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AIR EMISSION TESTING AND DISPERSION MODELLING OF THREE LANDFILL FLARES LOCATED IN KTK LANDFILL, KILCULLEN, CO. KILDARE.

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REFERENCE:	Waste licence 81-2
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REVIEWERS:	Mr. Michael Bergin and Mr. Thomas Vainio-Mattila

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1.   INTRODUCTION

This report has been prepared by Odour Monitoring Ireland and contains the results of emission testing carried out on 3 No. enclosed ground flares at KTK Landfill, Kilcullen, Co. Kildare. The emission testing was carried out in compliance with the requirements of waste licence 81-2 and in accordance with agency recommendations stipulated in audit report of 5th January 2005, Ref (81-2)04AR01DS.

Odour Monitoring Ireland was requested by Mr. Michael Bergin, KTK Landfill site to perform emission testing of the three flare stacks namely the Haase 500 m^3 hr^{-1}, Organics 1500 m^3 hr^{-1} and Haase 1500 m^3 hr^{-1}, respectively located within KTK landfill site, Kilcullen, Co. Kildare. The parameters listed in *Table 1.1* were monitored using the appropriate instrumentation as illustrated in *Table 1.1*.

Table 1.1. Monitored parameters and techniques for KTK Landfill flares, Kilcullen, Co. Kildare.

Sample location	Parameter	Analytical method
Landfill Flare inlet	Volumetric Flow Rate	Vane anemometer method and in accordance with ISO 10780, FM2 where possible
Landfill Flare stack	NO_x	Flue gas analyser, Testo 350/454 MXL
Landfill Flare stack	CO	Flue gas analyser Testo 350/454 MXL
Landfill Flare stack	Temperature ^0C	MGO coated K type thermocouple and PT100
Landfill Flare stack	HCL	Impinger/Ion chromatography (IC)
Landfill Flare stack	HF	Impinger/Ion chromatography (IC)
Landfill Flare stack	TOC (Total organic carbon)	Impinger/charcoal tube/GCFID and TOC analyser

This report presents details of this monitoring programme. This environmental monitoring was carried out by Dr. Brian Sheridan, Odour Monitoring Ireland on the 22nd February 2005. Methodology, Results, Discussion and Conclusions are presented herein.

2.   MATERIALS AND METHODS

This section provides brief details of the methodology employed to perform emission testing of the three-landfill flare stacks located in KTK landfill, Kilcullen, Co. Kildare.

2.1   VOLUMETRIC FLOW RATE MEASUREMENT

The volumetric flow rate was determined from theoretically calculated total volumetric flow rates using the assumptions presented in *Appendix II*. The inlet landfill gas velocity measurements were calculated using a vane anemometer connected to a digital readout. Measurements were carried out in accordance with ISO 10780 and USEPA Federal Method 2 where possible (i.e. sufficient duct diameters upwind and downwind of the sample location) Outlet flue gas volumetric flow rate measurement was not possible due to sampling port accessibility and location problems. Temperature traverse measurements were performed across the stack in one plane only. Only one plane was possible due to access port issues. This is a common occurrence on landfill flares previously tested by Odour Monitoring Ireland. A magnesium oxide K type and PT100 thermocouple was used for measuring temperature.

2.2   IN STACK ANALYSIS

Flue gas analysis was performed using a pre-calibrated Testo 350 MXL/454 flue gas analyser. Concentrations of oxygen, sulphur dioxide, carbon dioxide, temperature, carbon monoxide and oxides of nitrogen were measured using electrochemical cells within the analyser box and all data was logged electronically in 1 minute intervals during the sampling exercise. Data was downloaded from the control handheld using the Com soft software and average concentrations calculated are presented within. All results presented are at 273.15 K, 101.3 kPa on a dry gas basis.

2.3   HYDROGEN CHLORIDE (HCL) AND HYDROGEN FLUORIDE (HF) ANALYSIS

Volatile chloride and fluoride gas concentrations were determined using an impinger train containing 0.1 molar sodium hydroxide solution, in which such gases are readily soluble. The sampling methodology was based upon USEPA Method 26 and the European Standard, EN 1911. Small sorption liquid volumes were used to attain lower limits of detection. Impingers were placed in series to ensure effective trapping of chloride and fluoride gas concentrations.

A high temperature-sampling probe (Inconel 625) was placed within the stack and sample air was drawn through a heated PTFE line and two glass midget impingers containing 0.1 molar Sodium hydroxide positioned in series. Duplicate samples were taken over a 30-minute period (i.e. 60 minutes in total) and sampled solutions were sealed and transported to the UKAS accredited laboratory for analysis via ion chromatography (RPS Analytical laboratory, Manchester, UK).

2.4   TOTAL ORGANIC CARBON (TOC)

Total organic carbon gas concentrations (TOC's) were determined using an impinger train containing deionised water and charcoal tubes placed in series. A high temperature-sampling probe was placed within the flare stack and sample air was drawn through a heated PTFE sample line, one glass midget impinger containing deionised water and a charcoal tube. Duplicate samples were taken over a 30-minute period (i.e. 60 minutes in total) and sample solutions and sorbent tubes were sealed

and transported to a UKAS accredited laboratory for analysis (RPS Analytical laboratory, Manchester, UK).

Condensable organic carbon (i.e. TOC analysis of deionised water) and non-condensable organic carbon (i.e. TOC analysis of charcoal sorbent tube) provided the Total Organic Carbon of the sampled air stream. Results are presented at standard conditions of 273.15 K and 101.3 kPa.

2.5   DISPERSION MODELLING ASSESSMENT

2.5.1   US EPA SCREEN 3 DISPERSION MODELLING ASSESSMENT

Using the US-EPA dispersion model Screen 3 (which is recommended by the EPA as a screening tool to assess worst case impact), the worst-case dispersion impact of the individual tested emissions from the landfill flare burners were assessed. *Table 2.1* illustrates the scenarios examined to determine worst-case ground level impact for the three-landfill flares on resident locations.

Table 2.1. Dispersion modelling assessment of the ground level impact of the three-landfill flares located within KTK landfill site, Kilcullen, Co. Kildare.

Scenario and resident identity	Resident 6 grid coordinates	Base elevation of residents (m)	Base elevation and coords of Haase 500 flare burner (m)	Base elevation and coords of Organics 1500 flare burner (m)	Base elevation and coords of Haase 1500 flare burner (m)	Parameters compounds assessed Oxygen corrected to 5%
Scenario/ resident 1	285452:211472	135	126 (285741:211125)	135 (286038:211108)	143 (285821:211411)	CO, TOC, HF, HCL, NO_x, SO_2
Scenario/ resident 2	285280:211342	129	126 (285741:211125)	135 (286038:211108)	143 (285821:211411)	CO, TOC, HF, HCL, NO_x, SO_2
Scenario/ resident 3	285500:210632	119.50	126 (285741:211125)	135 (286038:211108)	143 (285821:211411)	CO, TOC, HF, HCL, NO_x, SO_2
Scenario/ resident 4	285714:210639	117.50	126 (285741:211125)	135 (286038:211108)	143 (285821:211411)	CO, TOC, HF, HCL, NO_x, SO_2
Scenario/ resident 5	286010:210758	119.50	126 (285741:211125)	135 (286038:211108)	143 (285821:211411)	CO, TOC, HF, HCL, NO_x, SO_2
Scenario/ resident 6	286260:210896	122	126 (285741:211125)	135 (286038:211108)	143 (285821:211411)	CO, TOC, HF, HCL, NO_x, SO_2
Scenario/ resident 7	286353:210937	121	126 (285741:211125)	135 (286038:211108)	143 (285821:211411)	CO, TOC, HF, HCL, NO_x, SO_2
Scenario/ resident 8	286368:211142	125.5	126 (285741:211125)	135 (286038:211108)	143 (285821:211411)	CO, TOC, HF, HCL, NO_x, SO_2

These scenarios were chosen as they represent a worst-case assessment for overall emissions and allow for examination terrain deviations in the vicinity of the landfill flare. *Table 2.2* illustrates typical input parameters to the dispersion model. *Table 3.5* illustrates the results from running the dispersion model for Total TOC, HF, HCL, NO_X as $NO + NO_2$, SO_2 and CO for the three landfill gas flares.

Graphical illustration of resident locations can be observed in *Section 8.3-Appendix II*.

Table 2.2. Input parameters used for dispersion modelling assessment of overall measured emissions from the three-landfill flare burners located in KTK Landfill, Kilcullen, Co Kildare.

Parameter	Input unit		
	Haase 500 m^3 hr^{-1}	Organics 1500 m^3 hr^{-1}	Haase 1500 m^3 hr^{-1}
Stack height (m)	6.4	7.6	8.4
Stack radius (m)	0.542	0.847	0.747
Volumetric flow rate (m^{3}Ns^{-1})	0.41	1.23	0.54
Efflux velocity (m s^{-1})	0.44	0.54	0.31
Exhaust temperature (K)	785.15	797.15	1324.15
Average ambient air temperature (K)	283	283	283
Screen mode	Rural	Rural	Rural
Emission concentrations O$_2$ corrected (g s^{-1})[1]	See Table 3.4	See Table 3.4	See Table 3.4
Meteorology	Full meteorological screen-All stability classes and wind speeds (worst case scenario)	Full meteorological screen-All stability classes and wind speeds (worst case scenario)	Full meteorological screen-All stability classes and wind speeds (worst case scenario)
Terrain Scenario 1 to 8 (m)	As per calculations in Table 2.1	As per calculations in Table 2.1	As per calculations in Table 2.1
Receptor height (m)	1.8	1.8	1.8
Output result (µg m^{-3})	Maximum emission impact and distance	Maximum emission impact and distance	Maximum emission impact and distance

Notes: [1] denotes emission value (kg hr^{-1}) ÷3600 sec ×1000 = g s^{-1}.

3.   RESULTS-EMISSION TESTING.

3.1   SAMPLING TIME

Table 3.1 summarises the time sampling was carried out on the stack. The three landfill flares namely the Haase 500 m^3 hr^{-1}, Organics 1500 m^3 hr^{-1} and the Haase 1500 m^3 hr^{-1} was operating at 447, 500 and 770 m^3 hr^{-1} of landfill gas during the monitoring schedule. *Table 3.2* illustrates the three-landfill flare parameters as characterised before monitoring using a GA2000 landfill gas analyser.

All samples were taken approximately 2.25 metres below the top of the stack using a 25 and 50 mm sampling port. A one-plane oxygen and temperature traverse was performed to assess any difference in oxygen concentrations and temperature. Temperature and Oxygen differences were less than the 15% deviation level as recommended by the UK Environmental Agency (Guidance for monitoring enclosed Landfill flares, 2002).

3.2   VOLUMETRIC FLOW RATE

Sampling for airflow rate was not performed in accordance with ISO 10780 (Iso-kinetic sampling standard from which airflow rate must be determined) or Federal Method 2 (USEPA) due to sample port position and access restrictions. *Table 3.3* summarises the theoretical airflow rate calculations from the three stacks and includes the stack velocity, expressed in metres per second (m s^{-1}) and exhaust volumetric airflow rate expressed in m^3 hr^{-1} at both actual and standard reference conditions of 273.15 K, 101.3 kPa (i.e. standard temperature and pressure).

3.3   FLUE GAS CONCENTRATIONS

Flue gas concentrations were monitored using a pre-calibrated Testo 350/454 MXL flue gas analyser. The results of SO_2, NO, NO_2, NO_x as $NO_2 + NO$, CO, and O_2 are presented in *Table 3.4*. The results of ppm have been converted to mg Nm^{-3} at 273.15 K, 101.3 kPa, on a dry gas basis with correction for oxygen content. In accordance with EPA flare monitoring requirements, Oxygen correction to 5% should be performed. The average temperature of the gas analyser on the day of sampling was 279.45 K.

3.4   HYDROGEN CHLORIDE (HCL) AND HYDROGEN FLUORIDE (HF) EMISSION DATA

Volatile chloride and fluoride gas concentrations were determined using an impinger train containing 0.1 molar sodium hydroxide solution, in which such gases are readily soluble. The results of HCL and HF are presented in *Table 3.4*. The results of are expressed as a concentration of mg Nm^{-3} at the reference standard conditions of 273.15 K, 101.3 kPa, on a dry gas basis with correction for oxygen content. In accordance to EPA flare monitoring requirements Oxygen correction to 5% should be performed. Due to possible inaccuracies (i.e. ± 40%) in airflow measurement, the amount of excess intake oxygen was theoretically calculated from the known exhaust oxygen concentration. Results are reported for oxygen correction to 5% (v/v). The sampling line was maintained at 374.15 K.

From the concentration of Cl^- and F^- analysed in the absorbing solution and the measured volume of the absorbing solution and sampled gas, the mass concentration in sampled gas and emission concentration could be calculated. Measurement was performed in a UKAS accredited laboratory using ion chromatography (RPS Laboratory, Manchester, UK).

3.5   TOTAL ORGANIC CARBON (TOC)

TOC concentrations were monitored using an impinger train containing deionised water and charcoal tubes placed in series and analysed via GCFID and a TOC analyser. The results of total TOC's (i.e. THC) are presented in *Table 3.4*. The results are expressed in mg Nm^{-3} at the reference standard conditions of 273.15 K, 101.3 kPa, with correction for oxygen content (5% (v/v)).

From the concentration of condensable TOC analysed in the absorbing solution and the measured volume of the absorbing solution and sampled gas, a total mass of condensable TOC was calculated using a TOC analyser.

For the concentration of TOC adsorbed on to the charcoal tube, the mass amount of absorbed TOC was measured using gas chromatography flame ionisation detector (GC-FID). Once the sampled volume is known then the mass concentration of TOC within the sampled gas could be calculated.

The total TOC of the sampled air stream was the additive concentration of condensable TOC and non-condensable TOC. In accordance with EPA flare monitoring requirements, Oxygen correction to 5% (v/v) should be performed. Due to possible inaccuracies (i.e. ± 40%) in airflow measurement, the amount of excess intake oxygen was theoretically calculated from the known exhaust oxygen concentration. Results are reported for oxygen correction to 5% (v/v). Measurement

was performed in a UKAS accredited laboratory using ion chromatography (RPS Laboratory, Manchester, UK). The sampling line was maintained at 374.15 K.

Table 3.1. Sampling time runs on the 22nd February 2005.

Parameter	Sampling period for Haase 500 landfill flare	Sampling period for Organics 1500 landfill flare	Sampling period for Haase 500 landfill flare
Volumetric air flow rate	Theoretically calculated	Theoretically calculated	Theoretically calculated
SO$_2$	10.45AM to 12.45PM	14.00PM to 15.44PM	16.00PM to 17.30PM
NO	10.45AM to 12.45PM	14.00PM to 15.44PM	16.00PM to 17.30PM
NO$_2$	10.45AM to 12.45PM	14.00PM to 15.44PM	16.00PM to 17.30PM
CO	10.45AM to 12.45PM	14.00PM to 15.44PM	16.00PM to 17.30PM
O$_2$	10.45AM to 12.45PM	14.00PM to 15.44PM	16.00PM to 17.30PM
Stack gas temp	10.45AM to 12.45PM	14.00PM to 15.44PM	16.00PM to 17.30PM
HCL and HF	10.45AM to 12.45PM	14.00PM to 15.44PM	16.00PM to 17.30PM
TOC	10.45AM to 12.45PM	14.00PM to 15.44PM	16.00PM to 17.30PM

Table 3.2. Characteristics of raw inlet gas to the three landfill gas burners.

Haase flare 500 m^3 hr^{-1}		
Inlet compound identity	Compound Loading	Unit values
CH$_4$	46.5	%
CO$_2$	26	%
O$_2$	0.8	%
CO	42	ppm
H$_2$S	65	ppm
Volumetric flow rate	447	m^3 hr^{-1}
Differential suction pressure	No value	mbar
Organics flare 1500 m^3 hr^{-1}		
Inlet compound identity	Compound Loading	Unit values
CH$_4$	25.2	%
CO$_2$	19.6	%
O$_2$	6	%
CO	300	ppm
H$_2$S	700	ppm
Volumetric flow rate	500	m^3 hr^{-1}
Differential suction pressure	188	mbar
Haase flare 1500 m^3 hr^{-1}		
Inlet compound identity	Compound Loading	Unit values
CH$_4$	43.2	%
CO$_2$	36.1	%
O$_2$	1	%
CO	349	ppm
H$_2$S	579	ppm
Volumetric flow rate	770	m^3 hr^{-1}
Differential suction pressure	84.8	mbar

Table 3.3. Theoretically calculated landfill gas exhaust volume and physical characteristics.

Identity[1]	Haase 500	Organics 1500	Haase 1500
Total Volumetric methane loading (m^3 hr^{-1})	207.855	126	332.64
Total Volumetric Oxygen loading (m^3 hr^{-1})	3.576	30	7.7
Ratio to complete combustion of methane assuming no excess Oxygen	9.97	9.97	9.97
Oxygen concentration level in flue gas (%)	8.41	18.1	11.87
Flue gas temperature (K)[2]	785.15	797.15	1324.15
Theoretical calculated Volumetric exhaust airflow rate (m^3 h^{-1})	4209.68	12885	9440.23
Normalised exhaust airflow rate (m^3 Nh^{-1})[3]	1464.53	4415.15	1947.36
Stack velocity (m s^{-1}) normalised[4]	0.44	0.54	0.31
Ratio of intake air over landfill gas	9.41	25.77	12.26

Notes: [1] denotes data from 22nd February 2005.

[2] denoted converted from degrees Celsius to Kelvin ($^0C + 273.15$);

[3] denotes normalised to 273.15 Kelvin and 101.3 kPa.

[4] denotes that a stack diameter of 1.084, 1.694 and 1.494 metre stack diameter was used for calculating normalised stack gas velocity.

Table 3.4. Emission value results from three-landfill gas flare burners monitored at KTK Landfill, Kilcullen, Co. Kildare.

Haase flare 500	Conc.	Units[2]	Adjusted units (mg/m3)	Theoretical Volumetric flow rate (m3/hr)	Normalised Volumetric flow rate (m3N/hr)	Vol. flow rate (m3N/s)	Area of stack	Efflux (m s⁻¹)	Normalised Emission concentration (mgN/m3)	Oxygen corrected emission concentration to 5% (mgN/m3)	Mass emission rate (Kg N/hr) at 5% O₂
Average TOC	745	mg/m3	745.02	4209.7	1464.50	0.41	0.92	0.44	-	-	-
Average TVOC	189	mg/m3	189.05	4209.7	1464.50	0.41	0.92	0.44	-	-	-
Total Organic Carbon	-	mg/m3	934.07	4209.7	1464.50	0.41	0.92	0.44	1275.52	1623.77	2.35
Average Hydrogen chloride	15.8	mg/m3	15.84	4209.7	1464.50	0.41	0.92	0.44	21.62	27.53	0.04
Average Hydrogen fluoride	12.4	mg/m3	12.45	4209.7	1464.50	0.41	0.92	0.44	17.00	21.65	0.03
Temperature	512	⁰C	785.15 K	4209.7	1464.50	0.41	0.92	0.44	-	-	-
CO	3058	ppm	3822.50	4209.7	1464.50	0.41	0.92	0.44	3912.06	4980.13	7.20
O	8.41	%	8.41	4209.7	1464.50	0.41	0.92	0.44	-	-	-
NO	4	ppm	5.36	4209.7	1464.50	0.41	0.92	0.44	5.48	6.98	0.01
NO₂	0.9	ppm	1.85	4209.7	1464.50	0.41	0.92	0.44	1.89	2.41	0.00
Total NO_X	-	-	7.21	4209.7	1464.50	0.41	0.92	0.44	7.37	9.39	0.01
SO₂	145	ppm	414.29	4209.7	1464.50	0.41	0.92	0.44	423.99	539.75	0.78
CO₂	11.38	%	11.38	4209.7	1464.50	0.41	0.92	0.44	-	-	-

<u>**Notes:**</u> [1] denotes refer to *Appendix II* for Oxygen correction calculations.
   [2] denotes units as measured.

Table 3.4 continued. Emission value results from three-landfill gas flare burners monitored with KTK Landfill, Kilcullen, Co. Kildare.

Organics flare 1500	Conc.	Units[4]	Adjusted units (mg/m3)	Theoretical Volumetric flow rate (m3/hr)	Normalised Volumetric flow rate (m3N/hr)	Vol. flow rate (m3N/s)	Area of stack	Efflux (m s⁻¹)	Normalised Emission concentration (mgN/m3)	Oxygen corrected emission concentration to 5% (mgN/m3)	Mass emission rate (Kg N/hr) at 5% O_2[3]
Average TOC	125.19	mg/m3	125.20	12885	4415.15	1.23	2.25	0.54	-	-	-
Average TVOC	4.25	mg/m3	4.25	12885	4415.15	1.23	2.25	0.54	-	-	-
Total Organic Carbon	-	mg/m3	129.45	12885	4415.15	1.23	2.25	0.54	176.77	1003.78	4.43
Average Hydrogen chloride[1]	21.18	mg/m3	21.18	12885	4415.15	1.23	2.25	0.54	28.93	164.27	0.73
Average Hydrogen fluoride[1]	>5.09	mg/m3	5.09	12885	4415.15	1.23	2.25	0.54	6.95	39.45	0.17
Temperature	524	°C	797.15 K	12885	4415.15	1.23	2.25	0.54	-	--	-
CO	101.3	ppm	126.63	12885	4415.15	1.23	2.25	0.54	129.59	735.90	3.25
O	18.1	%	18.10	12885	4415.15	1.23	2.25	0.54	-	-	-
NO	4.3	ppm	5.76	12885	4415.15	1.23	2.25	0.54	5.89	33.47	0.15
NO₂	0.4	ppm	0.82	12885	4415.15	1.23	2.25	0.54	0.84	4.77	0.02
Total NOₓ	-	-	6.58	12885	4415.15	1.23	2.25	0.54	6.73	38.24	0.17
SO₂	26	ppm	74.29	12885	4415.15	1.23	2.25	0.54	76.03	431.72	1.91
CO₂	2.12	%	2.12	12885	4415.15	1.23	2.25	0.54	-	-	-

<u>Notes:</u> [1] denotes that value is less than reported concentration as lower limits of detection of test method were achieved.

[2] denotes that due to the fact the oxygen concentration in the flue gas was elevated, the mass emission rate results are significantly biased and therefore may not represent accurate emissions.

[3] denotes refer to *Appendix II* for Oxygen correction calculations.

[4] denotes units as measured.

Table 3.4 continued. Emission value results from three-landfill gas flare burners monitored with KTK Landfill, Kilcullen, Co. Kildare.

Haase flare 1500	Conc.	Units[3]	Adjusted units (mg/m3)	Theoretical Volumetric flow rate (m3/hr)	Normalised Volumetric flow rate (m3N/hr)	Vol. flow rate (m3N/s)	Area of stack	Efflux (m s^{-1})	Normalised Emission concentration (mgN/m3)	Oxygen corrected emission concentration to 5% (mgN/m3)	Mass emission rate (Kg N/hr) at 5% O_2[2]
Average TOC	228.77	mg/m3	228.77	9440.23	1947.36	0.54	1.75	0.31	-	-	-
Average TVOC	4.35	mg/m3	4.35	9440.23	1947.36	0.54	1.75	0.31	-	-	-
Total Organic Carbon	-	mg/m3	233.12	9440.23	1947.36	0.54	1.75	0.31	318.34	555.00	1.08
Average Hydrogen chloride[1]	>12.43	mg/m3	12.43	9440.23	1947.36	0.54	1.75	0.31	16.98	29.60	0.06
Average Hydrogen fluoride[1]	>6.22	mg/m3	6.22	9440.23	1947.36	0.54	1.75	0.31	8.50	14.83	0.03
Temperature	1051	^{0}C	1324.15	9440.23	1947.36	0.54	1.75	0.31	-	-	-
CO	5	ppm	6.25	9440.23	1947.36	0.54	1.75	0.31	6.40	11.15	0.02
O	11.87	%	11.87	9440.23	1947.36	0.54	1.75	0.31	-	-	-
NO	17	ppm	22.77	9440.23	1947.36	0.54	1.75	0.31	23.30	40.62	0.08
NO_2	0.2	ppm	0.41	9440.23	1947.36	0.54	1.75	0.31	0.42	0.73	0.00
Total NO_x			23.18	9440.23	1947.36	0.54	1.75	0.31	23.72	41.36	0.08
SO_2	27.8	ppm	79.43	9440.23	1947.36	0.54	1.75	0.31	81.29	141.72	0.28
CO_2	8.22	%	8.22	9440.23	1947.36	0.54	1.75	0.31	-	-	-

Notes: [1]denotes that value is less than reported concentration as lower limits of detection of test method were achieved.

[2] denotes refer to *Appendix II* for Oxygen correction calculations.

[3] denotes units as measured.

Table 3.5. Respective calculated maximum 1-hour ground level concentrations (GLC's) of the tested compounds using the US EPA recommended Screen 3 (96403) dispersion model for Haase 500m^3 hr^{-1} flare burner.

Resident identity	Res 1 perceived worst case conc (μg m^{-3})	Res 2 perceived worst case conc (μg m^{-3})	Res 3 perceived worst case conc (μg m^{-3})	Res 4 perceived worst case conc (μg m^{-3})	Res 5 perceived worst case conc (μg m^{-3})	Res 6 perceived worst case conc (μg m^{-3})	Res 7 perceived worst case conc (μg m^{-3})	Res 8 perceived worst case conc (μg m^{-3})	Ground level maximum allowable conc. Limit/ guideline value (μgm^{-3}) [1,2,3,4]	
Resident distance from flare burner (metres)	520.6	562.6	453.1	510.2	453.4	568.3	643.3	634.8	-	
Resident base elevation (metres)	135	129	119.5	117.5	119.5	122	121	125.5	-	
TOC	196	156	102	84	102	109	96	119	Class 1	50
									Class 2	200
									Class 3	1000
HCL	3	2.4	1.6	1.3	1.6	1.7	1.5	1.9	TA Luft 1996	100
									Fractional exposure EH40	350
									Danish C value	50
HF	3	2.4	1.6	1.3	1.6	1.7	1.5	1.9	WHO guideline value	1000
									Fractional exposure of EH40	63
CO	602	482	318	261	319	351	309	390	30,000	
NO$_x$	1.2	0.95	0.63	0.51	0.63	0.7	0.62	0.78	200	
SO$_2$	66	53	34	28	34	38	33	42	350	

Notes: [1] denotes SI 271 of 2002, TA Luft of 2002 and 1/100th of EH40 were used to determine maximum allowable ground concentration values.
[2] denotes 1-hour worst case GLC value.
[3] denotes 98th percentile of 1 hour TA Luft.
[4] denotes 99th percentile of 1 hour of Danish C value

Table 3.6. Respective calculated maximum 1 hour ground level concentrations (GLC's) of the tested compounds using the US EPA recommended Screen 3 (96403) dispersion model for Organics $1500m^3 \ hr^{-1}$ flare burner.

Resident identity	Res 1 perceived worst case conc ($\mu g \ m^{-3}$)	Res 2 perceived worst case conc ($\mu g \ m^{-3}$)	Res 3 perceived worst case conc ($\mu g \ m^{-3}$)	Res 4 perceived worst case conc ($\mu g \ m^{-3}$)	Res 5 perceived worst case conc ($\mu g \ m^{-3}$)	Res 6 perceived worst case conc ($\mu g \ m^{-3}$)	Res 7 perceived worst case conc ($\mu g \ m^{-3}$)	Res 8 perceived worst case conc ($\mu g \ m^{-3}$)	Ground level maximum allowable conc. Limit/ guideline value (μgm^{-3}) [1,2,3,4]	
Resident distance from flare burner (metres)	254.2	393.7	376.8	553.6	683.1	677.9	714.1	611	-	
Resident base elevation (metres)	135	129	119.5	117.5	119.5	122	121	125.5	-	
TOC	106	71	46	41	54	63	59	77	Class 1	50
									Class 2	200
									Class 3	1000
HCL	17.3	11.59	7.51	6.69	8.81	10.28	9.63	12.57	TA Luft 1996	100
									Fractional exposure EH40	350
									Danish C value	50
HF	4.3	2.88	1.87	1.66	2.19	2.56	2.39	3.12	WHO guideline value	1000
									Fractional exposure of EH40	63
CO	78	52	34	30	40	46	43	57	30,000	
NOx	4.3	2.88	1.87	1.66	2.19	2.56	2.39	3.12	200	
SO2	46	31	20	18	23	27	26	33	350	

Notes: [1] denotes SI 271 of 2002, TA Luft of 2002 and $1/100^{th}$ of EH40 were used to determine maximum allowable ground concentration values.
[2] denotes 1-hour worst case GLC value.
[3] denotes 98th percentile of 1 hour TA Luft.
[4] denotes 99th percentile of 1 hour of Danish C value

Table 3.7. Respective calculated maximum 1 hour ground level concentrations (GLC's) of the tested compounds using the US EPA recommended Screen 3 (96403) dispersion model for Haase $1500m^3\ hr^{-1}$ flare burner.

Resident identity	Res 1 perceived worst case conc ($\mu g\ m^{-3}$)	Res 2 perceived worst case conc ($\mu g\ m^{-3}$)	Res 3 perceived worst case conc ($\mu g\ m^{-3}$)	Res 4 perceived worst case conc ($\mu g\ m^{-3}$)	Res 5 perceived worst case conc ($\mu g\ m^{-3}$)	Res 6 perceived worst case conc ($\mu g\ m^{-3}$)	Res 7 perceived worst case conc ($\mu g\ m^{-3}$)	Res 8 perceived worst case conc ($\mu g\ m^{-3}$)	Ground level maximum allowable conc. Limit/ guideline value (μgm^{-3}) [1,2,3,4]	
Resident distance from flare burner (metres)	254.2	393.7	376.8	553.6	683.1	677.9	714.1	611	-	
Resident base elevation (metres)	135	129	119.5	117.5	119.5	122	121	125.5	-	
TOC	32	21	13.8	11.3	13.1	14	13.3	16.6	Class 1	50
									Class 2	200
									Class 3	1000
HCL	2.2	1.44	0.95	0.78	0.90	0.96	0.91	1.14	TA Luft 1996	100
									Fractional exposure EH40	350
									Danish C value	50
HF	1.1	0.72	0.47	0.39	0.45	0.48	0.46	0.57	WHO guideline value	1000
									Fractional exposure of EH40	63
CO	1.1	0.72	0.47	0.39	0.45	0.48	0.46	0.57	30,000	
NO$_X$	2.2	1.44	0.95	0.78	0.90	0.96	0.91	1.14	200	
SO$_2$	8.6	5.6	3.7	3.0	3.5	3.8	3.6	4.5	350	

Notes: [1] denotes SI 271 of 2002, TA Luft of 2002 and 1/100th of EH40 were used to determine maximum allowable ground concentration values.
[2] denotes 1-hour worst case GLC value.
[3] denotes 98th percentile of 1 hour TA Luft.
[4] denotes 99th percentile of 1 hour of Danish C value

4.   DISCUSSION OF RESULTS

Tables 3.1 to *3.4* present the results of the emission monitoring carried out on the three-landfill flare stack burners located in KTK landfill, Kilcullen, Co. Kildare.

Table 3.5, 3.6 and *3.7* illustrate the results obtained during the worst-case dispersion modelling assessment of the individual exhaust emission values obtained during the monitoring exercise. All emission values are within their respective GLC's as determined by dispersion modelling using the US-EPA recommended Screen 3 worst-case dispersion model. It is predicted that no significant ground level impact exists in the vicinity of the landfill flare burner system.

All ground level concentration levels downwind at the resident locations are within the Class III concentration limit value. HCL and HF are well within the proposed emission limit value established by the VDI German engineers institute, the Danish EPA and the fractional analysis of the EH 40 OES exposure level value. CO, NO_x and SO_2 are within the SI 271 of 2002 ambient limit values.

There was very little variation at one traverse in oxygen and flue gas temperature profiles across the stack during the monitoring exercise (i.e. less than 15% as recommended by the Environment Agency, UK (Environment Agency, 2002)).

A high temperature Inconel 625 and ceramic probe (Testo, Germany) was used to prevent variations in CO emissions data. Normal stainless steel probes when subjected to temperatures above 600^0C can release CO from within the structure of the material and cause the recording of erroneous results (Environment Agency, 2002).

Correction of data to 5% oxygen was performed. Due to possible inaccuracies in airflow rate measurement, it was not possible to determine the oxygen intake of the flare through the louver system using measurement. Since the volume of intake air required for complete combustion was known and the oxygen concentration in the exhaust flue gas was known, the volume of intake excess fuel air could be theoretically calculated through numerous iterations using the Solver program (Microsoft Excel). This allow for the calculation of the volume of intake excess air through the louver landfill flare intake system. These calculations were validated through use of the published Environment Agency equation (see *Eqn 8.3.1*) (Environment Agency, 2002).

Landfill methane destruction efficiency was not calculated using the flue gas analyser as this would lead to the presentation of erroneous results. Since the combustion of methane is for the most part CH4 + 2O2 $\longrightarrow$ CO2 + 2H2O, every mole of oxygen used in combustion can be assumed to generate a mole of water. The overall oxygen content of the intake (landfill gas + air mixture) and the oxygen content of the emissions must be known to calculate the difference between the two to calculate the increase in moisture content. However, this would be required to be added to the amount of moisture already in the landfill gas/air intake to get the total moisture content of emissions. This would lead to in-depth analysis of moisture content, which was not performed during the monitoring. Using the flue gas analyser, the ratio of CO_2 to CO does not tell you the methane destruction efficiency, only how much of the methane that is destroyed and is converted to CO (a relatively small amount) and CO_2. The only other method is to measure inlet methane and outlet methane

concentration and based on this fact; calculate the destruction removal efficiency (DRE) of the landfill flare (McVay, M., per comm., 2003). This is not an easy task due to the limits of analytical equipment in such aggressive environment. Typical reported concentrations of methane from landfill flare burner systems are in the order of 0.040% to 0.52%. The complete combustion of methane results in the formation of CO_2 and H_2O. The incomplete combustion of methane results in the formation of CO. CO concentration levels were high in the Haase 500 and Organics 1500 flare flue gas exhaust in comparison to the Haase 1500 flare burner system. Operating temperature was also low and TOC concentrations in the outlet of the Haase 500 and Organics 1500 were higher than previously measured on other similar sites. It is recommended that the Haase 500 and Organics 1500 flare burners be checked for operation in order to improve temperature levels within the flare burner. The resulting increase in temperature above 1000 °C will facilitate the combustion of TOC and methane and result in a lower CO emission level value. It is suggested that due to the high CO level in the exhaust stream of the Haase 500 and Organics 1500 that the methane DRE is lower than what is attainable. A thorough examination and service of both Haase 500 and Organics 1500 flares and ancillary equipment is recommended so as to identify cause of below design combustion temperatures.

As CO concentrations are low in the exhaust flue gas of the Haase 1500 flare burner (i.e. in the order of 6.25 mg m^{-3}), it is suggested that this landfill flare is attaining a high DRE for methane destruction.

5.   CONCLUSION
The following conclusions can be drawn from this study:
1. Airflow rate measurement was not carried out in accordance with the required standards due to sample port restrictions and airflow rate measurement location. A theoretically exhaust flue gas volume was calculated.
2. NO_x, SO_2, CO, O_2, HCl, HF and TOC monitoring and analysis was carried out in accordance with specified requirements;
3. All data was standardised to 273 Kelvin, 101.3 kPa;
4. All data is presented as Oxygen corrected to 5% (v/v) using the appropriate equations as presented in *Section 8.3*;
5. A worst case dispersion modelling assessment was carried out using the recommended US EPA Screen 3 dispersion model. Those monitored parameters that have established maximum GLC limits are within these values.
6. CO emission rates are higher in the Haase 500 and Organics 1500 flare burner exhaust, it is suggested that the DRE for methane is reduced. Servicing of the flare burners and supplying a greater gas supply to the Organics 1500 flare should eliminate this problem and maintain higher operating temperatures within the flare burner.
7. As CO concentrations are low in the exhaust flue gas of the Haase 1500 (i.e. in the order of 6.75 mg m^{-3}), it is suggested that this landfill flare is attaining a high DRE for methane destruction.

6.   REFERENCES

1. Environment Agency. (2002). Guidance for Monitoring Enclosed Landfill Gas Flares. www.environment-agency.co.uk

2. McVay, M., (2003). Personal communication. Wales, UK.

3. ISO 10780, (1984). Stationary source emissions-Measurement of velocity and volume flowrate of gas streams in ducts.

4. Federal Method 2-Determination of stack gas velocity and volumetric flow rate (Type S pitot tube).

7.   APPENDIX 1-SAMPLING, ANALYSIS AND CALCULATION DETAILS

7.1.1   Location of Sampling

KTK Landfill flare, Kilcullen, Co. Kildare.

7.1.2   Date & Time of Sampling

22nd February 2003

7.1.3   Personnel Present During Sampling

Dr. Brian Sheridan, Odour Monitoring Ireland, Trim, Co. Meath.

7.1.4   Instrumentation

Testo 350 MXL/454 in stack analyser;

Federal Method 2 S type pitot and MGO coated thermocouple;

Testo 400 handheld and appropriate probes.

Impinger and TOC sampling train.

Ceramic and Inconel 625 sampling probes.

7.1.5   Software

Microsoft Excel and VBA applications.

Screen 3 Dispersion modelling package.

8.   APPENDIX 2-EXAMPLE CALCULATIONS AND CONVERSIONS

8.1   CONVERSION OF 5.0-PPM CARBON MONOXIDE TO MG M^{-3} AT 273.15 KELVIN AND 101.3 KPA (STP)

1 mole of an ideal gas occupies 22.4 litres at standard temperature and pressure of 273.15 Kelvin[1] and 101.3 kPa (STP), where a mole of any substance is equal to its molecular mass and expressed in grams.

This is known as molar mass (i.e. the volume occupied by one gram mole of a gas at STP).

Using the average recorded concentration (in ppm) for CO during the survey, the conversion is as follows:

1 mole of CO occupies 22.4 litres @ STP

28 grams (Molecular weight of CO) occupies 22.4 litres @ STP

mg Nm^{-3} CO = 5.0 × 28 / 22.4 = 6.25 mg Nm^{-3}

[1]denotes conversion of ^{0}C to Kelvin: ^{0}C + 273 = Kelvin

8.2 ADDITIONAL CALCULATIONS AND CORRECTION OF OXYGEN CONCENTRATION MEASURED TO REFERENCE OXYGEN CONCENTRATION OF 5% (V/V) FOR 6.25 MG M^{-3} OF CO.

If excess air is added to an enclosed landfill flare (i.e. to promote better combustion), measured flue gas emission concentration of non-combustion species will fall. Emission concentrations appear to be reducing, whilst in reality mass emission rates have remained constant (Environment Agency, 2002). Therefore, it is necessary to compare concentrations at a standard oxygen concentration.

The relationship between the measured oxygen concentration and measured emission species concentration is non-linear as oxygen from air is added or removed. For example, a halving of the flue gas oxygen content does not result in a doubling of the emission concentration. The oxygen concentration in the flue gases is a measure of the excess air over that required for theoretical complete combustion (i.e. stiochiometric air requirement). Therefore, the measured oxygen level is a measure of the dilution of the flue gases from the stoichiometric condition. The concentration of oxygen in dry air is 20.9% (v/v) and the proportion of excess air (X/V) can therefore be calculated from the following:

$$\frac{X}{V} = \frac{(O_2)_m}{(20.9 - (O_2)_m)} \quad \text{(Eqn 8.3.1)}$$

Where: X is the volume of excess air (m^3);
      V is the stoichiometric volume of the flue gas (m^3);
      $(O_2)_m$ is the percentage of oxygen (v/v) in the flue gas (on a dry basis).

If we know and calculate the following:

The volume of landfill gas was 770 m^3 hr^{-1} with a methane and oxygen concentration of 43.2% (v/v) and 1 %(v/v) as taken from the GA2000.

This equates to a methane and oxygen volume of 332.64 m^3 hr^{-1} and 7.7 m^3 hr^{-1}, respectively.

The stiochiometric ratio of oxygen to methane for combustion is **2:1** as shown below:

$$1CH_4 + 2O_2 + 7.52 N_2 \longrightarrow CO_2 + 2H_2O + 7.52 N_2 + Heat + Light$$

Ambient air contains 20.9% (v/v) oxygen, therefore stiochiometric volume ratio of air required for complete combustion of methane is **9.57 times** methane volume.

Since the volume of oxygen in inlet landfill gas and stiochiometric ratio required is known, the total amount of intake air required for complete combustion is:

$$(332.64 \text{ m}^3 \text{ h}^{-1} \times 9.57) - 7.7 \text{ m}^3 \text{ hr}^{-1} = \textbf{3308.72 m}^3 \textbf{ hr}^{-1}. \text{ (Eqn 8.3.2)}$$

Therefore the total volume of flue gases exhausted through stack assuming total combustion and 0% (v/v) oxygen in flue gas is:

Volume of landfill gas + Volume of Inlet air = Total Volume of flue gas

$$770 \text{ m}^3 \text{ hr}^{-1} + 3308.72 \text{ m}^3 \text{ hr}^{-1} = \textbf{4078.72 m}^3 \textbf{ hr}^{-1} \text{ (Eqn 8.3.3)}$$

In reality excess inlet air is taken into the landfill flare gas burner to ensure this combustion.

The measured oxygen concentration within the flue gas of the landfill flare in KTK was **11.87% (v/v) dry gas basis.**

Therefore excess amounts of inlet air are being taken in through the louver system. As the airflow rate measurement may be highly inaccurate a back calculation method is used to calculate the amount of excess air taken into the flare burner using known combustion volume and flue gas Oxygen concentration % (v/v). This is shown below:

The following units are known:

- Volume of flue gas assuming total combustion and 0% (v/v) oxygen in flue gas outlet $V_{Flue\ gas}$ = 4078.72 m³ hr⁻¹;
- Volume of measured excess Oxygen % (v/v) in flue gas outlet (O_2) outlet = 11.87 % (v/v);
- Volume of excess inlet air to increase flue gas to measured Oxygen % (v/v) concentration V_{inlet} = unknown
- Oxygen concentration in inlet air (O_2) inlet = 20.9% (v/v)

Using a back calculation formula, and numerous iterations using Solver formula equation in Microsoft Excel, the volume of excess air added to the landfill flare burner system is V_{inlet} = 5361.51 m³ hr⁻¹ which equates to a total excess Oxygen volume (O_2) volume = 1120.55m³ hr⁻¹. Based on this, the calculated total volume of flue gas from the landfill flare would be 9440.229 m³ hr⁻¹.

The following simple equation illustrates validation of the assumptions used and calculated:

$$\%O_{2Outlet} = (\frac{O_{2volume}}{V_{Fluegas} + V_{inlet}}) \times 100 \text{ (Eqn 8.3.4)}$$

Referring back to *Equation 8.3.1*, the percentage proportion of excess air can then be calculated as below:

$$\left(\frac{5361.51}{4078.72} = \frac{11.87}{20.9 - 11.87}\right) \times 100 \textbf{ (Eqn 8.3.5)}$$

Therefore the percentage proportion of excess air over required fuel air is 131%. *Equation 8.3.5* could also be used to calculate the volume of excess air.

Since the volume of excess air into the landfill flare burner is known, then the ratio of overall intake air over intake landfill gas can be calculated:

$$Ratio_{air} = \frac{770 m^3 hr^{-1}}{9440.229} \textbf{ (Eqn 8.3.6)}$$

Therefore Ratio $_{air}$ = 12.26 which can be expressed as **1:12.26**. This is a common occurrence in landfill flare burners although a value closer to 9 is more frequent.

For oxygen correction, the following calculation can be performed:

$$C_r = C_m \times \frac{(20.9 - (O_2)_r)}{(20.9 - (O_2)_m)} \textbf{ (Eqn 8.3.7)}$$

Where: C_r = referenced concentration;
C_m = measured concentration;
$(O_2)_r$ = reference oxygen concentration (5% (v/v) for Landfill flare burners);
$(O_2)_m$ = measured oxygen concentration in flue gas (10.78% (v/v).

Hence the equation can be written as follows:

$$C_r = C_m \times \frac{15.9\%}{11.87\%} = C_r = C_m \times 1.33 \textbf{ (Eqn 8.3.8)}$$

For a CO concentration of 6.25 mg m^{-3} then the oxygen corrected value (5% (v/v)) would be as follows:

$$C_r = 6.25 \times 1.33 = \textbf{8.31 mg m}^{-3} \textbf{ at referenced to 5\% oxygen (v/v) dry gas.}$$

8.4 Graphical illustration of resident locations in relation to flare burners