Characterization of Emissions from a 26 kW_e Micro Turbine Fired with Landfill Gas

Shepard Landfill
Calgary, Alberta

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1. INTRODUCTION

The Kyoto Protocol encourages the reduction of emissions of greenhouse gases. Landfill gas, a product of the decomposition of organic waste in landfills, is roughly 50% methane. Methane is a potent greenhouse gas having 21 times the global warming potential of carbon dioxide. In Canada, six million tonnes of carbon dioxide equivalent is being reduced annually through the combustion of landfill gas. The potential exists to double this capture rate.

While the combustion of landfill gas greatly reduces the impact of greenhouse gases, landfill gas contains numerous aliphatic, aromatic and halogenated compounds. These volatile organic compounds (VOCs) are present in the order of a few hundred parts per million (ppm) and are major precursors for smog formation while Freons are known ozone-depleting substances. Volatile organic compounds also contain vinyl chloride and 1,3-butadiene, which are known carcinogens.

The effectiveness of flares, engines, boilers and micro turbines in the destruction of non-methane components of landfill gas has only been studied in a preliminary fashion in Canada. As a result, a joint program was initiated among the Waste Prevention Division (NOPP), landfill operators/developers and ERMD. The objective of this program is to evaluate the effectiveness of landfill gas combustors for the destruction of VOCs and the potential formation of significant substances such as criteria air contaminants (NO_x, SO_2 and CO), polycyclic aromatic hydrocarbons (PAHs), dioxins and furans (PCDDs/PCDFs), hexachlorobenzene (HCB) and octachlorostyrene (OCS). Sampling also included measurement of particulate, hydrogen chloride (HCl) and hydrogen fluoride (HF) emissions.

The testing program has evaluated three types of landfill gas combustors; three engines, one enclosed flare and a boiler. This report documents testing at a micro turbine producing 26 kW_e operating at the Shepard landfill site in the City of Calgary, Alberta. In addition to this document, detailed reports are available for the testing of other landfill gas combustion sources described above.

The sampling level of effort at the micro turbine was pared down due to the difficulties associated with the sampling of a small and short stack. No sampling was completed for the determination of particulate and acid gases and the number of tests were reduced for the collection of semi-volatile organics (PCDDs/PCDFs, PAHs, HCB and OCS), VOCs and flue gases (NO_x, SO_2, CO, O_2). Co-planar PCBs or dioxin-like PCBs were added to the semi-volatile organic compound analyses.

2. SAMPLING SITE AND LOCATION

Located at the Shepard landfill site in the city of Calgary, a single 26 kW_e Capstone 330 micro turbine was setup to operate on conditioned landfill gas extracted from a series of drilled wells. All generated electricity from the unit was fed directly into the local electrical grid. At the time of testing no adjustments were made to the turbine operation.

The exhaust sample location was a single 0.5 inch threaded port located on the side of the turbine's six (6) inch exhaust stack. This point was approximately 18 to 20 inches above the exhaust exit of the turbine. The landfill gas inlet sample location was a 0.25 inch threaded port located upstream of the landfill gas conditioning system and far enough downstream of the wells convergence point to ensure thorough mixing of the landfill gas from each of the contributing wells.

3. SAMPLING METHODS

3.1 Landfill Gases

Landfill gas composition and inlet gas flow rate were measured using a Land Tec GEM 500. The unit, supplied by CH2M Hill, was calibrated to read both the gaseous composition and the inlet flow rate from the landfill.

3.2 Flue Gases

An integrated gaseous sample method was employed to collect a representative sample from the turbine exhaust stack. This was accomplished by drawing exhaust gas through a stainless steel probe located directly in the exhaust stream. A length of Teflon sample line joined the probe to an inline water trap, removing any condensate that may have formed from cooling. The sample gas was drawn through a stainless steel/Teflon head pump into a large volume aluminized Tedlar sample bag. A bag was collected at a sampling rate of 1.0 Lpm every 15 minutes (total 20 bags) and analyzed immediately with the Horiba PG-250. A schematic of the system is shown in Figure 1.

Each integrated sample was analyzed using the Horiba PG-250 portable combustion gas analyzer. The PG-250 measures target compound concentrations by: chemiluminescence (CLD) for NO_x, Non-dispersive infrared (NDIR) for CO, CO_2 and SO_2 and a zirconia detector cell for O_2. The analyzer was calibrated using two ranges of certified gas standards. Initial calibration was carried out prior to the commencement of sampling, once all sampling equipment had reached operating conditions and final calibration was performed at the end of sampling.

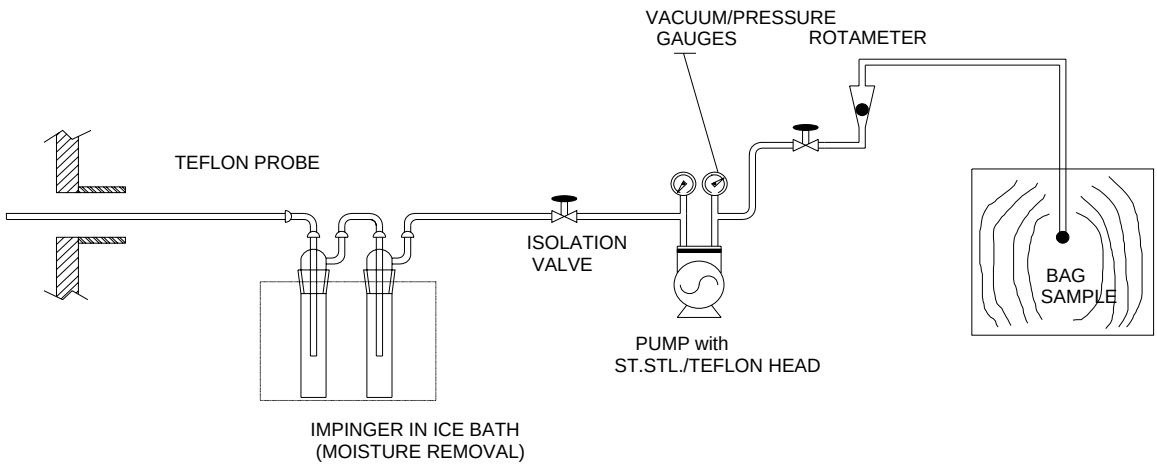

Figure 1 Flue Gas Monitoring System

3.3 Volatile Organic Compounds (VOCs)

VOCs are classified as organic compounds having a saturated vapour pressure greater than 10^{-1} mm Hg at 25°C. The collection method is based on the capture of a gaseous sample in a cleaned, verified and evacuated 3-liter stainless-steel canister. The canister's interior surface is coated with a pure chrome-nickel oxide making a stable, non-reactive sample collection and storage media for a variety of organic compounds.

A modified method TO-14 *(Compendium Method TO-14 Quality Assurance Division, Environmental Monitoring Systems Laboratory, U.S. EPA, May 1988)* was used as the basis for the VOC sampling train. The train consisted of a stainless steel probe followed by a Teflon sampling line, a condensate trap, a Teflon/stainless steel-coated pump, a mechanical flow controller and a canister. A schematic is shown in Figure 2.

Two canisters were collected simultaneously at the inlet and outlet for each of the three VOC runs. Three canisters were collected of the raw unprocessed inlet gases, while the other three sampled the combustion gases at the outlet of the turbine. The sampling duration for the VOC collection was approximately 40 minutes at a flow rate of 200 cc/min. The samples were collected into the evacuated canisters to a final pressure of approximately 20 psig. Following sample collection, the canister valve was closed and the canisters were properly documented and transported to the Analysis and Air Quality Division (AAQD) of Environment Canada for analysis.

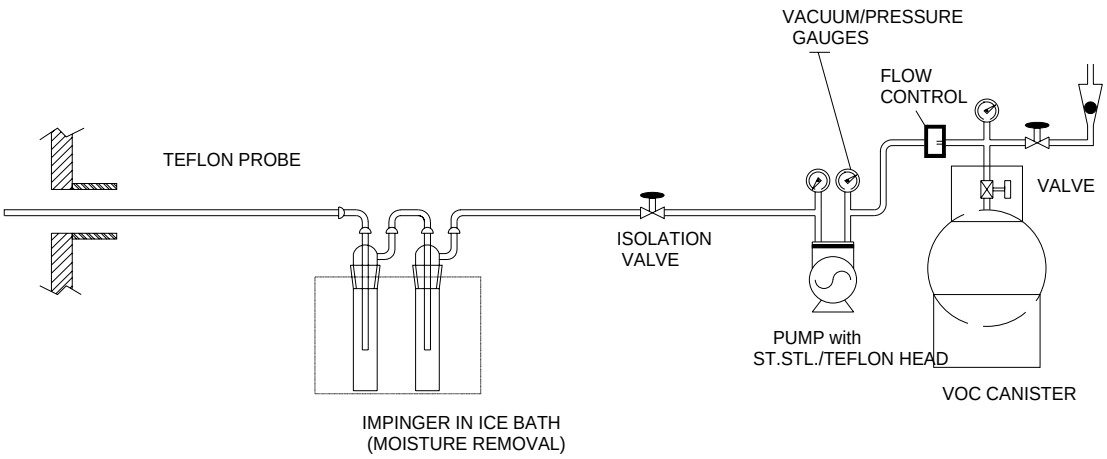

Figure 2 Volatile Organic Compounds Sampling Train

3.4 Semi-Volatile Organic Compounds (SVOCs)

For the collection of semi-volatile organic compounds (SVOCs), a modified train derived from the Environment Canada Reference Method EPS 1/RM/2 *"Reference Method for Source Testing: Measurement of Releases of Semi-volatile Organic Compounds from Stationary Sources"* was used to determine the emissions of PCDDs/PCDFs, co-planar PCBs, CBs, and PAHs from the turbines exhaust. Semi-volatile compounds have boiling points above 100°C. A schematic of the modified sampling train is shown in Figure 3. Note that no filter was used in the modified SVOC train.

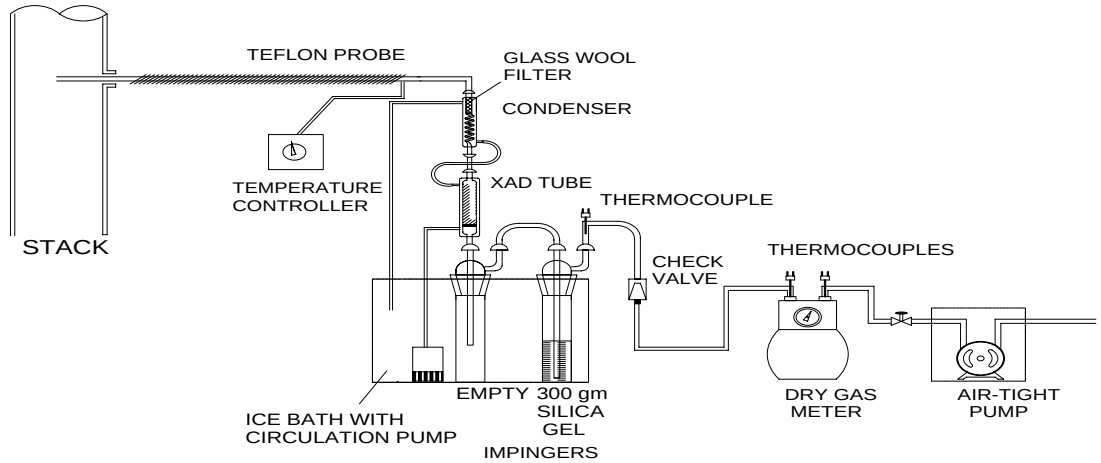

Figure 3 Modified Semi-volatile Organic Compounds Sampling Train

A sample of the exhaust was drawn through a stainless steel probe and then a Teflon-coated heated line, where the sample was trapped in a single adsorbent tube containing approximately 40 grams of Amberlite XAD-2 resin. A small vacuum pump was used to draw the exhaust sample through the train with the volume being measured and recorded on a dry gas meter. For optimal collection efficiency the temperature of the resin was kept below 20°C. The hot exhaust gases leaving the heated sample line were cooled by passing them through a condenser and the XAD-2 resin tube both cooled with ice water. Condensate formed in the cooling coil percolated through the resin bed and was collected in a condensate trap. To prevent photo degradation of the trapped organics the resin tube was covered with aluminium foil during sampling, as well as, during storage. All glassware joints were wrapped with Teflon tape for a positive seal, as vacuum greases are not permitted for organic sampling.

3.4.1 Glassware Cleaning and Proofing

Prior to the test program, all train glassware; probe brushes, glass wool and aluminium foil were cleaned following the rigorous procedure in Reference Method EPS 1/RM/2. The glassware cleaning procedures were verified by analyzing the proofing rinses of the sampling trains. The XAD-2 was pre-cleaned and analyzed for contamination prior to the survey. All reagents were distilled-in-glass grade. Details of the cleaning and proofing procedures are given in Report EPS 1/RM/2.

3.4.2 Sample Recovery

Following the completion of the run, the Amberlite resin tube was capped and re-wrapped in aluminium foil and was kept refrigerated following recovery. The sample was forwarded to the Analysis and Air Quality Division (AAQD) of Environment Canada for organic analysis.

4. QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

All sampling equipment was calibrated prior to sampling using accepted techniques. Items that were calibrated included:

- Dry Gas Meter (γ)
- Low Flow Controller (LFC)
- Barometers (P_{bar})
- Temperature Readers (T)

The dry gas was calibrated against a spirometer. Barometers were calibrated against a standard reference mercury barometer and thermocouple readers were calibrated using an ice bath and boiling water. The low flow controllers were calibrated using a certified Aalborg mass airflow sensor. The Horiba PG-250 combustion gas analyzer and back up analyzers were verified before the start of the program and daily during the sampling program with traceable certified calibration gas standards.

5. ANALYTICAL METHODS

5.1. Volatile Organic Compounds (VOCs)

The Air Toxics lab of AAQD analyzed VOCs. The canister samples were quantitatively analyzed by GC/MSD (Hewlett-Packard 5890 GC and 5971 MSD) using a cryogenic pre-concentration technique. One hundred and forty-five VOC species (from C_2 to C_{10}) were quantified in the samples. The VOCs were separated on a 50-meter HP-1 liquid phase, 0.31 mm fused silica capillary column with 1.0 µm film thickness.

5.2. Semi-volatile Organic Compounds (SVOCs)

Stack samples were analyzed by the AAQD at the Environmental Technology Centre for dioxins, furans, co-planar polychlorinated biphenyls, selected chlorobenzenes, octachlorostyrene and polycyclic aromatic hydrocarbons using HRGC/HRMS/MS. The recovered stack samples were spiked with surrogates to monitor recoveries followed by extraction by a mixture of 80:20 cyclohexane/toluene. Sample clean up followed to separate target from non-target species. A detailed summary of the analytical procedure for the determination of PCDDs/PCDFs, co-planar PCBs, CBs, OCS and PAHs is included in Appendix II.

6. RESULTS

6.1. General Sampling Data

The general sampling data for the turbine test program is presented below in Table 1. This table includes the average calculated (see Section 6.3) flow rate (referenced to 25°C and 101.3 kPa).

Table 1 Summary of General Sampling Data

Fuel to Micro Turbine		**Micro Turbine Exhaust**	
Fuel Type	LFG	**Flow Rate (m^3/min)***	8.94
$CH_4/CO_2/O_2$ Content (%)	58.6 / 35.3 / 0.7	**Temperature (°F)**	559
Landfill Gas in (CFM)	8.67	**O_2 (%, dry v/v)**	17.7
Power Output (kW)	25.5	**CO_2 (%, dry v/v)**	2.8

Sampling Summary			
Date	**7/27/2004**	**7/28/2004**	**7/29/2004**
Type	VOCs	Flue Gas	SVOC
Sample	3 canisters at inlet 3 canister at outlet	20 integrated bag samples at outlet	single run at outlet
Rate and/or volume collected	0.2 Lpm for 40 min	1.0 Lpm for 15 min	16.08 Lpm / 3.137 m^3
Sampling Times (local)	0900 - 1200	0925 - 1425	1300 - 1630
Test Duration	120 minutes	5 hours	3.25 hours

** calculated value*

6.2 Landfill Gas and Micro Turbine Exhaust

A summary of the measured concentrations for methane, oxygen and carbon dioxide in the unprocessed landfill gas are given in Table 2. These were based on the measurements conducted on July 27 and July 28.

Table 2 Summary of Average Inlet Gaseous Concentrations

CH_4 (%)	**CO_2 (%)**	**O_2 (%)**	**Balance* (%)**
58.6	35.3	0.7	5.4

** by difference*

Table 3 contains a summary of the measured flue gas concentrations from the 20 integrated bag samples for oxygen, carbon dioxide, carbon monoxide and nitrogen oxides from the exhaust of the turbine. Results are also corrected to 15% O_2. The individual readings for each run are detailed in Appendix I. No SO_2 emissions were observed in the exhaust.

Table 3 Summary of Gaseous Emissions

Compound	O_2 (%)	CO_2 (%)	CO (ppm)	NO_x (ppm)
At stack conditions	17.7	2.8	122.1	0.28
At 15% O_2	Not applicable	Not applicable	228.9	0.51

All values on a dry basis, v/v

6.3 Exhaust Flow Calculation

Due to the turbine layout an actual direct exhaust flow measurement was not attainable. With the data collected from both the turbine inlet and exhaust, flow determination was calculated by "F" factor as per the Environment Canada Report EPS 1/PG/7, "*Protocols and Performance Specifications for Continuous Monitoring of Gaseous Emissions from Thermal Power Generation.*"

Landfill Gas Parameters

Gross Heating Value of methane = 1013 BTU/ ft^3
Average methane content of landfill gas = 58.6%
Average inlet flow of landfill gas = 8.67 ft^3/min

Gross Heating Value

Gross Heating Value (BTU/ ft^3) of landfill gas:

$= 1013 \text{ BTU/ ft}^3 \times 0.586$
$= 593.618 \text{ BTU/ ft}^3 \text{ of LFG}$

Gross Heating Value (BTU/lb) of landfill gas:

$= [(593.618 \text{ BTU/ ft}^3 \times 379.483 \text{ ft}^3\text{/lb-mol})] / 26.67 \text{ lb/lb-mol}$
$= 8446.492 \text{ BTU/lb}$

Heat Input

Heat Input to Turbine (MMBTU/hr):

$= (8.67 \text{ ft}^3\text{/min} \times 60\text{min/hr}) \times (593.618 \text{ BTU/ ft}^3 \times \text{MMBTU}/10^6 \text{ BTU})$
$= 0.3088 \text{ MMbtu/hr}$

F-factor Determination

Customized "F" factor (ft^3/MMbtu):

$$F_d = 10\ [(K_{hd}\%H) + (K_c\%C) + (K_s\%S) + (K_n\%N) + (K_o\%O)]\ /GCV_d$$

% by weight LFG: C = 42.27%, H = 8.85%, O = 43.2%, N = 5.67%

= 9391.019 ft^3/MMBTU for stoichiometric combustion

Exhaust Flow Determination

Excess Air Factor Determination:

$= F_d \times (20.9/20.9\text{-}O_{2d})$
= 61335.1 ft^3/MMBTU

Flow of Turbine exhaust (dry):

= 61335.1 ft^3/MMBTU × 0.3088 MMBTU/hr
= 18940.3 ft^3/hr
= 8.939 m^3/min

6.4 Emission Rates

The CO and NO_x emissions in the exhaust were expressed in terms of the methane input to the turbine and the power output. The average flow of LFG to the turbine for each run ranged between 8 and 9 CFM. Methane concentration in the landfill gas ranged from 57.9% to 59.8 %. The methane flow was calculated based from the average flow of LFG and the average measured methane concentration. The electrical output was the average of all readings. CO and NO_x emissions in the exhaust are summarized below.

Table 4 Summary of CO and NO_x Emissions

Location	Output (kW)	Methane in (m^3/hr)	CO		NO_x*	
			(g/kW-hr)	(g/m^3 CH_4)	(g/kW-hr)	(g/m^3 CH_4)
Outlet	25.5	8.63	2.94	8.69	0.007	0.020

**expressed as NO_2*

6.5 Volatile Organic Compounds (VOCs)

Samples for VOCs were collected simultaneously from the unprocessed landfill gas inlet and the turbine exhaust for each of the three VOC runs. In total, six canister samples were submitted for VOC analysis. The determination of the VOC destruction efficiency (DE) was based on an average of the three canisters at each location. As illustrated in Table 5, the VOC variation at the outlet of the turbine was minimal, with some variation in the VOC inlet levels.

Table 5 Total VOC Concentrations (µg/m^3)

Location	Sample 1	Sample 2	Sample 3	Average
Inlet	455388	375896	371575	400953
Outlet	69.13	64.96	59.55	64.55

The full VOC target list contains 145 compounds; however this list was pared down as many of the species are of lesser interest. For this exercise, the reported VOCs include ODS (ozone depleting substances) such as Freons, BTEX (benzene, ethylbenzene, toluene and xylenes) and halogenated hydrocarbons. Halogenated hydrocarbons include vinyl chloride, dichloromethane, tri and tetrachloroethene, chlorobenzene and dichlorobenzene. Where applicable, compounds have been listed as Schedule 1 and CEPA-toxic. Naphthalene, a PAH compound was also included since it cannot be reliably determined using the modified Method 5 type train. The full list of VOC concentrations and emission rates for the inlet and outlet locations is given in Appendix II.

VOC destruction efficiencies (based on mass emissions) for selected compound groups are summarized in Table 6. Destruction efficiencies were calculated using the following equation:

$$DE = \frac{VOC_{inlet} - VOC_{outlet}}{VOC_{inlet}} \times 100$$

In general, the overall destruction efficiency for VOCs was very good. The destruction efficiency for all 145 VOCs was 99.4%. The selected VOCs listed in Table 6 represented 28 and 38% of the VOCs measured in the landfill gas and the turbine outlet respectively.

One Track 1 substance, hexachlorobutadiene, was not detected in the either the exhaust or landfill gas. Interestingly though, a few CEPA toxics were formed during the combustion process. These included; 1,3-butadiene, 1,2-dichloroethane and carbontetrachloride. In the case of carbontetrachloride as well as 1,2-dichloroethane, chlorobenzene and 1,3-dichlorobenzene, the formation across the micro turbine was mainly due to the background levels of these compounds in the ambient air used for the combustion. Most compounds, with the exception of five VOCs, had destruction efficiency greater than 90%, with the majority above 99%. The destruction efficiencies for these five ranged 9.67% for indane to 80.53% for chloromethane.

The two largest components in the landfill gas were propane and isobutene accounting for 26% of the total VOCs. The largest component in the turbine exhaust was propene accounting for 27% of the total. Propene along with six other compounds in the exhaust (propane, chloromethane, toluene, Freon 12, 1-butene/2-methylpropene and propyne) made up 71% of the total VOCs.

Table 6 Destruction Efficiencies of Selected VOCs (%)

Compound	Type	Inlet VOCs (ug/min)	Outlet VOCs (ug/min)	Destruction Efficiency (%)
Ozone Depleting Substances				
Freon 22 (Chlorodifluoromethane)	ODS	3654.23	1.85	99.95
Freon 12 (Dichlorodifluoromethane	ODS	1802.92	42.75	97.63
Freon 114 (1,2-Dichlortetrafluoroe	ODS	194.49	2.54	98.69
Freon 11 (Trichlorofluoromethane)	ODS	390.57	9.19	97.65
Freon 113 (1,1,2-Trichlorotrifluoro	ODS	11.13	3.31	70.26
	Total ODS	**6053.34**	**59.65**	**99.01**
BTEX				
Benzene	CEPA-toxic	242.14	14.25	94.11
Toluene		11221.12	45.42	99.60
Ethylbenzene		987.01	4.67	99.53
m,p-Xylene		2513.76	5.67	99.77
o-Xylene		693.86	1.29	99.81
	Total BTEX	**15657.89**	**71.30**	**99.54**
Halogenated Hydrocarbons				
Chloromethane		240.87	46.90	80.53
Vinylchloride (Chloroethene)	CEPA-toxic	779.76	4.03	99.48
1,3-Butadiene	CEPA-toxic	0.00	13.92	Formed
Chloroethane		656.07	0.42	99.94
1,1-Dichloroethene		28.96	0.76	97.38
Dichloromethane	CEPA-toxic	1934.22	10.23	99.47
t-1,2-Dichloroethene		25.15	0.91	96.38
1,1-Dichloroethane		212.00	0.00	100.00
c-1,2-Dichloroethene		805.81	0.79	99.90
Chloroform		4.17	0.13	97.00
1,2-Dichloroethane	CEPA-toxic	0.00	0.08	Formed*
1,1,1-Trichloroethane	CEPA-toxic	51.29	0.02	99.96
Carbontetrachloride	CEPA-toxic	0.00	1.25	Formed*
Dibromomethane		0.00	0.00	0.00
1,2-Dichloropropane		0.00	0.00	0.00
Trichloroethene	CEPA-toxic	412.58	1.35	99.67
Tetrachloroethene	CEPA-toxic	798.94	1.91	99.76
Chlorobenzene		0.00	0.04	Formed*
Benzyl Chloride		0.00	0.00	0.00
1,3-Dichlorobenzene		0.00	0.17	Formed*
1,4-Dichlorobenzene		0.86	0.27	68.09
1,2-Dichlorobenzene		0.57	0.00	100.00
1,2,4-Trichlorobenzene		2.58	0.00	100.00
Naphthalene	PAH	2.33	5.73	Formed
Hexachlorobutadiene	CEPA-toxic	0.00	0.00	0.00
	Total halogenated	**5956.17**	**88.91**	**98.51**
	Total (all of the above)	**27667.42**	**219.86**	**99.21**
	Total (all VOCs)	**98398.93**	**576.97**	**99.41**

"0" denotes not detectable, totals may not add due to rounding, significant digits ignored.
** formation due mainly to the presence of these compounds in the ambient air.*

Table 7 shows the individual destruction efficiencies for the three groups of selected VOCs and the emission rates based on power output and methane input.

Table 7 Summary of Destruction Efficiencies and VOC Emissions

Substance	Output (kW)	Methane in (m^3/hr)	DE (%)	VOC Emissions*	
				(mg/kW-hr)	(mg/m^3 CH_4)
Ozone Depleting Substances	25.5	8.63	99.01	0.14	0.41
Benzene, Toluene, Ethylbenzene, Xylenes			99.54	0.17	0.50
Halogenated Hydrocarbons*			98.51	0.21	0.62
Total all VOCs (145 compounds)			99.41	1.36	4.01

**excluding ozone depleting substances*

6.6 Dioxins and Furans/Co-planar PCBs

PCDD/PCDF data is reported on the basis of the seventeen 2,3,7,8-substituted dioxin and furan congeners. This data is further transformed by multiplying each of the 17 congeners by their respective toxicity equivalency factors (I-TEFs). The factors range from 1.0 for 2,3,7,8-TCDD to 0.001 for OCDD and OCDF. The sum of all the 17 factored compounds is known as the I-TEQ. More recently, analysis has included 12 co-planar PCB compounds. These congeners, which have dioxin-like properties have been assigned a toxicity equivalent factor (TEF) by the World Health Organization (WHO98-TEQ). In this study, only the I-TEQ emission results will be presented however, a separate table will be presented showing the levels of the co-planar PCBs without a toxicity equivalent correction. This has been done to avoid confusion between the two sets of toxicity equivalents. Analytical results of the loaded trains, blank train and control samples are presented in Appendix II.

The emission summary of the TEQ dioxins and furans for the turbine are given in Table 8. The samples are corrected for the blank and all concentrations are corrected to 11% O_2. Two congeners, 1,2,3,7,8-P5CDD and 2,3,7,8-T4CDF accounted for 97% of the total TEQ dioxins and furans emissions.

The concentrations of the 12 co-planar PCB congeners are given in Table 9. As noted earlier, the concentration values are not corrected for the toxicity equivalent. The sample was corrected for the blank. PCB-118 and PCB -105 were the two largest components accounting for 35 and 34%, respectively, of the total. The next abundant congener was PCB-77 at 17%. These three compounds accounted for 86% of the total co-planar PCB congeners.

Table 8 Concentrations and Emission Rates of Dioxins and Furans (Corrected to 11% oxygen)

Congener	Concentration (pg TEQ/m^3 @ 11% O_2)	Emission Rate (µg TEQ / year)
2378-T4CDD	0.000	0.000
12378-P5CDD	0.148	0.225
123478-H6CDD	0.000	0.000
123678-H6CDD	0.000	0.000
123789-H6CDD	0.000	0.000
1234678-H7CDD	0.009	0.013
OCDD	0.001	0.001
2378-T4CDF	0.138	0.210
12378-P5CDF	0.000	0.000
23478-P5CDF	0.000	0.000
123478-H6CDF	0.000	0.000
123678-H6CDF	0.000	0.000
234678-H6CDF	0.000	0.000
123789-H6CDF	0.000	0.000
1234678-H7CDF	0.001	0.001
1234789-H7CDF	0.000	0.000
OCDF	0.000	0.000
Total	0.297	0.450

Concentrations are expressed on a dry basis referenced to 25°C and 101.325 kPa and corrected to 11% O_2.
"0" denotes not detected.
Totals may not add due to rounding.

Table 9 Concentrations and Emission Rates Co-planar PCBs (Corrected to 11% oxygen) (Toxic Equivalent Factor not applied)

Compound/(IUPAC Number)	WHO98 TEF	Conc. (pg/m^3)	Emission Rate (ng/hr)
Non-ortho Polychlorinated Biphenyls (PCBs)			
3,3',4,4'-tetraCB (77)	0.0001	124.3	21.54
3,4,4',5-tetraCB (81)	0.0001	0.0	0.0
3,3',4,4'5-pentaCB (126)	0.1	5.2	0.91
3,3',4,4',5,5'-hexaCB (169)	0.01	2.3	0.39
Mono-ortho Polychlorinated Biphenyls (PCBs)			
2,3,3',4,4'-pentaCB (105)	0.0001	259.1	44.91
2,3,,4,4',5-pentaCB (114)	0.0005	16.4	2.84
2,3',4,4',5-pentaCB (118)	0.0001	267.0	46.28
2',3,4,4',5-pentaCB (123)	0.0001	43.6	7.56
2,3,3',4,4',5-hexaCB (156)	0.0005	22.4	3.88
2,3,3',4,4',5-hexaCB (157)	0.0005	4.8	0.84
2,3',4,4',5,5'-hexaCB (167)	0.00001	5.8	1.01
2,3,3',4,4',5,5'-heptaCB (189)	0.0001	1.2	0.21
	Total	752	130.36

All values are expressed on a dry basis referenced to 25°C and 101.325 kPa.
"0" denotes not detected.
Totals may not add due to rounding.
IUPCA-International Union of Pure and Applied Chemistry

6.7 Chlorobenzenes

The analysis of the modified SVOC train sample also included chlorobenzenes (CBs). Chlorobenzene compounds included 1,2,3,5-tetrachlorobenzene, 1,2,4,5-tetrachlorobenzene, 1,2,3,4-tetrachlorobenzene, pentachlorobenzene, hexachlorobenzene and octachlorostyrene. Concentrations for the six selected chlorobenzenes are summarized in Table 10.

Hexachlorobenzene represented the largest component of the reported chlorobenzenes at 77% followed by pentachlorobenzene, accounting for 23% of the total. Octachlorostyrene was not detected in the exhaust. Chlorobenzene concentrations are not corrected to 11% oxygen.

Table 10 Concentrations and Emission Rates of Chlorobenzenes

Compound	Concentration (ng/m^3)	Emission Rate (µg/hr)
1,2,3,5-Tetrachlorobenzene	0.049	0.026
1,2,4,5-Tetrachlorobenzene	0.000	0.000
1,2,3,4-Tetrachlorobenzene	0.000	0.000
Pentachlorobenzene	2.375	1.274
Hexachlorobenzene	7.995	4.288
Octachlorostyrene	0.000	0.000
Total selected CBs	10.419	5.588

Concentrations are expressed on a dry basis referenced to 25°C and 101.325 kPa.

6.8 Polycyclic Aromatic Hydrocarbons (PAHs)

PAH emissions are summarized in Tables 11 and 12. Train catches were corrected for the PAHs detected in the blank sample. A number of compounds were detected in the blank but many of these were at or slightly above the detection limit. PAH analytical results of the loaded trains, blank train, proofing and control samples are presented in Appendix II.

PAH concentrations and emission rates at the turbine exhaust are detailed in Table 11. These concentrations are not corrected to 11% oxygen. Phenanthrene was found to be the most abundant compound at 42% of the total PAH emissions with pyrene at 18% and fluoranthene at 11%.

A summary of the mass emission rates for PAHs in terms of power output and methane input for each SVOC run are summarized in Table 12.

Table 11 Concentrations and Emission Rates of PAHs

Compound	Concentration (ng/m^3)	Emission Rate (µg/hr)
Acenapthylene	0.22	0.12
Acenapthene	0.32	0.17
Fluorene	1.72	0.92
2-Methyl-Fluorene	1.02	0.55
Phenanthrene	10.20	5.47
Anthracene	0.38	0.21
Fluoranthene	2.61	1.40
Pyrene	4.40	2.36
Retene	1.31	0.70
Benzo(a)Fluorene	0.32	0.17
Benzo(b)Fluorene	0.00	0.00
1-Methyl-Pyrene	0.70	0.38
Benzo(g,h,i)Fluoranthene	0.00	0.00
Benzo(a)Anthracene	0.00	0.00
Chrysene	0.41	0.22
Triphenylene	0.41	0.22
7-Methyl-Benzo(a)Anthracene	0.00	0.00
Benzo(b)Fluoranthene	0.00	0.00
Benzo(k)Fluoranthene	0.00	0.00
Benzo(e)Pyrene	0.00	0.00
Benzo(a)Pyrene	0.00	0.00
Perylene	0.00	0.00
3-Methyl-Cholanthrene	0.00	0.00
Indeno(1,2,3-cd)Fluoranthene	0.00	0.00
Indeno(1,2,3-cd)Pyrene	0.00	0.00
Dibenzo(a,h)Anthracene	0.00	0.00
Benzo(b)Chrysene	0.00	0.00
Benzo(g,h,i)Perylene	0.00	0.00
Anthanthrene	0.00	0.00
Total	24.04	12.89

Values expressed on a dry basis at 25°C and 101.325 kPa.

Table 12 Summary of PAH Emission Rates

Location	Output (kW)	Methane in (m^3/hr)	PAHs	
			(µg/kW-hr)	(µg/m^3 CH_4)
Outlet	25.5	8.63	0.51	1.49

7. SUMMARY

Concentration and emission rate data is summarized in Table 13 below. No modifications were made to the turbine controls or the landfill gas condition system during the testing program. The emission rates of the various measured components are expressed in terms of power produced and methane input into the turbine.

Table 13 Summary of Exhaust Concentrations and Emission Rates

Component	Concentration	Emission Rate	
CO	122.1 ppm	2.94 (g/kW-hr)	8.69 (g/m^3 CH_4)
NO_x*	0.3 ppm	0.007 (g/kW-hr)	0.020 (g/m^3 CH_4)
SO_2	0 ppm	0 (g/kW-hr)	0 (g/m^3 CH_4)
VOCs	64.55 µg/m^3	1.36 (mg/kW-hr)	4.01 (mg/m^3 CH_4)
PAHs	24.04 µg/m^3	0.51 (µg/kW-hr)	1.49 (µg/m^3 CH_4)
PCDDs/PCDFs**	0.297 pg TEQ/m^3	0.45 µg TEQ/year	
Co-PCBs**	752 pg/m^3	1142 µg /year	
Chlorobenzenes	10.419 ng/m^3	48951 µg /year	

0 denotes not detected.
**as NO_2*
***at 11% oxygen*

The average destruction efficiency for the 145 VOC compounds was 99.4 % for the three sample runs. The destruction efficiency for the three selected groups of VOC compounds was 99.0% for the ozone depleting substances, 99.5% for the BTEX group and 98.5% for the halogenated hydrocarbon group.

While the parameters for the LFG and flue gas remained constant throughout the sampling period, the emissions reported above were based on a discrete set of samples. Emissions are representative of the micro turbine however they do not reflect any possible variations due to changes in the landfill gas composition or operation of the micro turbine that would be encountered over prolonged periods of operation.

APPENDIX I

- **SVOC Data**
- **Turbine Exhaust Readings**
- **Landfill Gas Analyses**

APPENDIX II

- **Dioxin, Furan, CB, PCB and PAH Analytical Report**
- **VOC Analysis**