction. The centre of the map represents zero separation. Major and minor directions of anisotropy are revealed by the elongation of contour lines.

3. SPATIAL CORRELATION IN LANDFILL SITES

The degree of spatial correlation in landfill sites will be a function of the materials landfilled, their method of placement and subsequent history. Treating landfill as a geological material, the following may be said of its 'geological history':

- Deposition in a series of layers with random mixing of materials and local lateral redistribution.
- Compaction by traffic and successive layers of waste.
- Wetting by percolating rainwater and leachate from higher horizons
- Onset of 'diagenetic' changes such as degradation of organic matter and solution of soluble component.

The generation of methane within a landfill will therefore be controlled by the spatial variability of the waste, its moisture content and environmental conditions such as pH and temperature. The emission of methane at the surface will be influenced further by the nature of pathways by which methane may migrate through the waste and any cap to reach the surface.

Uncapped landfill sites may be assumed to contain many pathways by which methane may reach the surface. Their emission characteristics will reflect the underlying waste and major high permeability routes. Sites capped with a permeable layer will have a more homogeneous pattern of methane emission as the capping layer will act to diffuse high fluxes. Sites capped with clay will have a more heterogeneous pattern of emissions reflecting diffusion through the clay layer and transfer through high permeability zones created by subsidence or desiccation cracking.

In this work, measurements of methane emission have been assumed to be equivalent; any differences in pathway characteristics have been ignored.

4. CASE STUDIES

Measurements of gas concentrations were used to investigate the extent of spatial correlation that may be expected at a landfill site. The case studies consider measurements of methane, carbon dioxide and oxygen gas concentration.

Case study A

This is based on an active landfill site in Nottinghamshire. Readings from 14 points were available (Fig. 1). The measurement locations are essentially randomly spread across the site. The north west corner of Fig 1 is outside the site boundary.

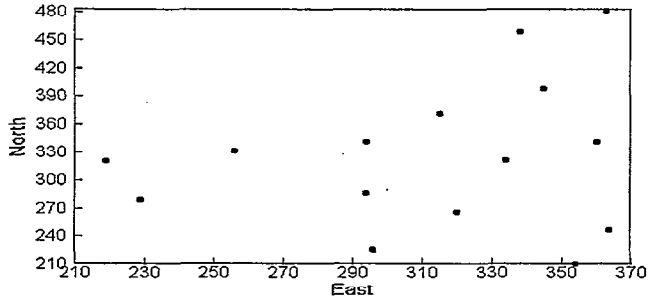
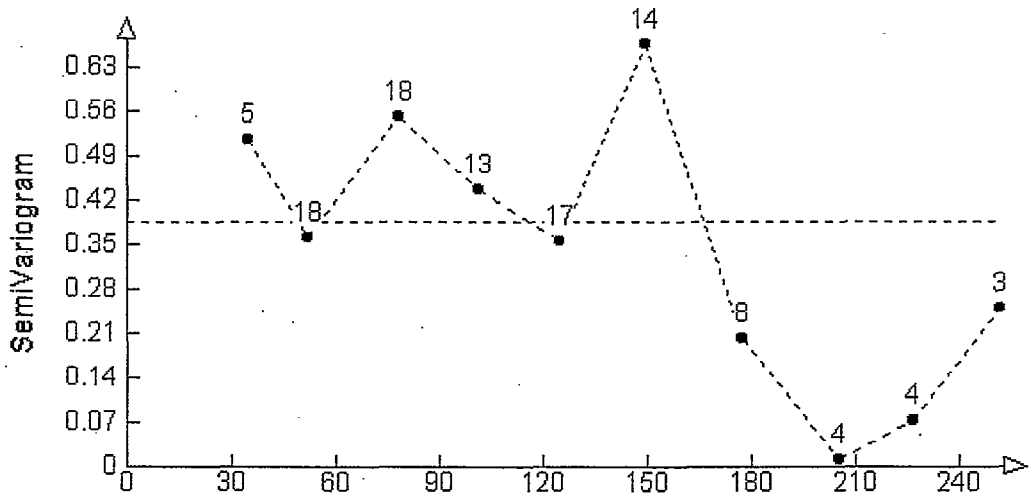


Figure 1. Case study A: Location of monitoring points

Isotropic variograms of readings taken on 17 July and 23 November 1994 (Figures 2 & 3) were calculated. The limited number of samples meant that only a few pairs of samples were available at each lag distance (Fig 2 & 3). The first point on the variogram has only 5 pairs of samples and is discarded from the analysis. The variograms showed a component of random behaviour (approx. 30 %) and a component of spatial correlation (70 %) with a range of only some 60 m to 100 m. The variogram surface, used to study spatial correlation in different directions, did not reveal any signs of anisotropy (Fig. 4). Carbon dioxide and oxygen concentrations (Figs 5 & 6) show almost completely random behaviour.



Lag Distance

Figure 2. *Case study A: Isotropic variogram of methane concentration on 17 July 1994*[1]

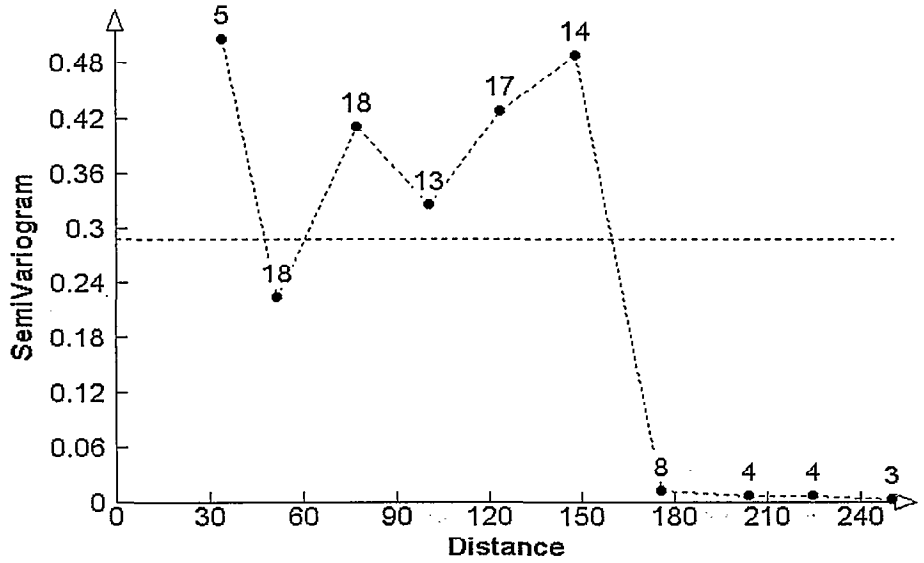


Figure 3. Case study A: Isotropic variogram of methane concentration on 23 November 1994

[1] The horizontal dashed line represents the value of the variance of the entire dataset. A dashed line connects the points on the variogram. This is automatically generated by the software and does not represent any attempt to fit a model variogram.

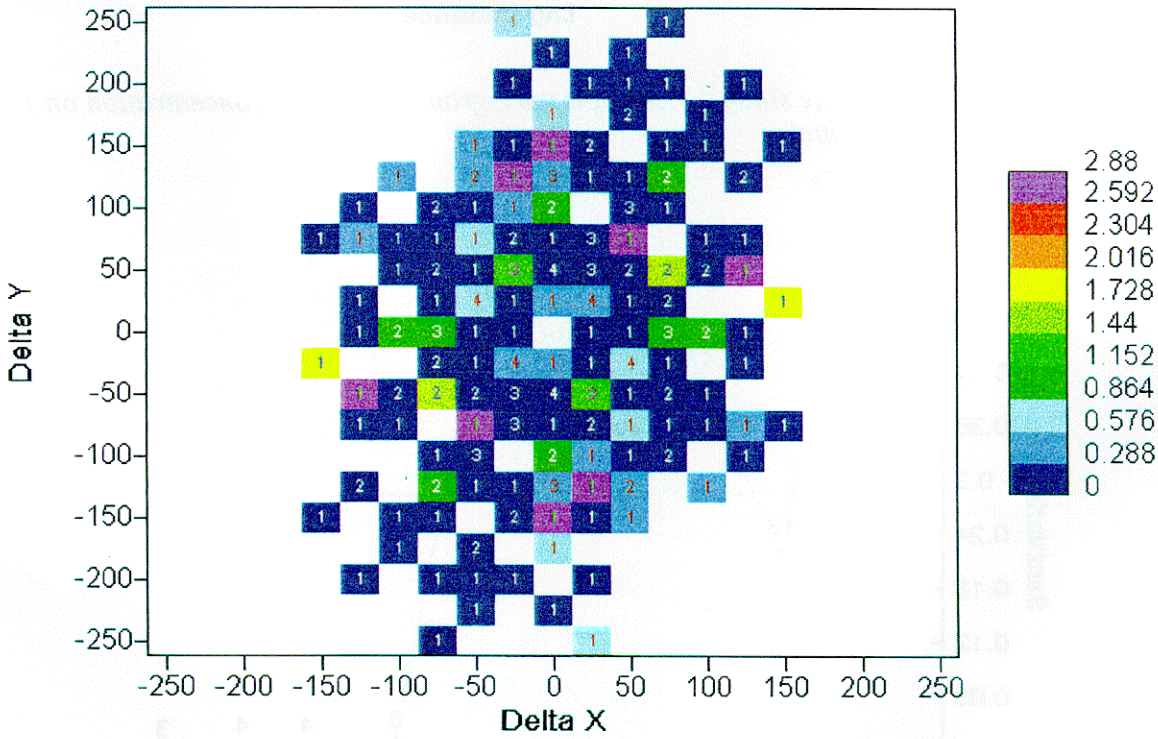


Figure 4. *Case study A: Variogram surface of methane concentration on 17 July 1994 (Numbers of pairs in each panel are displayed)*

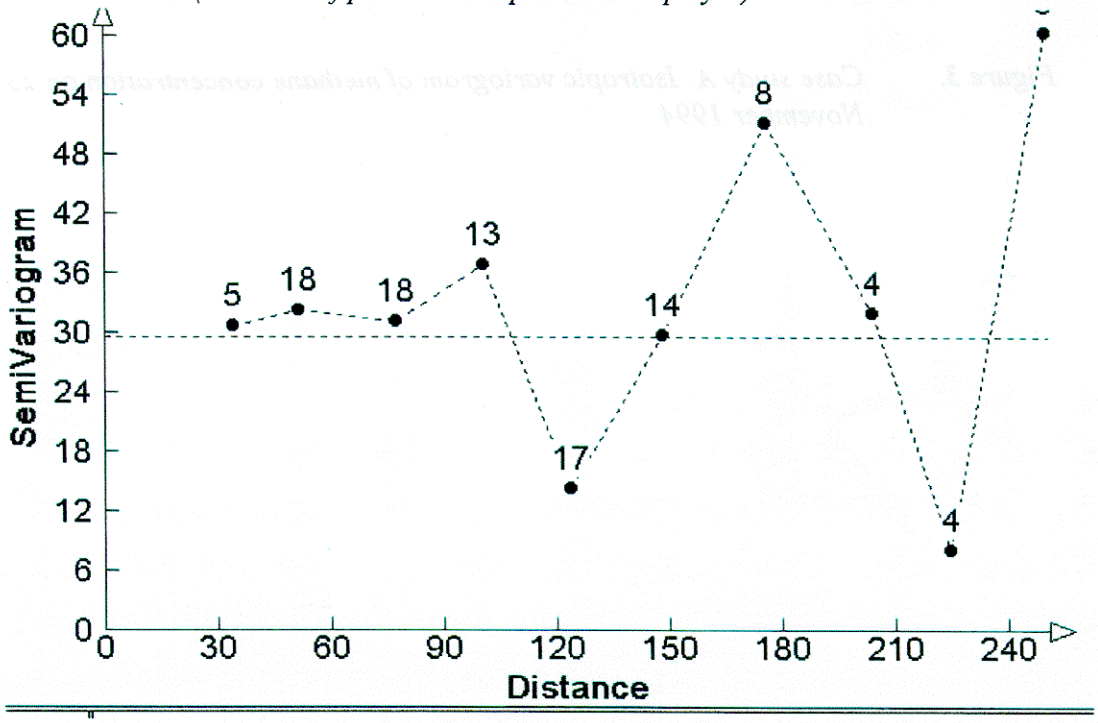


Figure 5. *Case study A: Isotropic variogram of carbon dioxide concentration on 17 July 1994*

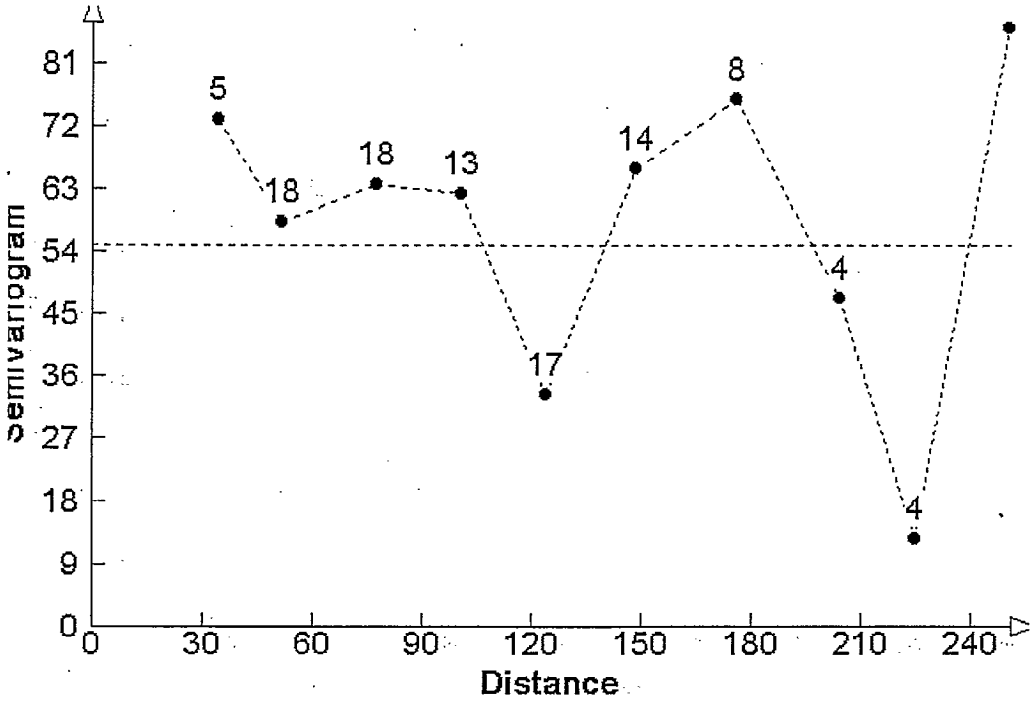


Figure 6. Case study A: Isotropic variogram of oxygen concentration on 17 July 1994

Given the small number of sample points and therefore of pairs at each sample separation distance, the nature of the spatial correlation at site A is only very poorly constrained.

Case study B

This is based on monitoring of a closed landfill in the Home Counties. Waste materials are thought to consist principally of domestic waste and building rubble. Readings from 102 points were available (Fig. 7). The site has an elongate lozenge shape with a long north east to south west axis. The spread of measurement points in Fig. 7 reflects the extent of the site. The symbols group the measurements into quartile classes. The first two quartiles comprise points where methane was not detected. The maximum methane concentration detected was 90% by volume.

The readings showed a heavily skewed, truncated distribution with widely differing values for mean and median (Fig. 8). This reflects the large number of locations where no methane was detected.

The large number of measurements meant that there were sufficient pairs of samples to study the variogram at a number of lag distances. A lag spacing of 10m was used to generate the experimental variogram (Fig. 9). The experimental variogram (Fig. 9) showed a large component of spatially dependent variation (approx. 90 - 100 %) and only a small component of random non-spatial variation (10 - 0 %). The range, however, was only some 30 m to 40 m. The contoured variogram surface (Fig. 10) did not reveal any signs of anisotropy in the data.

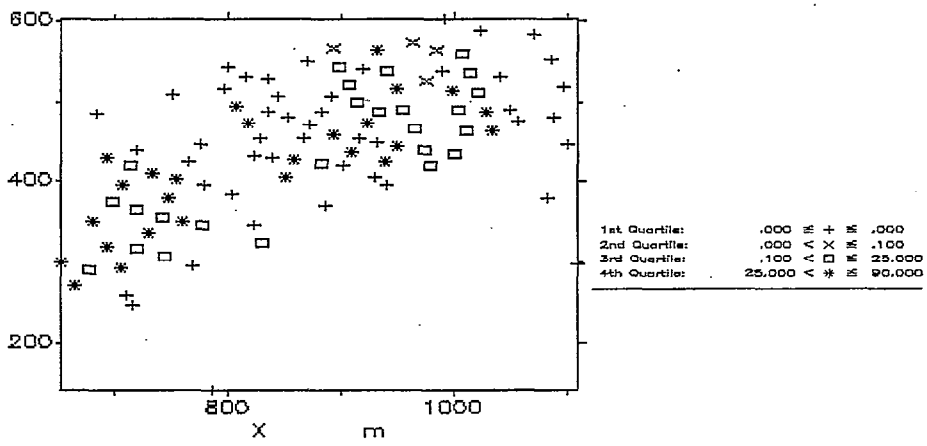


Figure 7. *Case study B: Location of methane measurements - postplot of quartiles of methane concentration, % by volume*

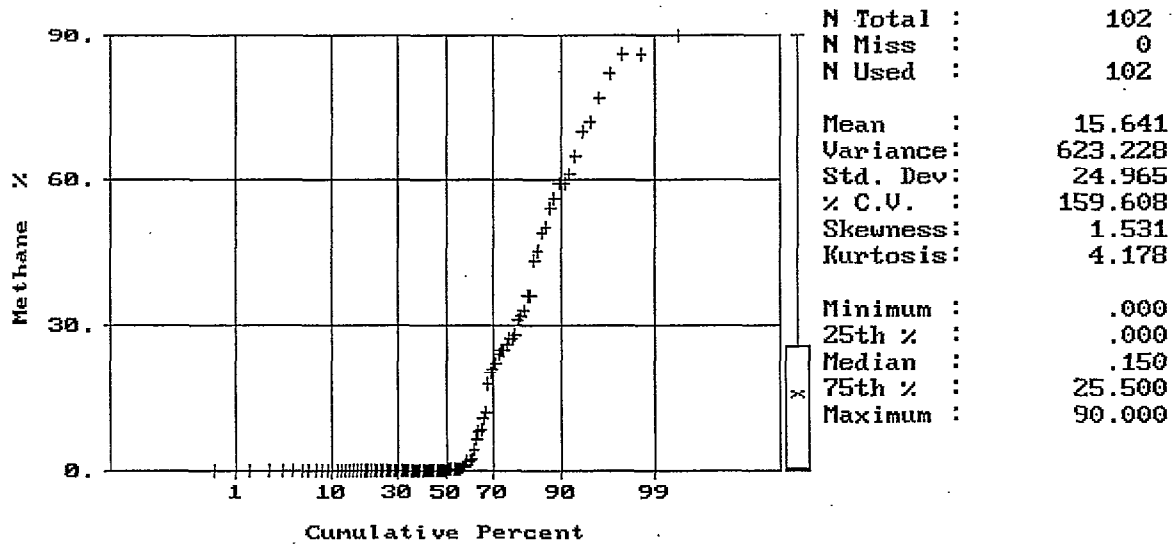


Figure 8. *Case study B: Cumulative histogram of methane concentration*

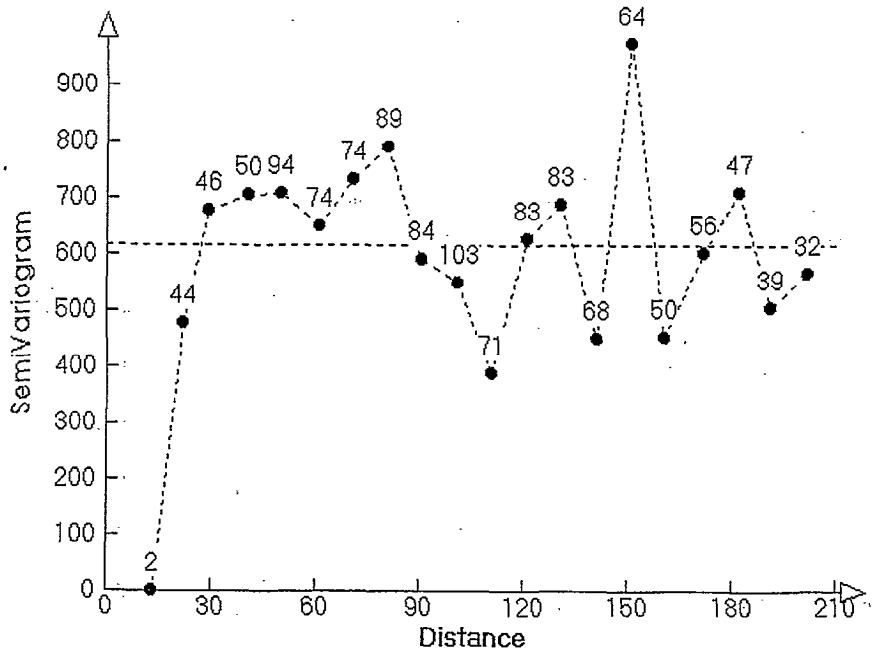


Figure 9. Case study B: Isotropic variogram of methane concentration

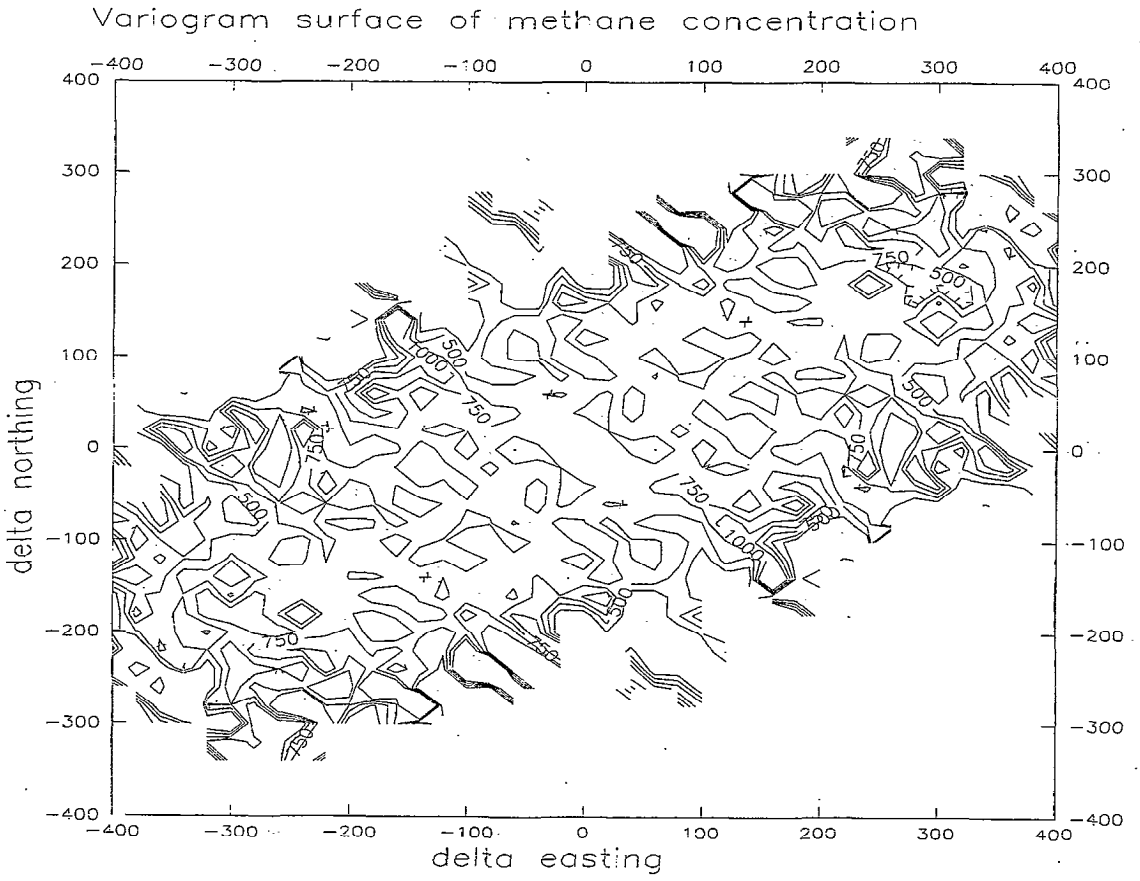


Figure 10. Case study B: Variogram surface of methane concentration

5. CONCLUSIONS

On the basis of the two completed case studies, gas concentrations in landfills tend to show a degree of spatial correlation over short distances (40 m to 70 m). Coincidentally, this is also the range at which gas recovery wells are typically spaced on landfills with gas collection systems for subsequent flaring or energy utilisation. For the purposes of estimating methane emissions from landfill sites, it is recommended that measurements be carried out at a spacing of approximately 40 m. This is slightly less than the likely range and should result in good estimates of methane emission that adequately reflect the likely spatial correlation over the part of the site studied.

Experimental variograms may be calculated to confirm the spatial correlation on a site specific basis. If measurements are made at more widely spaced points, there is a significant possibility that the site's characteristics will not have been adequately studied and estimates of methane emission will have larger uncertainties.

APPENDIX 5: BASE DATA FOR COST BENEFIT ANALYSIS

Contents

APPENDIX 5: BASE DATA FOR COST BENEFIT ANALYSIS

1 INTRODUCTION

This appendix presents the base data used to generate the estimates of cost for measures to reduce landfill gas emissions. The estimated costs of materials used for the gas control schemes and capping proposed are set out in the following sections, including any assumptions on which the estimates are made. Total costs for generic sites of different sizes, ages and depths are estimated. For a comparison of costs by variable, and a discussion of cost benefits, see Section 4 of the main report.

An estimate of methane emission potential yield (assuming no control measures), has been made using a gas production model (Revans, 1997) for comparison with costs of aversion, based on the following assumptions:

- 100% domestic waste immediately in place;
- emission rates will halve every 10 years over a 50 year period.

An estimate of capping costs has been made for three standards of caps, suitable for different emission potentials and purpose of use as follows:

- 1200 mm thick layered cap for 'active' sites;
- 950 mm thick layered cap for 'intermediate' sites;
- 300 mm thick single layer 'minimal' cap for sites with flaring as well.

In order to identify if 'economies of scale' or 'time of implementation' influence the costing exercise, this has been undertaken for various landfill scenarios using the following combinations:

- three site ages: 3, 10 and 30 years;
- three site areas: 3, 10 and 30 hectares;
- two different depths of waste: 10 and 20 metres

For each of the eighteen combinations of size of site, age of site and depth of waste, an analysis of the costs and benefits associated with changing the class of emissions has been undertaken. It should be remembered that site emissions, costs of remediation and benefits accruing are highly site specific, therefore the costings generated are for a generic site only.

In the early years of a site life there is a large amount of methane evolved and the site can be deemed to be in an 'active' phase. As the site ages the methane evolution decreases thus it can be deemed to be in an 'intermediate' phase. Active and intermediate phases have different capping and flaring requirements and therefore there are different costings related to these activities. For the purposes of this costing analysis 3 year old sites will be classified as active and sites of 10 and 30 years of age will be classified as intermediate. A minimal cap will be included in costings of gas control schemes unless a higher specification cap is designated.

2 GAS CONTROL

2.1 Methane emission potential

An estimate of methane emission potential yield (assuming no control measures), has been made using a gas production model (Revans, 1997) for comparison with costs of aversion, on the following assumptions:

- 100% domestic waste immediately in place;
- emission rates will halve every 10 years over a 50 year period.

Each age of site will have a potential abatement value dependent on the residual volume of methane and discounted cost associated with it. The potential abatement value is taken from the model output shown in Figure 2.1a.

These values have been converted to units of methane emission per unit volume of waste per hour (m^3 (CH_4) per m^3 (waste) per hour) to allow comparison with flare capacities as follows:

- 3 year old site has estimated emissions of $1x10^{-3}$ $m^3 m^{-3} hour^{-1}$;
- 10 year old site has estimated emissions of $5x10^{-4}$ $m^3 m^{-3} hour^{-1}$
- 30 year old site has estimated emissions of $6x10^{-5}$ $m^3 m^{-3} hour^{-1}$.

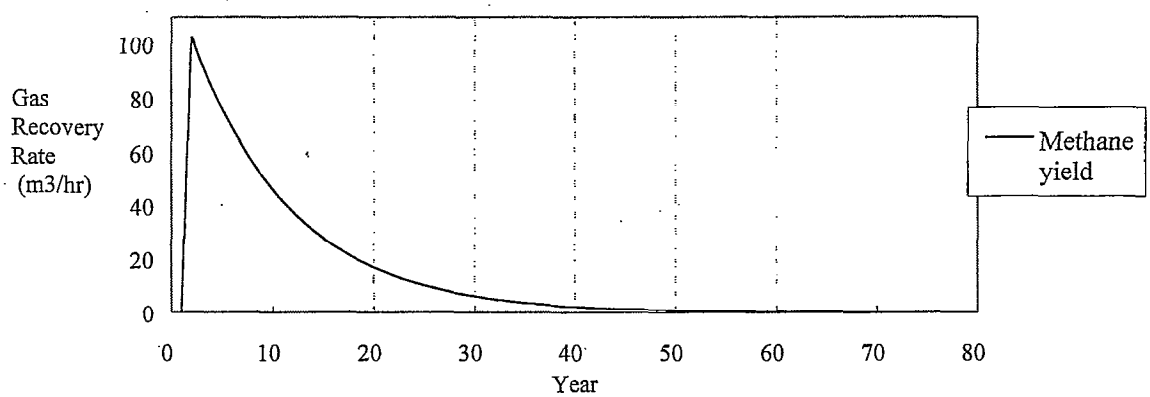


Figure 2.1a Gas emission model output

Additionally, the model estimates the cumulative yield from an initial waste volume of methane over the lifetime of an example site. It is possible to estimate the residual volume at any given point in time from the model. The following

residual volumes of methane per cubic metre (tonne) of waste in place have been used to estimate abatement cost ratios:

- 3 year old site has a residual volume of 70.2 m^3 tonne $waste^{-1}$;
- 10 year old site has a residual volume of 34.8 m^3 / tonne $waste^{-1}$
- 30 year old site has a residual volume of 4.71 m^3 / tonne $waste^{-1}$.

Thus for each combination of area and depth of site (i.e. volume) there is an estimated residual volume as shown in Table 2.1a.

Table 2.1a. Residual volume of methane (available for remediation)

Site Area	Depth of Waste (m)	Age of Waste (y)	Residual Volume (m^3 methane)
3 ha (30 000 m^2)	10	3	2.11×10^7
		10	1.04×10^7
		30	1.41×10^6
	20	3	4.21×10^7
		10	2.09×10^7
		30	2.83×10^6
10 ha (100 000 m^2)	10	3	7.02×10^7
		10	3.48×10^7
		30	4.71×10^6
	20	3	1.40×10^8
		10	6.96×10^7
		30	9.42×10^6
30 ha (300 000 m^2)	10	3	2.11×10^8
		10	1.04×10^8
		30	1.41×10^7
	20	3	4.21×10^8
		10	2.09×10^8
		30	2.83×10^7

2.2 Costs of gas control equipment

The costs of installation of gas control equipment comprise the following basic components:

- flare and associated infrastructure;
- pipework and extraction wells.

Flare and associated infrastructure

Flare stacks have been assumed to be available in three capacities. Current (1997) quotes for flare stacks approximate as follows:

- $1000m^3$ per hour capacity costing £22 000;
- $500m^3$ per hour capacity costing £18 000;
- $250m^3$ per hour capacity costing £12 000.

An appropriate combination of the above units has been used to meet the throughput demands estimated for each landfill scenario, as shown in Table 2.1a. Compound costs have been estimated, based on the following composition, to total £8 650:

- condensate unit costing £650;
- blower unit costing £5 000;
- control panel costing £3 000.

2.3 Pipeworks and extraction wells

A unit layout of pipework and gas extraction wells is illustrated below, with the associated estimated costs as follows.

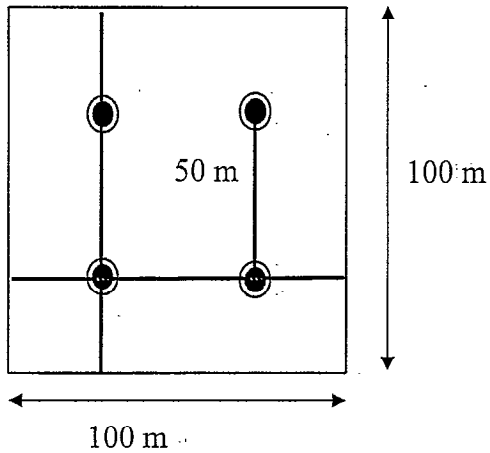
Pipework: horizontal plain HDPE pipes, assumption 6bar pressure rated;
150mm diameter;
£25 m^{-1} installed.

Wells: shell and auger drilling 250 - 300mm diameter, £30 m^{-1} ;
slotted pipes, 150mm diameter, assumption 6bar pressure
rated £30 m^{-1} ;
Total £60 m^{-1} installed.
well head assembly £400 per well.

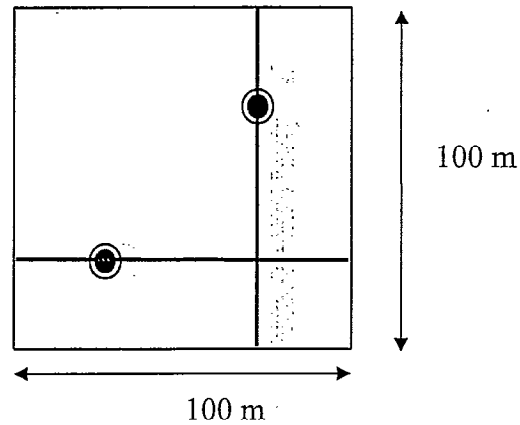
Installation of a gas control scheme during the active phase (as defined above) of a site life requires more wells, and consequently more pipework for each unit of landfill area.

The unit hectare considered for costing purposes:

Active system:
4 wells and 250m pipework



Intermediate system:
2 wells and 200m pipework



Sites with 10m depth			
well costs	£4000	well costs	£2000
pipe costs	£6250	pipe costs	£5000
Total	£10250	Total	£7000

Sites with 20m depth			
well costs	£6000	well costs	£3000
pipe costs	£6250	pipe costs	£5000
Total	£12250	Total	£8000

2.4 Flare optimisation

As the costs and benefits of flare optimisation are site specific, a single figure of £15 000 has been assumed. This is on the basis of £12 000 for additional flare capacity and an additional £3 000 for technical input.

3 CAPPING

A cap installed during the active phase of a site life (as defined above) is likely to need to be both thicker and 'well engineered' than for the intermediate phase. Consequently more material is required for each unit of landfill area for the active phase than for the intermediate phase. Additionally, a minimal cap would be required for Class I sites which are focusing on installation of gas control to prevent the drawing in of air to the system and to reduce residual emissions. The composition of the three proposed capping systems (active, intermediate and minimal) are shown in Table 3.1.

In reality a cap is installed for gas and leachate control. Therefore costs and benefits are shared between leachate and gas control. However for clarity and simplicity this scenario assumes costs and benefits are for gas control only. This gives a conservative estimate of cost benefit.

Table 3.1 Cap composition and component costs.

System	Cap Component	Depth	Est. Cost per m^2
active	topsoil	150 mm	£2.25
	subsoil	350 mm	£3.50
	membrane	1 mm	£2.50
	clay	700 mm	£11.00
			total (say) £20
intermediate	topsoil	150 mm	£2.25
	subsoil	350 mm	£3.50
	terram	separator	£1.50
	sand[1]	300 mm	£4.30
	membrane	1 mm	£2.50
	sand[1]	150 mm	£2.15
	terram	separator	£1.50
			total (say) £18
			or £15 (no terram)
minimal	clay	300 mm	£5.00
			total (say) £5.00

Note: [1]or other protective medium

For an active site the cost per m^2 used in the calculations was £20 m^{-2} and for intermediate sites an estimated value of £16.50 m^{-2} was used. The unit cost of a minimal cap is £5.00 m^{-2}. The resultant costs are given in the following table.

Table 3.2 Cost of caps for landfill sites.

Site area	Capping system	cost £m^{-2}	total capping cost (£)
3ha - 30000m^2	active	20	600 000
	intermediate	16.5	495 000
	minimal	5	150 000
10ha - 100000m^2	active	20	2 000 000
	intermediate	16.5	1 650 000
	minimal	5	500 000
30ha - 300000m^2	active	20	6 000 000
	intermediate	16.5	4 590 000
	minimal	5	1 500 000

4 SUMMARY

The undiscounted costs and maximum potential methane yield for the different landfill scenarios are set out in Table 4.4a. The figures show the estimated methane emissions (unremediated) from the sites and the costs of remediation measures to reduce the emissions. The information in this table has been combined with the emission reduction factors given in Table 4.3b of the main report to compile a table of costs, benefits and cost per unit of benefit of class conversion for each site size, depth and age combination. These are given as Tables 4.4b to 4.4g in this appendix.

The results of this analysis are presented in Figures 4.4a to 4.4f. These figures reinforce the observation that economies of scale (total costs per m^3 waste) are obtained for deeper sites, not sites of a larger surface area. The optimum time for installation of gas control measures is early in the site life when the methane available for abatement is greatest. For measures introduced at a later stage, total costs are lower due to discounting but the methane available for abatement has also dropped quite considerably. Consequently the costs per m^3 methane controlled approximately double between a 10 year old site to a 30 year old site.

Table 4.4a Estimated methane potential yield and undiscounted costings for the different landfill scenarios

Site area (ha)	site depth (m)	site age (y)	Emissions m3/h	Residual Volume (m^3 methane)	Flare stacks (capacity m^3h^{-1})	Stack costs + compound costs (£)	Pipework / well costs (£)	Capping costs[1] (£)	Minimal cap (£)	total flare costs (£)	Total control costs (£)	**Costs to remediate full residual volume £/m^3 methane**
						A	B	C_1	C_2	E (A+B)	E +(C_1 or C_2)	
3	10	3	300	$2.11x10^7$	500	26650	30750	600000		57400	657400	**0.03**
3		10	150	$1.04 x10^7$	250	20650	21000	495000		41650	536650	**0.05**
3		30	18	$1.41 x10^6$	-	-	-		150000	0	150000	**0.11**
3	20	3	600	$4.21 x10^7$	1000	30650	36750	600000		67400	667400	**0.016**
3		10	300	$2.09 x10^7$	500	26650	24000	495000		50650	545650	**0.03**
3		30	36	$2.83 x10^6$	-	-	-		150000	0	150000	**0.05**
10	10	3	1000	$7.02 x10^7$	1000	30650	102500	2000000		133150	2133150	**0.03**
10		10	500	$3.48 x10^7$	500	26650	70000	1650000		96650	1746650	**0.05**
10		30	60	$4.71 x10^6$	-	-	-		500000	0	500000	**0.11**
10	20	3	2000	$1.40 x10^8$	2 x 1000	52650	122500	2000000		175150	2175150	**0.016**
10		10	1000	$6.96 x10^7$	1000	30650	80000	1650000		110650	1760650	**0.03**
10		30	120	$9.42 x10^6$	250	20650	80000		500000	100650	1600650	**0.06**
30	10	3	3000	$2.11 x10^8$	3 x 1000	74650	307500	6000000		382150	6382150	**0.03**
30		10	1500	$1.04 x10^8$	1000+500	48650	210000	4950000		258650	5208650	**0.05**
30		30	180	$1.41 x10^7$	250	20650	210000		1500000	230650	1730650	**0.12**
30	20	3	6000	$4.21 x10^8$	6 x 1000	140650	367500	6000000		508150	6508150	**0.016**
30		10	3000	$2.09 x10^8$	3 x 1000	74650	240000	4950000		314650	5264650	**0.03**
30		30	360	$2.83 x10^7$	500	26650	240000		1500000	266650	1766650	**0.06**

Note: [1]Assumes capping costs are for gas control only

The following tables present the abatement cost data for each of the site size, depth and age combinations.

Figure 4.4b Abatement/cost data for a 3 hectare site of 10m depth

Year	Initial class	Final class	Action taken	Abatement (m3/hr)	Discounted cost (£)	Cost of abatement (£m-3)	Added value
3	1	2	Cap emplacement	20007000	5.18E+05	0.026	Leachate control
	1	2	Gas control and minimal cap installed	20638800	1.79E+05	0.009	Energy recovery + leachate control
	1	4	Cap and gas control installed	21038940	5.68E+05	0.027	Energy recovery + leachate control
	2	4	Cap emplacement	1010880	5.18E+05	0.513	Leachate control
	2	4	Gas control installed	404352	3.60E+04	0.089	
	3	4	Optimisation of flare	379080	1.30E+04	0.034	
10	1	2	Cap emplacement	9918000	3.04E+05	0.031	Leachate control
	1	2	Gas control and minimal cap installed	10231200	1.18E+05	0.011	Leachate control
	1	4	Cap and gas control installed	10429560	3.29E+05	0.032	Leachate control
	2	4	Cap emplacement	501120	3.04E+05	0.606	Leachate control
	2	4	Gas control installed	200448	2.56E+04	0.128	
	3	4	Optimisation of flare	187920	9.21E+03	0.049	
30	1	2	Cap emplacement	1342350	1.15E+05	0.085	Leachate control
	1	2	Gas control and minimal cap installed	1384740	4.43E+04	0.032	Leachate control
	1	4	Cap and gas control installed	1411587	1.24E+05	0.088	Leachate control
	2	4	Cap emplacement	67824	1.15E+05	1.689	Leachate control
	2	4	Gas control installed	27130	9.64E+03	0.355	
	3	4	Optimisation of flare	25434	3.47E+03	0.136	

Figure 4.4c Abatement/cost data for a 3 hectare site of 20m depth

Year	Initial class	Final class	Action taken	Abatement (m3/hr)	Discounted cost (£)	Cost of abatement (£m-3)	Added value
3	1	2	Cap emplacement	39995000	5.18E+05	0.013	Leachate control
	1	2	Gas control and minimal cap installed	41258000	1.88E+05	0.005	Energy recovery + leachate control
	1	4	Cap and gas control installed	42057900	5.77E+05	0.014	Energy recovery + leachate control
	2	4	Cap emplacement	2020800	5.18E+05	0.256	Leachate control
	2	4	Gas control installed	808320	3.86E+04	0.048	
	3	4	Optimisation of flare	757800	1.30E+04	0.017	
10	1	2	Cap emplacement	19855000	3.04E+05	0.015	Leachate control
	1	2	Gas control and minimal cap installed	20482000	1.23E+05	0.006	Energy recovery + leachate control
	1	4	Cap and gas control installed	20879100	3.35E+05	0.016	Energy recovery + leachate control
	2	4	Cap emplacement	1003200	3.04E+05	0.303	Leachate control
	2	4	Gas control installed	401280	2.74E+04	0.068	
	3	4	Optimisation of flare	376200	9.21E+03	0.024	
30	1	2	Cap emplacement	2688500	1.15E+05	0.043	Leachate control
	1	2	Gas control and minimal cap installed	2773400	4.50E+04	0.016	Leachate control
	1	4	Cap and gas control installed	2827170	1.25E+05	0.044	Leachate control
	2	4	Cap emplacement	135840	1.15E+05	0.843	Leachate control
	2	4	Gas control installed	54336	1.03E+04	0.190	
	3	4	Optimisation of flare	50940	3.47E+03	0.068	

Figure 4.4d Abatement/cost data for a 10 hectare site of 10m depth

Year	Initial class	Final class	Action taken	Abatement (m3/hr)	Discounted cost (£)	Cost of abatement (£m-3)	Added value
3	1	2	Cap emplacement	66690000	1.73E+06	0.026	Leachate control
	1	2	Gas control and minimal cap installed	68796000	5.47E+05	0.008	Energy recovery + leachate control
	1	4	Cap and gas control installed	70129800	1.84E+06	0.026	Energy recovery + leachate control
	2	4	Cap emplacement	3369600	1.73E+06	0.513	Leachate control
	2	4	Gas control installed	1347840	7.83E+04	0.058	
	3	4	Optimisation of flare	1263600	1.30E+04	0.010	
10	1	2	Cap emplacement	33060000	1.01E+06	0.031	Leachate control
	1	2	Gas control and minimal cap installed	34104000	3.66E+05	0.011	Energy recovery + leachate control
	1	4	Cap and gas control installed	34765200	1.07E+06	0.031	Energy recovery + leachate control
	2	4	Cap emplacement	1670400	1.01E+06	0.606	Leachate control
	2	4	Gas control installed	668160	5.57E+04	0.083	
	3	4	Optimisation of flare	626400	9.21E+03	0.015	
30	1	2	Cap emplacement	4474500	3.82E+05	0.085	Leachate control
	1	2	Gas control and minimal cap installed	4615800	1.37E+05	0.030	Leachate control
	1	4	Cap and gas control installed	4705290	4.03E+05	0.086	Leachate control
	2	4	Cap emplacement	226080	3.82E+05	1.689	Leachate control
	2	4	Gas control installed	90432	2.10E+04	0.232	
	3	4	Optimisation of flare	84780	3.47E+03	0.041	

Figure 4.4e Abatement/cost data for a 10 hectare site of 20m depth

Year	Initial class	Final class	Action taken	Abatement (m3/hr)	Discounted cost (£)	Cost of Abatement (£m-3)	Added value
3	1	2	Cap emplacement	133380000	1.73E+06	0.013	Leachate control
	1	2	Gas control and minimal cap installed	137592000	5.83E+05	0.004	Energy recovery + leachate control
	1	4	Cap and gas control installed	140259600	1.88E+06	0.013	Energy recovery + leachate control
	2	4	Cap emplacement	6739200	1.73E+06	0.256	Leachate control
	2	4	Gas control installed	2695680	8.69E+04	0.032	
	3	4	Optimisation of flare	2527200	1.30E+04	0.005	
10	1	2	Cap emplacement	66120000	1.01E+06	0.015	Leachate control
	1	2	Gas control and minimal cap installed	68208000	3.75E+05	0.005	Energy recovery + leachate control
	1	4	Cap and gas control installed	69530400	1.08E+06	0.016	Energy recovery + leachate control
	2	4	Cap emplacement	3340800	1.01E+06	0.303	Leachate control
	2	4	Gas control installed	1336320	6.18E+04	0.046	
	3	4	Optimisation of flare	1252800	9.21E+03	0.007	
30	1	2	Cap emplacement	8949000	3.82E+05	0.043	Leachate control
	1	2	Gas control and minimal cap installed	9231600	1.39E+05	0.015	Leachate control
	1	4	Cap and gas control installed	9410580	4.05E+05	0.043	Leachate control
	2	4	Cap emplacement	452160	3.82E+05	0.844	Leachate control
	2	4	Gas control installed	180864	2.33E+04	0.129	
	3	4	Optimisation of flare	169560	3.47E+03	0.020	

Figure 4.4f Abatement/cost data for a 30 hectare site of 10m depth

Year	Initial class	Final class	Action taken	Abatement (m3/hr)	Discounted cost (£)	Cost of abatement (£m-3)	Added value
3	1	2	Cap emplacement	200450000	5.18E+06	0.026	Leachate control
	1	2	Gas control and minimal cap installed	206780000	1.63E+06	0.008	Energy recovery + leachate control
	1	4	Cap and gas control installed	210789000	5.51E+06	0.026	Energy recovery + leachate control
	2	4	Cap emplacement	10128000	5.18E+06	0.512	Leachate control
	2	4	Gas control installed	4051200	1.99E+05	0.049	
	3	4	Optimisation of flare	3798000	1.30E+04	0.003	
10	1	2	Cap emplacement	98800000	3.04E+06	0.031	Leachate control
	1	2	Gas control and minimal cap installed	101920000	1.08E+06	0.011	Energy recovery + leachate control
	1	4	Cap and gas control installed	103896000	3.20E+06	0.031	Energy recovery + leachate control
	2	4	Cap emplacement	4992000	3.04E+06	0.609	Leachate control
	2	4	Gas control installed	1996800	1.42E+05	0.071	
	3	4	Optimisation of flare	253800	9.21E+03	0.036	
30	1	2	Cap emplacement	13395000	1.15E+06	0.086	Leachate control
	1	2	Gas control and minimal cap installed	13818000	4.00E+05	0.029	Leachate control
	1	4	Cap and gas control installed	14085900	1.20E+06	0.085	Leachate control
	2	4	Cap emplacement	676800	1.15E+06	1.692	Leachate control
	2	4	Gas control installed	270720	5.34E+04	0.197	
	3	4	Optimisation of flare	253800	3.47E+03	0.014	

Figure 4.4g Abatement/cost data for a 30 hectare site of 20m depth

Year	Initial class	Final class	Action taken	Abatement (m3/hr)	Discounted cost (£)	Cost of abatement (£m-3)	Added value
3	1	2	Cap emplacement	399950000	5.18E+06	0.013	Leachate control
	1	2	Gas control and minimal cap installed	412580000	1.73E+06	0.004	Energy recovery + leachate control
	1	4	Cap and gas control installed	420579000	5.62E+06	0.013	Energy recovery + leachate control
	2	4	Cap emplacement	20208000	5.18E+06	0.256	Leachate control
	2	4	Gas control installed	8083200	2.25E+05	0.028	
	3	4	Optimisation of flare	7578000	1.30E+04	0.002	
10	1	2	Cap emplacement	198550000	3.04E+06	0.015	Leachate control
	1	2	Gas control and minimal cap installed	204820000	1.11E+06	0.005	Energy recovery + leachate control
	1	4	Cap and gas control installed	208791000	3.23E+06	0.015	Energy recovery + leachate control
	2	4	Cap emplacement	10032000	3.04E+06	0.303	Leachate control
	2	4	Gas control installed	4012800	1.60E+05	0.040	
	3	4	Optimisation of flare	3762000	9.21E+03	0.002	
30	1	2	Cap emplacement	26885000	1.15E+06	0.043	Leachate control
	1	2	Gas control and minimal cap installed	27734000	4.09E+05	0.015	Energy recovery + leachate control
	1	4	Cap and gas control installed	28271700	1.21E+06	0.043	Energy recovery + leachate control
	2	4	Cap emplacement	1358400	1.15E+06	0.843	Leachate control
	2	4	Gas control installed	543360	6.03E+04	0.111	
	3	4	Optimisation of flare	509400	3.47E+03	0.007	

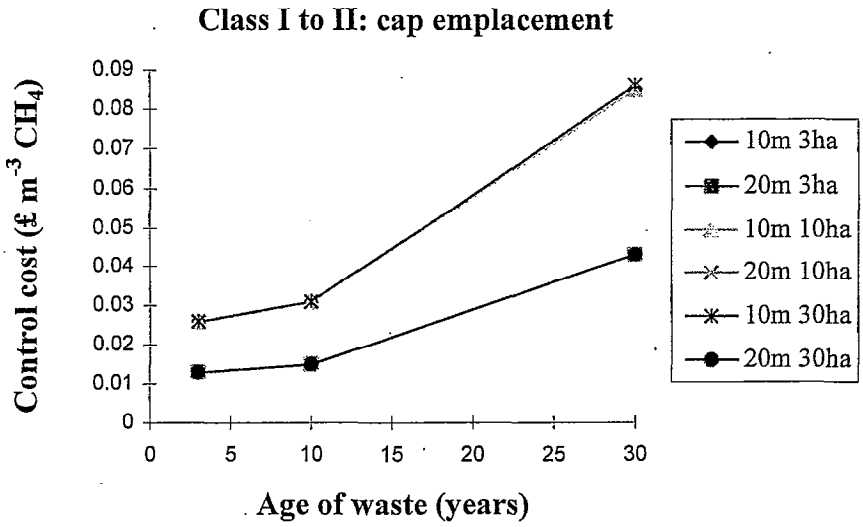


Figure 4.4a Control costs per unit abatement for class conversion I-II by cap emplacement

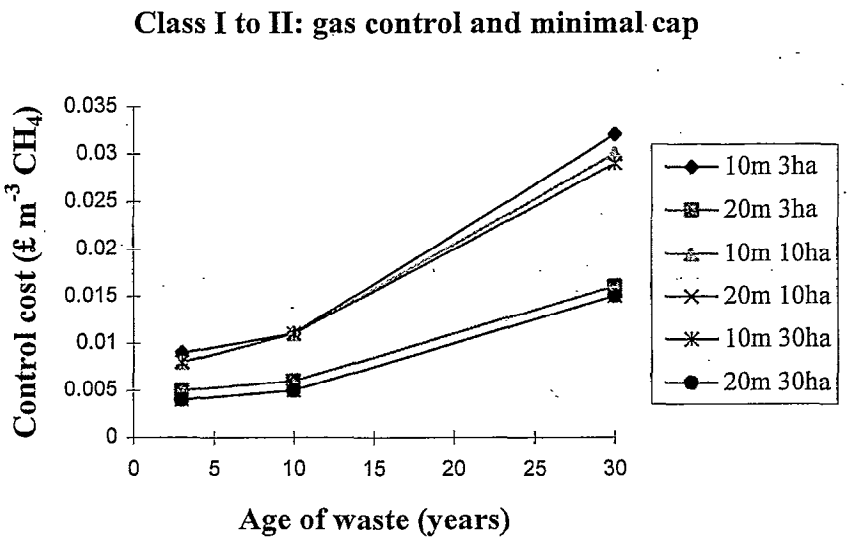


Figure 4.4b Control costs per unit abatement for class conversion I-II by gas control and minimal cap installation

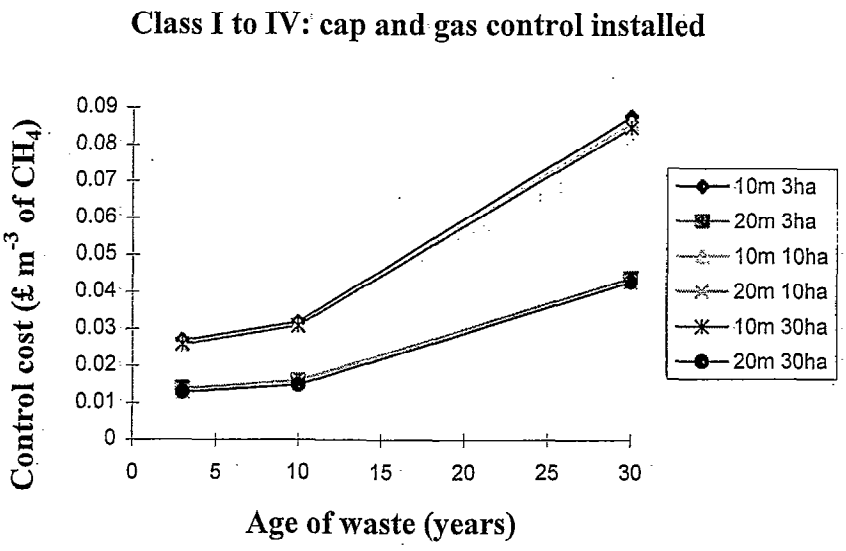


Figure 4.4c Control costs per unit abatement for class conversion I-IV by gas control and full cap installation

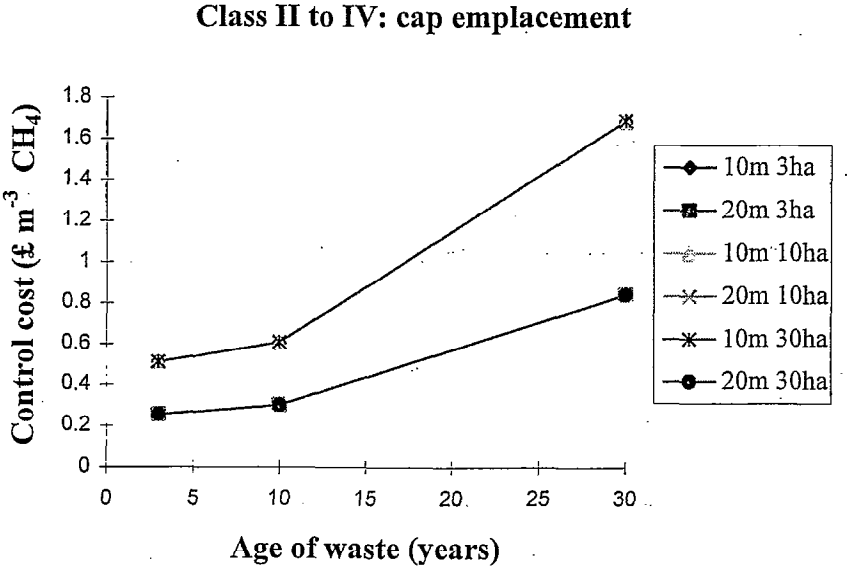


Figure 4.4d Control costs per unit abatement for class conversion II-IV by cap emplacement

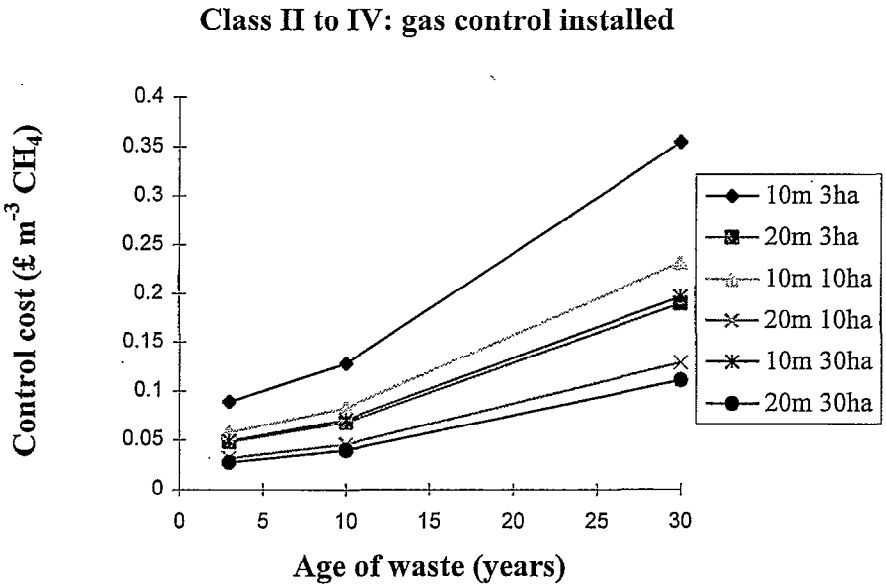


Figure 4.4e Control costs per unit abatement for class conversion II-IV by gas control installation

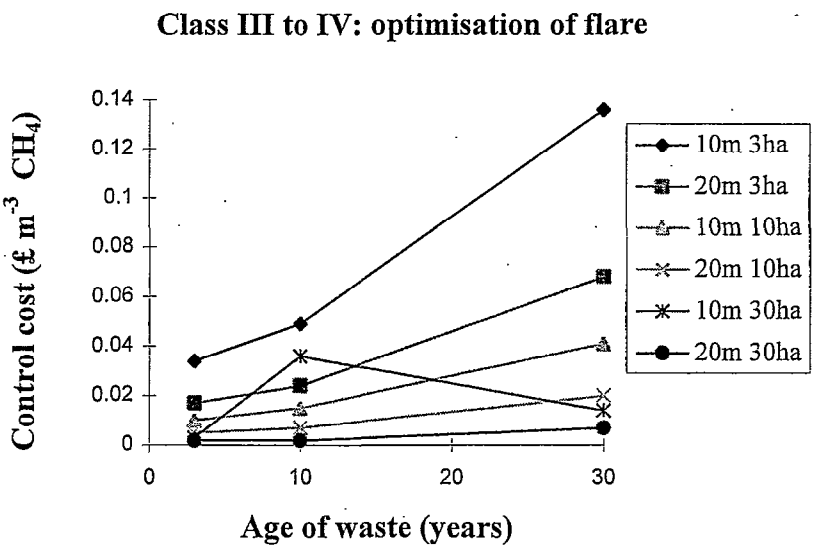


Figure 4.4f Control costs per unit abatement for class conversion III-IV by flare optimisation