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Flare Test Facility – Equipment and Calculations

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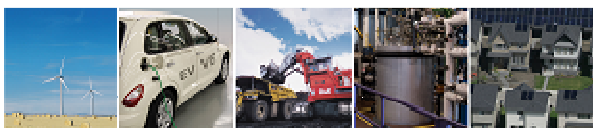
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TABLE OF CONTENTS

1.0	Introduction.....	1
2.0	The Air Supply, Cold Duct Section and Test Section	4
2.1	The Flare Pipe and Fuel System	6
2.2	Steam-assist Flare Tip.....	7
2.3	Steam Supply System	8
2.4	Pilot Burners	8
2.5	Gas Sampling.....	11
2.6	Particulate Sampling.....	16
2.7	Instrumentation	17
3.0	Testing of Sampling System.....	18
3.1	Bias Testing of Sampling System.....	18
4.0	Standard Procedure for Flare Start-up	20
5.0	Calculations.....	22
5.1	Calculation of Performance Measures	22
5.2	Analytical test cases for flaring calculations	23
5.3	Sensitivity of Calculations	25
5.4	Estimating Uncertainty	30
6.0	Conclusion	37
7.0	References.....	39
8.0	Appendix.....	40
A.	Imperial Figures and Graphs.....	41

B. Analyzer Descriptions and Specifications	43
C. Correlations.....	56

LIST OF FIGURES

Figure 1 - Schematic of Flare Test Facility.	4
Figure 2 - Photo of steam ring with pilot burners.....	9
Figure 3- Schematics of steam ring and pilot burners	10
Figure 4 – Steam ring and pilots in operation with ethylene fuel (10kg/h ethylene and 20 kg/h steam).....	11
Figure 5 – Photo of new sample conditioning system.	12
Figure 6 - Velocity profiles in stack at the sampling location.	13
Figure 7 - Concentration profiles for CO ₂ in stack, with the probe value indicated by the line.....	13
Figure 8 - Concentration profiles for CO in stack, with the probe value indicated by the line.....	14
Figure 9 - Concentration profiles for CH ₄ in the stack, with the probe value indicated by the line.....	14
Figure 10 - Division of stack cross-section for averaging point probe.....	16
Figure 11 - Uncertainty curves for carbon conversion efficiency (CCE).....	35
Figure 12 - Uncertainty curves for the destruction efficiency (DE).	36
Figure 7 - Concentration profiles for CO ₂ in stack, with the probe value indicated by the line.....	41
Figure 8 - Concentration profiles for CO in stack, with the probe value indicated by the line.....	41
Figure 9 - Concentration profiles for CH ₄ in the stack, with the probe value indicated by the line.....	42

LIST OF TABLES

Table 1 - Summary of results of segregation study showing averaging properties of the sample probe.	15
Table 2 - Bias test results with old and new conditioning unit in line.....	18
Table 3 - Results of bias testing of the new sample conditioning system with methane and propane span gas.	19
Table 4 - Sensitivity of main performance indicators to changes in input variables. Low dilution case with low wind and high fuel flow.....	27
Table 5 - Sensitivity of main performance indicators to changes in input variables. High dilution case with high wind and low fuel flow.....	29
Table 6 - Uncertainty values for measurements for estimation of uncertainty of CCE and DE.	34

NOMENCLATURE

α	The dimensionless value of the destruction efficiency as defined in equation 5-9
ε_{CH_4}	Error in stack methane concentration, ppm
ε_{CO}	Error in stack carbon monoxide concentration, ppm
$\varepsilon_{CO_2,in}$	Error in inlet carbon dioxide concentration, ppm
$\varepsilon_{CO_2,out}$	Error in stack carbon dioxide concentration, ppm
η	Carbon conversion efficiency.
σ_c	Reciprocal of increase of carbon in stack gas, summed over all species, equation (5-23), ppm ⁻¹ .
x	Number of moles of Oxygen used to calculate extent of the reaction (equation 5-10)
$x_{CO_2,f}^c$	Mole fraction of carbon in carbon dioxide in fuel.
$x_{CO_2,out}^c$	Mole fraction of carbon in carbon dioxide in stack gas.
$\{x_i\}_{allcompounds}$	Composition of gas, the mole fraction of all species.
BMS	Burner Management System
BTEX	Benzene, toluene, ethylbenzene, xylenes.
CB	Carbon Balance, %.
CCE	Carbon Conversion Efficiency, the mass percentage of carbon in the flare gas converted to carbon dioxide, %.

DE	Destruction Efficiency, the percentage of a species in the flare gas that is converted into any other species. $DE = 100\% - FS$.
FS	Fuel Slip, $=100\% - DE$.
FTF	Flare Test Facility
HRVOC	Highly reactive volatile organic compounds (eg. Ethylene, propylene, 1-butene, cis/trans-2-butene, 1,3-butadiene)
IFC	International Flaring Consortium
\dot{m}_a	Mass flow of air, kg/h.
\dot{m}_{bucket}	Mass flow of steam measured by the bucket, kg/h.
$\Delta\dot{m}^c_{CO}$	Net mass flow of carbon as carbon monoxide, kg/h.
$\Delta\dot{m}^c_{CO_2}$	Net mass flow of carbon as carbon dioxide, kg/h.
\dot{m}_f	Mass flow of fuel, kg/h.
$\Delta\dot{m}^c_{HC}$	Net mass flow of carbon as hydrocarbon, kg/h.
\dot{m}_{meter}	Mass flow of steam as measured by the steam flow meter, kg/h.
P	Pressure, kPa.
RH	% Relative Humidity
SDE	Specific Destruction Efficiency, %.
T	Temperature, °C.
X_i	Place holder variable for input value i .
$y_{CO_2,out}$	Mole fraction of carbon dioxide in stack gas, ppm

$y_{CO_2,in}$	Mole fraction of carbon dioxide in inlet air, ppm
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1.0 INTRODUCTION

Flares are the primary technology used for the safe and economical disposal of combustible gases at production sites and refineries. Flare performance and associated emissions are current environmental issues in some jurisdictions. This is partly because of genuine gaps in the flare research literature, as identified in a recent literature review (Gogolek et al., 2009). Also, there is confusion about the applicability of some published results to industrial scale flares. The literature review provides some structure and clarity regarding applicability of the various published data. Firstly, we distinguish the jetting and wake-stabilized regimes as distinct limiting modes of operation for flares. The research results from one regime may not be applicable to flares operating in other regimes. For example, the continuous decrease of efficiency with increasing cross-wind speed, which is well-established for the wake-stabilized production flares, may not apply to jetting refinery flares. Secondly, there is a minimum flare pipe size, around 7.5 cm (3 inches), for results to be scalable to industrial-scale flares. This means that some results in the literature are not representative of full-scale operating flares.

The International Flaring Consortium (IFC) was formed to review and address crucial gaps in the science of flares. The first objective of the IFC is to produce a method of predicting flare efficiency from operating variables: flare gas composition and flow rate; steam-assist rate; and wind speed. The method developed will rely upon original experimental work as well as published data. The second objective is to measure the emissions of: NO_x ; the most important HRVOCs (ethylene, propylene, 1-3 butadiene, and the butenes) and BTEX (benzene, toluene, ethylbenzene, and the xylenes); and to attempt to predict emission factors for these species based on the same set of operating variables. The third objective is to identify optimal operating conditions and identify the operating envelope for flares.

Based upon the literature review, the following six areas of flare performance need to be addressed:

1. Experimental studies of the flare efficiency in the transition between jetting and wake-stabilized regimes.

2. Experimental studies of the effect of wind on steam-assisted flares.
3. Experimental studies on the limiting hydrogen concentration for steam-assisted flares, pilots, and wind blown flares.
4. Experimental studies of HRVOC and NO_x emissions, with and without steam-assist.
5. Correlation of flare efficiency with fuel properties and flare gas composition, particularly the inert gases nitrogen and carbon dioxide, and the impact of hydrogen.
6. Correlation of flare efficiency with steam-assist rate that considers flare gas composition, perhaps unifying steam with the approach used for correlating the effect of nitrogen and carbon dioxide dilution.

These are specific research areas that formed the general objectives of the IFC.

This report describes the experimental equipment and methods used in the program of the IFC. The experiments are conducted at the Flare Test Facility of CanmetENERGY at Bells Corners in Ottawa. This facility is a single-pass wind tunnel originally constructed for testing full-sized solution gas flares (10 cm and 15 cm) firing mixtures of natural gas and propane. Its capabilities have been expanded to fire different gases, and to provide steam-assist and pilots. The high-precision GC-based analysers for HRVOCs and BTEX are described in a separate report (Caravaggio and Caverly, 2008).

Note on terminology: We use the following definitions of performance measures.

- **Carbon Conversion Efficiency (CCE):** = the conversion of fuel-bound carbon to carbon dioxide, expressed as a percentage of the mass of carbon as carbon dioxide in the stack gas relative to mass of fuel-bound carbon.
- **Carbon Conversion Inefficiency (CCI):** = the failure to convert fuel-bound carbon to carbon dioxide, $CCI = 100\% - CCE$.
- **Fuel Slip (FS):** = percentage of mass of carbon as original fuel species in stack gas relative to the mass of fuel-bound carbon.

- **Destruction Efficiency (DE)**:= the destruction of a particular combustible species, expressed as percentage of 100% minus the mass of carbon of the combustible species in the stack gas relative to the mass of fuel-bound carbon of that combustible species. For a single hydrocarbon species, $DE = 100\% - FS$.

2.0 THE AIR SUPPLY, COLD DUCT SECTION AND TEST SECTION

The flare test facility is shown schematically in Fig. 1. The combustion air is provided by a tubular acoustofoil fan with a rating of 1416 m³/min at 15.2cm WC (50,000 cfm at 6".WC). Its inlet is equipped with a silencer and it is powered by a 56 kW (75 hp) electric motor with a variable frequency drive. The fan is located outside the building, sheltered from the weather by a tent. The cold duct section, 1.2 m wide and 1.8 m high (4 ft wide and 6 ft high) leads from the fan through the building wall to the upstream end of the test section. This section has a series of narrow gage wire mesh screens to flatten the velocity profile and dampen flow turbulence from the fan.

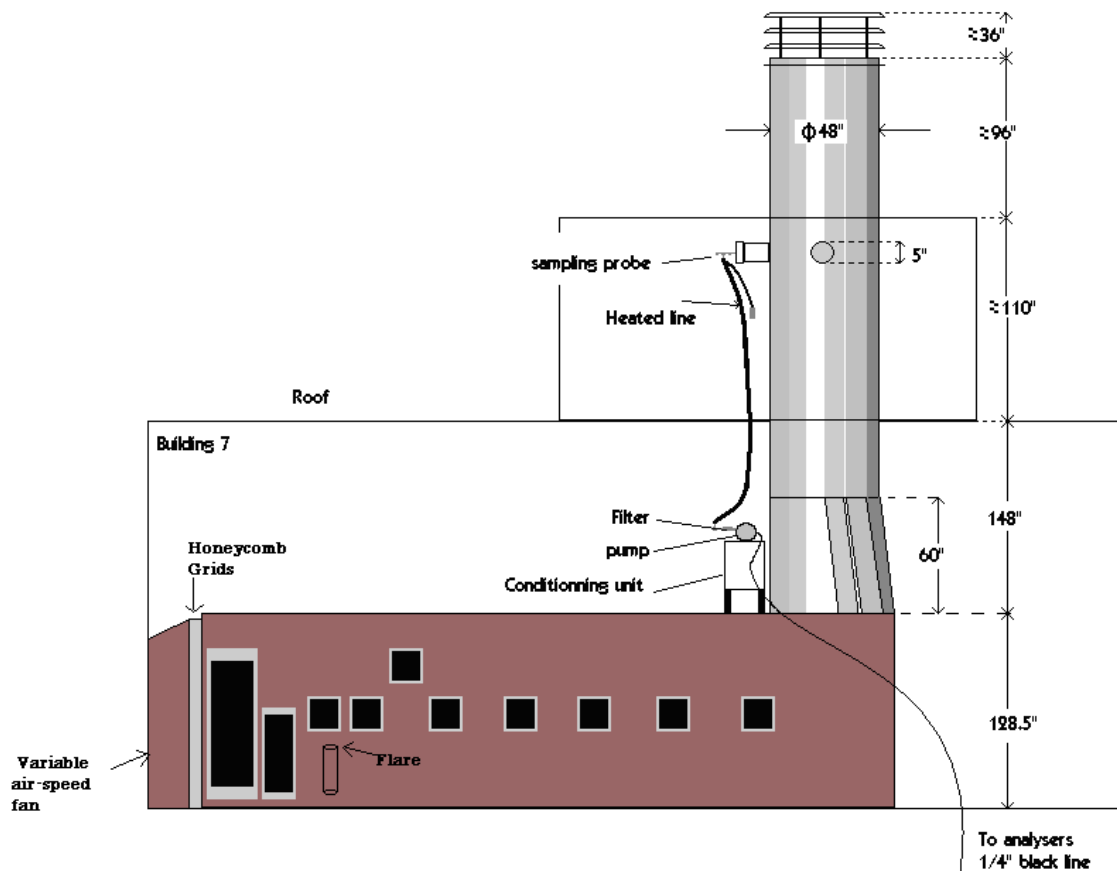


Figure 1 - Schematic of Flare Test Facility.

The airflow measuring station (AFMS) is a fixed array of 56 static and total pressure ports. The array covers the cross-section of the air duct. The average of the pressure measurements is fed to a pressure transmitter with readout in kg/h. Combustion airflow is corrected for barometric pressure, temperature and relative humidity. The temperature is determined by a thermocouple array in the measuring grid. The relative humidity is measured at a local weather station.

Inside dimensions of the test section are 3m high, 1.2m wide and 8.2 m long (10 ft high, 4 ft wide and 27 ft long). At the upstream end is a final flow straightener consisting of a metal honeycomb section 7.6 cm (3") thick. The cold duct from the fan expands to the full size of the flow straightener, but within the expansion an adjustable plate confines the airflow to whatever ceiling height prevails in the test section.

The test section itself has an adjustable ceiling. Channels to support the ceiling along each side of the test section are located at heights of 1.5, 1.8, 2.1 and 2.6 m (5, 6, 7 and 8.5 ft) from the floor. Four modules comprise the ceiling; each is 119cm (47") wide, 140cm (55") long and 7.6 cm (3") thick. The sidewalls, floor and rear end wall of the test section are double-walled, the inner walls being of Type 304 stainless steel, the outer walls of carbon steel. The hollow walls and floor accommodate cooling air, and the ceiling modules are likewise air-cooled, by means of flexible ducting. The floor has four parallel longitudinal cooling passages, with air entering at the rear and discharging sideways at the front. Each sidewall has four cooling sections, each having four passes, with air entering from the top and discharging from the bottom. The ceiling modules also have four passes of cooling air. A blower rated at 340 m³/min at 25.4 cm WC (12,000 cfm at 10 in. WC), is located on the roof of the building, providing the cooling air. Cooling the walls reduces back radiation to the flame, which could artificially stabilize combustion.

An access door into the test section is located next to the flow straightener. In it is a window almost the full size of the door. There are nine other windows of varying size along the accessible side of the test section, plus two windows in the rear wall, under the transition to the stack, plus four windows in the roof above the flare pipe. Thus, the flare pipe and flare flame can be viewed and photographed from several angles. Each window

has two layers: high-temperature tempered glass on the inside and scratch-resistant Lexan on the outside.

There are eight sampling ports in the sidewall of the test section; three are at 1.2 m another three are at 3 m and two more are at 4.3 m (4 ft, 10 ft, and 14 ft respectively) all located downstream from the flare pipe. There are also two ports in the rear wall and three ports at two levels in the stack. The ports are all 5.1 cm or 10.2 cm (2" or 4") pipe.

A stack, fabricated from Type 304 stainless steel, 1.2 m (4 ft) in diameter and 7.3 m (24 ft) tall, is connected to the downstream end of the test section by a transition section 1.5 m (5 ft) long, also made of Type 304 stainless steel. At the stack outlet is a perforated plate with 51 % opening, above that are a weather cap and two tiers of rain gussets. All these combine to reduce chimney effect and wind effects on draft, and thus improve uniformity of flow in the stack. The cap and rain gussets also serve to keep precipitation out of the stack. An access slot has been provided between the transition section and the base of the stack, by means of which screens or baffles can be inserted, if required, to accomplish more uniform flow in the stack. The primary sampling point is in the stack, 3.7 m (12 ft) above the end of the transition section.

2.1 The Flare Pipe and Fuel System

The flare pipe was located on the centerline of the test section, 2.4 m (8 ft) downstream from the flow straightener. The unassisted flare tips are called "basic pipe". Basic pipe flare tips were made from nominal 2.5 cm to 15.2 cm (1" to 6") diameter Schedule 40 carbon steel pipe. These were fitted to a 5.1 cm (2") threaded coupling in the floor. This coupling comprises the terminal of the fuel supply system.

The main test fuels are natural gas, propane, ethylene, and propylene. Two lines are used for the fuel gases. One line is dedicated to natural gas. The other line is used for one of propane, propylene, or ethylene. There is a third line for carbon dioxide or nitrogen. Propane is supplied in liquid form from a 3785 L (1000 gallon) storage tank through a train which includes a vaporiser, pressure control valve, flow control valve, and a mass flow meter with safety shutoff features. Natural gas comes from the utility mains and flows through a similar train. The compositions of the local natural gas and propane are

given in Table A-1. The propylene and ethylene were supplied from 8 gas cylinders coupled with a manifold equipped with a two-stage pressure regulator. The ethylene manifold and regulator were wrapped with electrical heating tape to protect the piping from the cooling due to the expansion of the ethylene.

The two trains feed into a common 3.8 cm (1.5") pipe, from which a 1.9 cm (0.75") line branches off through a further flow control train to supply the flare igniter. The igniter is fully retractable. The main 3.8 cm (1.5") flare gas line continues through another train measuring and controlling flow and runs 4 m (13 ft) to the coupling where the flare pipe is connected. The flare gas temperature is measured with a K-type thermocouple. Each line has a thermal mass flow meter calibrated for the specific gas. Table A 2 has the correction factors (K values) supplied by the vendor to be applied the flow meter reading when flowing propane, ethylene or propylene.

Carbon dioxide or nitrogen joins the main flare gas line just downstream from its final flow control train. There is a mass flow meter and flow control valve for the diluent gas. The flow meter specifications are given in Table A 3.

2.2 Steam-assist Flare Tip

The steam-assist flare tip comprises the flare pipe, the steam manifold and nozzles, and the pilot burners.

The flare tip used with steam assist is Nominal 7.6 cm (3"), Schedule 80 stainless steel, with a Flare Retention Ring (FRR). The FRR is composed of a number of s-shaped tabs welded inside the pipe. It is a common appurtenance in industrial flares. The open area of the pipe with the FRR is equivalent to a 5.1 cm (2") pipe (21.7 cm^2 or 3.36 in^2). In this case, the tip with the FRR will consume less gas for a given exit velocity. This configuration is more representative of the actual operating equipment than a simple pipe. This tip was also run unassisted, without the steam manifold in place. A Nominal 15.2 cm (6"), Schedule 80, stainless steel pipe with a FRR was also used for some unassisted tests. It is a direct two times scale-up of the 7.6 cm (3") tip and has open area equivalent to a 10.2 cm (4") pipe (81.1 cm^2 or 12.73 in^2).

The assist steam is provided through 12 nozzles, mounted on risers attached to a single manifold. The risers are in groups of four equally spaced around the circumference. The three gaps allow the placement of the pilot burners at the top of the flare pipe. The nozzles inject the steam at the top of the flare pipe. There are two nozzle openings; one large, one small.

2.3 Steam Supply System

The steam is generated by an electric boiler, rated to 50 kg/h (110 lb/h) at 100 psig saturated steam. It is delivered in 1/2" pipe. The flow is controlled by a flow control valve and measured with a mass flow meter. It passes through a superheater (Chromalox MTX-250A, 5 kW (6.7 hp)) to give a temperature boost to minimize condensation in the steam manifold and risers, particularly during the cold winter months. Condensation would produce droplets that intermittently plug the steam nozzles and degrade flare performance. There are three steam traps, with one placed as the steam line enters the wind tunnel. The steam pipe enters the wind tunnel through the wall near the floor, 0.3 m (1 ft) downwind of the flare pipe. It is insulated inside the wind tunnel, from the wall to the manifold.

2.4 Pilot Burners

The pilot burners have three heads off a ring manifold as shown in Figure 2.



Figure 2 - Photo of steam ring with pilot burners

They are evenly spaced around the perimeter of the flare pipe, one burner directly upwind of the flare pipe, the remaining two downstream as seen in Figure 3.

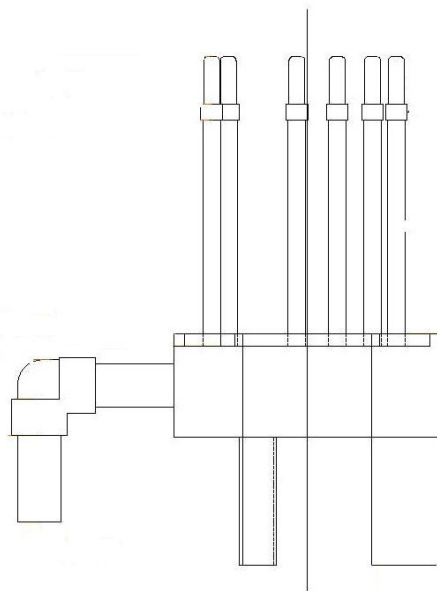
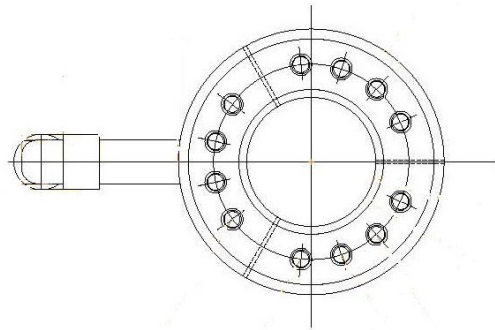


Figure 3- Schematics of steam ring and pilot burners

The pilot burner heads are modified commercial propane torch heads. The total heat input from the pilot burners is 5.3 MJ/h (5000 Btu/h). The fuel is entrained via an eductor operating with compressed air and the air orifice is designed to provide air at approximately a stoichiometric combustion ratio. A flow control valve controls the fuel flow to the eductor. There is a flow meter for the fuel to the pilot burners, and this flow is continuously recorded by computer. The burners receive a controlled stoichiometric air-fuel mixture. The pilot burner and steam ring in operation can be seen in Figure 4.

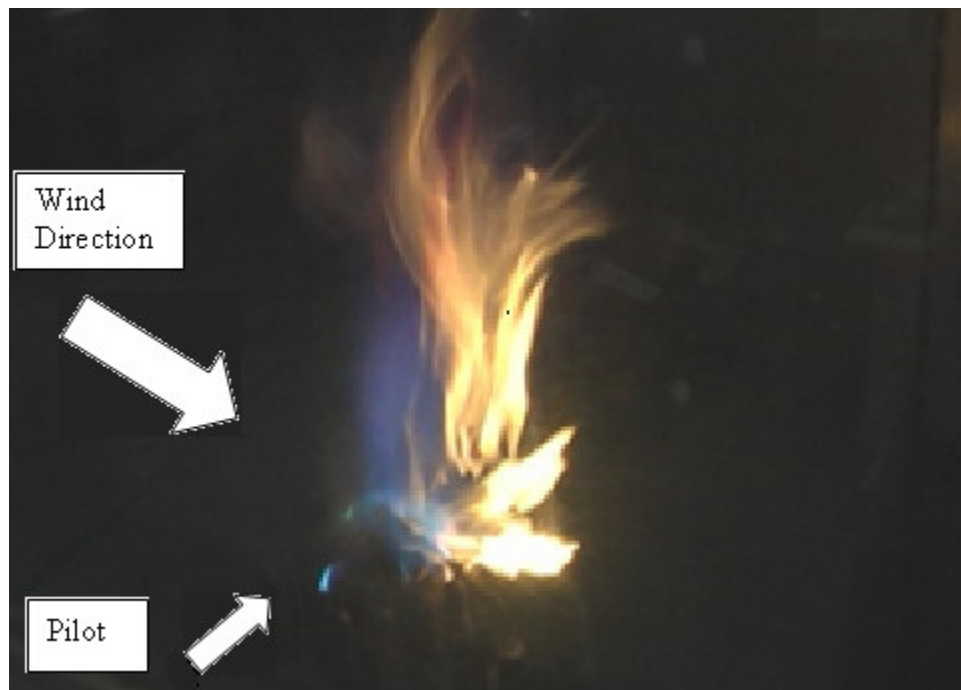


Figure 4 – Steam ring and pilots in operation with ethylene fuel (10kg/h ethylene and 20 kg/h steam).

2.5 Gas Sampling

The gas sampling probe consists of a sintered stainless steel tube, 2.5 cm (1") diameter and 18 in. long, that has been installed in the stack, three diameters (3.7 m or 12 ft) from the last disturbance, i.e., from the end of the transition section. By means of a heated-head pump, this probe extracts a sample from a 45.7 cm (18")-long strip across the centreline of the stack and passes it through a heat-traced sample line (Teflon™ 0.64 cm diameter (0.25 inch), 15.2 m (50 ft.) long) to a conditioning system that removes moisture

and particulates. The specifications for the conditioning system can be found in section A-9 and Figure 5 is a photo of the system.



Figure 5 – Photo of new sample conditioning system.

The clean, dry sample is then passed to the analysers which are described in section 2.7.

The sample probe filters particulate matter from the gas stream. It also provides an average sample from the stack, reducing the effect of segregation. A segregation study of the stack was performed. Figure 6 shows the vertical velocity profile measured with a pitot-probe. Figures 7, 8 and 9 show the concentration profiles for CO_2 , CO and CH_4 .

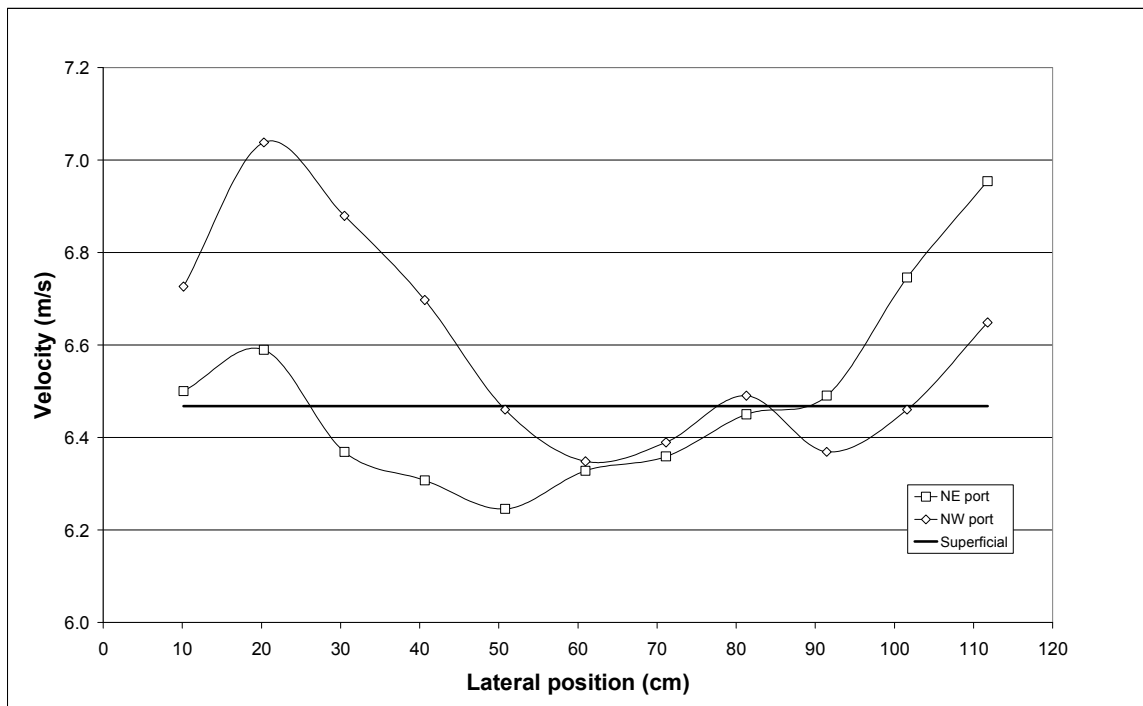


Figure 6 - Velocity profiles in stack at the sampling location.

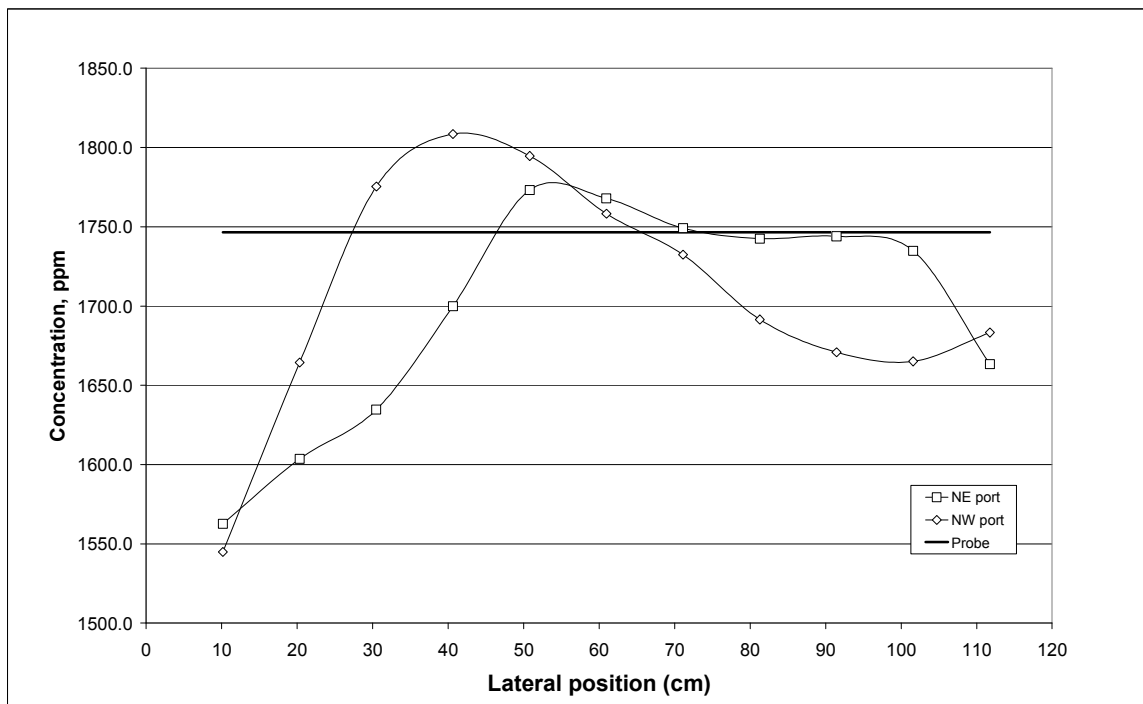


Figure 7 - Concentration profiles for CO₂ in stack, with the probe value indicated by the line.

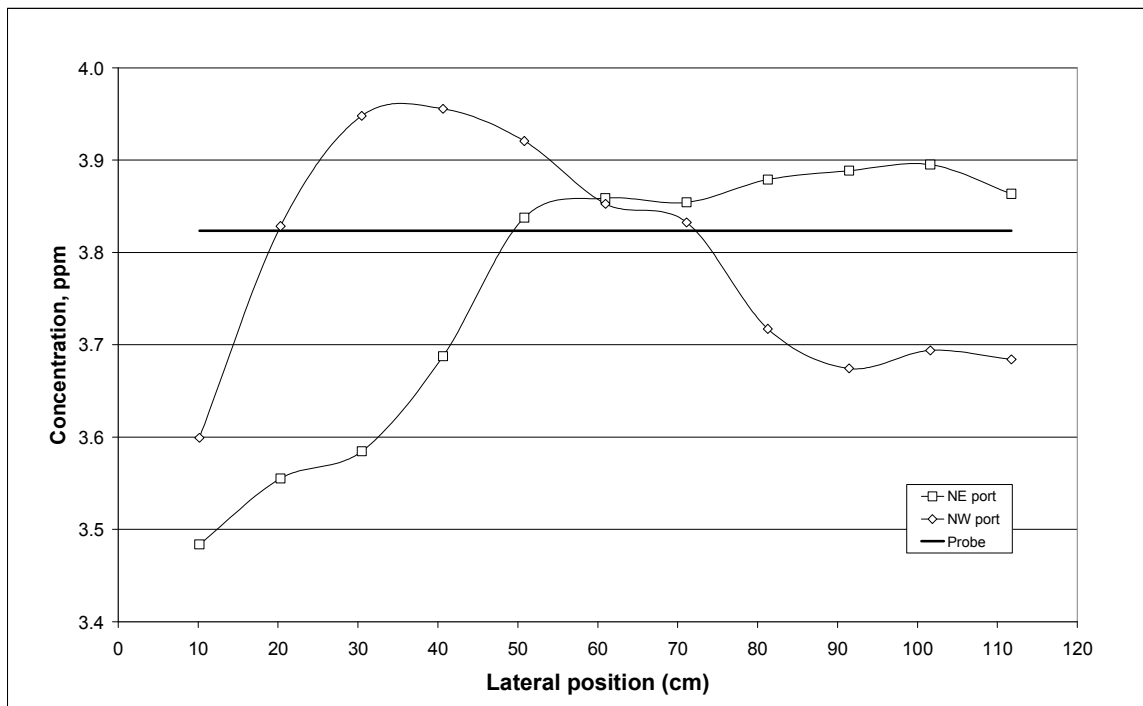


Figure 8 - Concentration profiles for CO in stack, with the probe value indicated by the line.

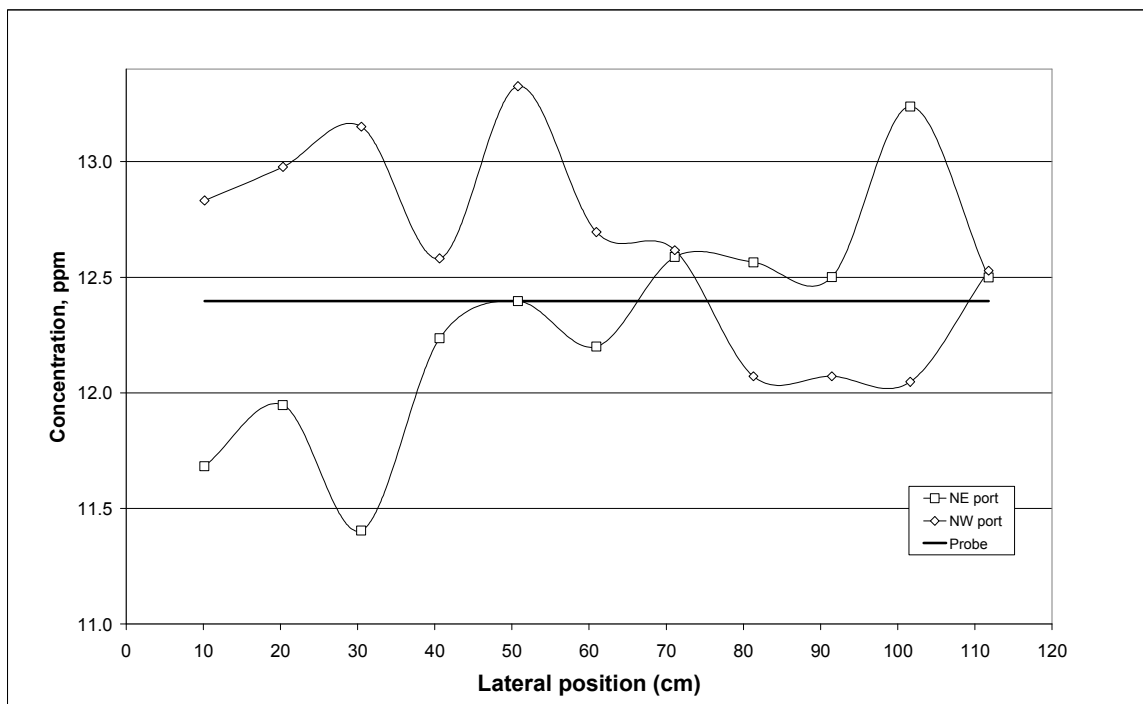


Figure 9 - Concentration profiles for CH₄ in the stack, with the probe value indicated by the line.

The traverses were performed through the two sampling ports in the stack, at 10.2 cm (4 inch) intervals. The gas was sampled through a stainless-steel goose-neck probe. The conditions for the test were: 10 kg/h (22 lb/h) natural gas to the flare and 453 m³/min (16000 cfm) air flow. The air flow translates into a superficial velocity of 6.5 m/s (21 ft/s) in the stack. The results of the study are summarized in Table 1.

Table 1 - Summary of results of segregation study showing averaging properties of the sample probe.

	Velocity	Velocity	CO ₂	CO	CH ₄
	m/s	ft/s	ppm	ppm	ppm
Average	6.61	21.69	1663	3.73	12.43
Probe/Superficial	6.47	21.23	1747	3.82	12.40
Difference	-0.14	-0.46	83.22	0.10	-0.04
% Deviation	2.19	2.19	4.76	2.52	-0.28

The averages are calculated using annular slices shown in Figure 10. Each slice is assumed to have the flow of the value of point sample it contains. The average velocity using the point samples is thus the sum of the point velocity multiplied by the slice area divided by the total area. The average velocity compares well with the superficial velocity calculated from the volumetric flow of air. The average concentrations are weighted using the volumetric flow at each sample point. The averages are compared to the value measured by the probe, using the arithmetic average of the central traverse points on the NE port (Fig 10) that cover the probe.

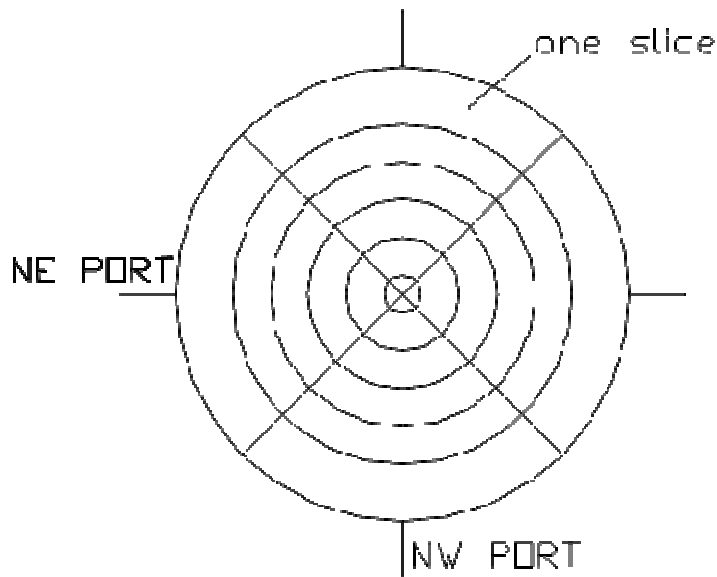


Figure 10 - Division of stack cross-section for averaging point probe.

The carbon dioxide concentration showed the largest difference between the traverse and the probe, but the deviation was still less than 5%.

2.6 Particulate Sampling

A particulate sample is drawn isokinetically from the same sampling location from where the gas sample is drawn. This means gas sampling is interrupted while a particulate sample is being taken. The probe is a gooseneck suction probe, the tip of which can be changed, depending on the gas suction velocity required at the tip. The probe is operated at a suction rate that provides an isokinetic sample. The velocity is determined by a pitot-tube measurement. The suction is controlled by a constant volume vacuum pump. The sample is drawn through a glass-fibre filter, 47 mm (1.9") in diameter, supported on a stainless steel mesh. The predetermined volume of gas is drawn through the filter which has a pore size of $1\ \mu\text{m}$. The filter is weighed before and after sampling. The weigh scale has 0.0001 g (0.000004 oz) precision. The sampling rate matches the velocity of the gas in the stack. The sampling time is calculated for given air flow and fuel supply rate such that a 0.1% conversion of fuel-carbon to particulate matter would produce 1 mg (0.00004 oz) mass capture on the filter paper. This gives ten times the minimum reading on the scale with this low conversion. If more soot is produced, the sample size will be

correspondingly larger. Samples were weighed immediately after collection, and not dried.

2.7 Instrumentation

The test section is fitted with numerous thermocouples to measure temperature of the inner skin of the enclosure, and temperature of the cooling air. These values are continuously recorded by an automated data logging system. Temperature and flow from the combustion air fan are also logged continuously. Likewise monitored are temperature, pressure, relative humidity and flow rate of the fuel gas and dilution gases. The facility is equipped with a Burner Management System (BMS) to control the air and fuel flows, and maintains safe operations of the system through the flame scanner and automatic shutdown.

The data acquisition system is a National Instruments SCXI 1100, with LabView software running on a PC. The calibration data and run data are logged to a file at 8 second intervals.

Continuous gas analysis is provided by infrared analysers for CO₂, CO, and SO₂, a paramagnetic analyzer for O₂, and a chemiluminescence analyzer for NO_x. There are two analyzers each for CO₂ and CO, with one set having very low ranges (0 to 500 ppm for CO₂, 0 to 50 ppm for CO). Unburned hydrocarbons are determined by FID gas chromatography. The full descriptions of the analysers are given in the appendix sections A-4 to A-7. All the foregoing analyser outputs are recorded by the data acquisition system. The two GC-based analysers use column separation for HRVOCs and BTEX compounds are described in a separate report (Caravaggio and Caverly, 2008). The specifications of the GCs are listed in A-8.

3.0 TESTING OF SAMPLING SYSTEM

3.1 Bias Testing of Sampling System

Bias testing involves putting standard gas through the sampling system to verify that the analysers achieve the same readings. The gas conditioning system was changed during the testing. The first system, a chiller, was failing and caused problems closing the carbon balance. It was replaced with the Nafion membrane based system. The results of the bias testing of the two systems are shown in Table 2.

Table 2 - Bias test results with old and new conditioning unit in line.

	CO ₂	CO
Bottle Concentration, ppm	2540	39.6
Old Conditioning Unit, Reading, ppm	2042	30.7
Deviation, %	-19.6	-22.4
New Conditioning Unit, ppm	2579	40.2
Deviation, %	1.5	1.4

There is a loss of 20% of the carbon dioxide and carbon monoxide when using the old conditioning unit. This is sufficient to account for the problem with the carbon balance. It indicates also that tests with the old gas conditioning unit should have significant deficit in the carbon balance.

The slight elevation in the reading for the new unit can be attributed to the slightly elevated pressure in the sample line from the compressed gas cylinder. Exact matching of the pressures in the line was difficult to obtain.

The new sample conditioning unit was also tested with the hydrocarbon span gas. The methane/nonmethane hydrocarbon analyser is self-calibrating. It accepts a deviation of 5% on the span before it re-calibrates. Therefore, these readings show that there is accurate measurement with respect to hydrocarbons with the new conditioning system.

Table 3 - Results of bias testing of the new sample conditioning system with methane and propane span gas.

	CH ₄	C ₃ H ₈
Bottle Concentration, ppm	20.5	9.9
New Conditioning Unit, ppm	20.3	9.6
Deviation, %	-0.8	-3.4

4.0 STANDARD PROCEDURE FOR FLARE START-UP

Each analyser is given a zero (N₂) and span (full-scale) twice except for the hydrocarbon analyser which has its own calibration and will recalibrate itself until the % error is less than 2%. The zero and span are left running through the analysers until they settle out and are then corrected to either the span gas or zeroed if necessary. The analysers were also put through a zero and span at the end of the day, but no drift was detected. So this practice was stopped. Typically it takes 30-45 min to zero and span each analyser twice. The analysers take ambient samples for at least 30 min before warm up is started.

The morning start-up before a run consists of opening the manual air valve for the actuators/controls and any fuel valves that are to be used. If steam is to be used the boiler is turned on and the warm-up line opened to get as much condensate out of the system as possible before runs start. The igniter is pushed into the tunnel for light up after an ambient sample is taken.

To light the flare, the fan is started and left at a flow rate of 20,000 kg/h (44,080 lb/h) in manual and local position on the control of the Burner Management System (BMS) while a sample of the ambient air is taken. After the ambient sample is taken the fan speed is increased to 24,000 kg/h (52,896 lb/h) and placed in automatic and remote on the BMS control. The local and remote positions are part of the BMS and are used to prevent accidental lighting of the flare. The flare can only be lit when the fan control is in the remote position and then the fan control is moved back to the local position so that flow rates can be changed.

NG is always used as the warm-up fuel and is always set at a level of 10 kg/h (22 lb/h) for every warm up. The NG valve setting must be placed at 15% open for lighting, which is part of the internal program of BMS. This setting prevents ignition with a high firing rate which could damage the facility or cause it to fill with gas. If the pilots are being used the valve is opened to 62% because the existing pilots work best at this setting. The start button is depressed and the BMS increases fan speed to its maximum speed as a pre-purge. The air is then slowly decreased until it returns to 24,000 kg/h (52,896 lb/h).

At this point the igniter will start and ignition will be verified by the flame scanner and then the BMS will open the main gas valve. Once the flare tip is lit, the fan is restored to the local setting but left in automatic and increased to 35,000 kg/h (77,140 lb/h) (warm up speed) and the fuel valve is opened to 22-23% which gives the 10 kg/h (22 lb/h) required for warm up. If steam is to be used during testing the warm up line is closed and the steam is allowed to enter the line which feeds the steam ring and tips. Warm-up occurs for at least 45 min before the first test is started.

5.0 CALCULATIONS

5.1 Calculation of Performance Measures

The following quantities are measured:

- Air flow into the wind tunnel.
- Air composition (dry basis) into the wind tunnel.
- Fuel flow and composition into the flare tip.
- Assist flow to the flare tip.
- Fuel and air flow into the pilots.
- Composition of the stack gas (dry basis).

There are three main measures of flare performance calculated from these data. The first is the Carbon Conversion Efficiency (CCE). This is sometimes called the combustion efficiency, and is calculated in the following steps:

- Calculate the mass flow of C as CO_2 in the air.
- Calculate the total mass flow of C in the fuel gas and in the pilot burners.
- Calculate the mass flow of nitrogen in the air, assuming nitrogen is the balance from the air composition (nitrogen-tie).
- Calculate the total mass flow of dry gas in the stack using the nitrogen-tie and the composition of the stack gas.
- Calculate the mass flow of C in carbon containing species CO_2 , CO , CH_4 , and NMHC (as C_3H_8).
- Calculate the net mass flow of C as CO_2 in the stack, which is the total mass flow of C as CO_2 less the mass flow of C as CO_2 in the air.
- Calculate the net mass flow of C in all other carbon-containing species in the stack.

The CCE is given by

$$CCE = 100\% \times \frac{\dot{m}_{CasCO2net}}{\sum \dot{m}_{Cnet}} \quad (5-1)$$

which is the measure of the conversion of fuel carbon to carbon dioxide. The summation sign indicates summation over all species.

The Carbon Balance (CB) is the mass balance of all carbon entering and leaving the FTF and is given by the ratio of the mass flow of carbon over all species in the stack to the mass flow of carbon in all species in the air and fuel.

$$CB = 100\% \times \frac{\sum \dot{m}_{Cstack}}{\sum \dot{m}_{Cair} + \sum \dot{m}_{Cfuel}} \quad (5-2)$$

The Specific Destruction Efficiency of a single hydrocarbon fuel gas species, not found in the air, is given as

$$SDE = 100\% \times \left(1 - \frac{\dot{m}_{CasXinstack}}{\sum \dot{m}_{Cnet}} \right) \quad (5-3)$$

5.2 Analytical test cases for flaring calculations

It is a useful exercise to take a simplified situation for which the results can be calculated and feed these results into the spreadsheet as a validation and a tool for estimating the sensitivity of the calculations to perturbations of the inputs. Here we describe the solution of the simple test cases used for the validation and sensitivity analysis.

The given data is:

- Air flow rate, \dot{m}_a .
- Air temperature, pressure, and relative humidity, $T, P, \%RH$.
- Composition of dry air, $\{x_i\}_{allcompounds}$.
- Fuel flow rate, pure compound, \dot{m}_f .
- Destruction efficiency, $\%DE$.
- Carbon conversion efficiency, $\%CCE$.

- The reaction is $C_nH_m + xO_2 \rightarrow aCO_2 + bCO + cH_2O$

From these data, the dry gas composition can be calculated. This will give the necessary data to check the flaring calculations.

The following conditions were considered for testing the flaring calculations:

1. Fuels are methane, ethylene, propylene.
2. Air flow is 35,000 kg/h (77,140 lb/h) and fuel flow 30 kg/h (66 lb/h); Air flow is 95,000 kg/h (209,380 lb/h) and fuel flow is 10 kg/h (22 lb/h). These give the extreme combinations of stack concentrations.
3. Relative humidity of 0% and 100%. These check the humidity calculations.
4. Destruction efficiency, carbon conversion efficiency both 100%; destruction efficiency 95%, carbon conversion efficiency 90%. These test the efficiency calculations.

These conditions give a total of 24 test cases, 8 for each fuel.

The calculations proceed as follows:

1. Convert fuel flow from mass to moles. $\dot{C}_f = \frac{\dot{m}_f}{MW_f}$ (5-4)

2. Calculate dry air molecular weight. $MW_{dry} = \sum_i x_i MW_i$ (5-5)

3. Calculate water fraction in air.

4. Calculate wet air molecular weight. $MW_{wet} = x_{H_2O} MW_{H_2O} + (1 - x_{H_2O}) MW_{dry}$ (5-6)

5. Calculate molar flow of wet air. $\dot{C}_{wet} = \frac{\dot{m}_a}{MW_{wet}}$ (5-7)

6. Calculate molar flow of each species in air. $\dot{C}_{wet i} = (1 - x_{H_2O})x_i \dot{C}_{wet}$,

$$\dot{C}_{H_2O} = x_{H_2O} \dot{C}_{wet} \quad (5-8)$$

7. Calculate chemical reaction coefficients, using destruction efficiency and combustion efficiency.

$$\alpha = \%DE / 100; \lambda = \frac{100 - \%CCE}{\%CCE}; a = \frac{n}{1 + \lambda}; b = \lambda a; c = \frac{m}{2}; x = a + \frac{(b + c)}{2} \quad (5-9)$$

8. Apply chemical reaction to molar flows – 1 mole of fuel uses x moles of O_2 , produces a moles of CO_2 , b moles of CO , and c moles of H_2O .

$$\begin{aligned} \dot{C}_p &= \dot{C}_{wet} + (a + b + c - x)(1 - \alpha)\dot{C}_f + \alpha\dot{C}_f; \quad \dot{C}_{pO_2} = \dot{C}_{wetO_2} - x(1 - \alpha)\dot{C}_f; \\ \dot{C}_{pCO_2} &= \dot{C}_{wetCO_2} + a(1 - \alpha)\dot{C}_f; \quad \dot{C}_{pCO} = \dot{C}_{wetCO} + b(1 - \alpha)\dot{C}_f; \\ \dot{C}_{pH_2O} &= \dot{C}_{wetH_2O} + c(1 - \alpha)\dot{C}_f; \quad \dot{C}_{pf} = \alpha\dot{C}_f \end{aligned} \quad (5-10)$$

9. Calculate dry gas composition from molar flows. $x_{pi} = \frac{\dot{C}_{pi}}{\dot{C}_p - \dot{C}_{H_2O}}$ (5-11)

5.3 Sensitivity of Calculations

The calculations of the performance indicators – carbon balance, conversion efficiency, and destruction efficiency - include many measured variables and many steps. The errors in the measured variables propagate through the calculations to the performance indicators. The effect of these measurement errors on the performance indicators is not obvious. Of particular interest is whether the error is amplified by the calculations.

The sensitivity of the calculations to these errors is most easily estimated using the calculated test cases. A specified change is applied to an input variable in the test case. This produces a change in the calculated performance indicators. The magnitude of the change indicates the sensitivity of the calculations to errors in the reading for that input variable.

The sensitivity of the calculations was estimated for the following input variables:

- Air flow
- Fuel flow
- Inlet carbon dioxide
- Stack carbon dioxide
- Stack methane
- Relative humidity

Two test cases were used, both with natural gas for fuel. The two cases represent the extremes of dilution: low dilution with low air flow and high fuel flow; high dilution with high air flow and low fuel flow. The air temperature was measured to be 25°C (77°F) and relative humidity was 50%.

The errors were taken as the quoted accuracy of the flow meters and analysers in use at the Flare Test Facility. The flow meters have a relative accuracy of 1.5% and 1% of reading for the air and fuel mass flows. The analysers have an absolute accuracy of 1% of full scale. The absolute error for relative humidity was selected to be 2%.

Table 4 shows the sensitivities for the low dilution case, with the low air flow of 35,000 kg/h (77,140 lb/h) and high fuel (natural gas) flow of 30 kg/h (66 lb/h). This case gives the highest concentration of combustion products in the stack gas. The error of 1.5% in the air flow gives a change of 1.2% in the carbon balance. The calculation of carbon balance is only slightly sensitive to the errors in fuel flow rate and relative humidity. The conversion efficiency and destruction efficiency are insensitive to these three variables.

The errors in the stack gas compositions do have an effect on the efficiency calculations, though the effect is small in all cases. A change in stack carbon dioxide measurement of 50 ppm produces a change of 2.5% in the carbon balance. The stack carbon dioxide measurement is the most sensitive variable. Or correctly stated, the accuracy of the carbon dioxide analyser is the most significant part of the system.

All the errors can be combined to produce a maximum change in the performance indicators. For this low dilution case, the maximum change is a little over 5% for the

carbon balance, but less than 0.25% for the efficiencies. The changes are roughly symmetrical in this case, equal in magnitude for both positive and negative changes.

Table 4 - Sensitivity of main performance indicators to changes in input variables. Low dilution case with low wind and high fuel flow.

Sensitivity Table - Low Wind of 35,000 kg/h (77,140 lb/h) and High Fuel of 30 kg/h (66 lb/h)							
Input Variable	Change	Dependent Variable					
		Carbon Balance		Conversion		Destruction Efficiency	
		%	diff	%	diff	%	diff
Base Case	0	101.73		90		95	
Air Flow	+1.5%	102.95	1.22	90	0	95	0
	-1.5%	100.5	-1.23	90	0	95	0
Fuel Flow	+1%	101.92	0.19	90	0	95	0
	-1%	102.54	0.81	90	0	95	0
Inlet CO ₂	+ 5 ppm	101.47	-0.26	89.97	-0.03	94.98	-0.02
	- 5 ppm	101.98	0.25	90.03	0.03	95.01	0.01
Stack CO ₂	+ 50 ppm	104.24	2.51	90.29	0.29	95.15	0.15
	- 50 ppm	99.22	-2.51	89.68	-0.32	94.84	-0.16
Stack CH ₄	+ 1 ppm	101.78	0.05	89.94	-0.06	94.94	-0.06
	- 1 ppm	101.68	-0.05	90.05	0.05	95.06	0.06
Relative Humidity	+2	101.47	-0.26	90	0	95	0
	-2	101.98	0.25	90	0	95	0
Maximum Change	+	106.98	5.25	90.23	0.23	95.11	0.11
	-	96.68	-5.05	89.75	-0.25	94.88	-0.12

Table 5 shows the high dilution case, with high air flow of 95,000 kg/h (209, 380 lb/h) and low fuel rate of 10 kg/h (22 lb/h). This case gives the lowest concentrations of combustion products in the stack. The rest of the conditions of the test case were unchanged.

The inlet flow variable, air flow rate, fuel flow rate, and relative humidity have little effect on the carbon balance and no effect on the conversion efficiency and destruction efficiency.

The errors in the inlet carbon dioxide concentration and the stack methane concentration have relatively little effect on any of the three performance indicators. However, all three performance indicators are sensitive to the stack carbon dioxide measurement. The carbon balance is particularly sensitive, producing a change of 8.5%. Note that the change in the conversion efficiency and destruction efficiency is not symmetric. The positive change from over-estimating the carbon dioxide is smaller than the negative change from under-estimating. This means that when the carbon balance is low due to error in the carbon dioxide measurement, the efficiencies will be significantly lower as well.

The maximum error, due to the combined errors, is around 10% in the carbon balance, around 3% for the conversion efficiency and around 1.25% for the destruction efficiency.

This sensitivity analysis indicated that the carbon balance can be expected to vary by up to 10% due simply to the combined effect of small errors. We could conclude that runs with carbon balance in the range from 90% to 110% have good carbon balance and the results are reliable. The errors in the conversion efficiency and destruction efficiency are smaller and in the same direction as the carbon balance. That is, when there is a low carbon balance, the efficiencies are underestimated.

Table 5 - Sensitivity of main performance indicators to changes in input variables. High dilution case with high wind and low fuel flow.

Sensitivity Table - High Wind of 95,000 kg/h (209, 380 lb/h) and Low Fuel of 10 kg/h (22 lb/h)							
Input Variable	Change	Dependent Variables					
		Carbon		Conversion		Destruction	
		%	diff	%	diff	%	diff
Base Case		100.72		90		95	
Air Flow	+1.5%	101.22	0.5	90	0	95	0
	-1.5%	100.22	-0.5	90	0	95	0
Fuel Flow	+1%	100.38	-0.34	90	0	95	0
	-1%	101.6	0.88	90	0	95	0
Inlet CO ₂	+ 5 ppm	99.89	-0.83	89.74	-0.26	94.87	-0.13
	- 5 ppm	101.59	0.87	90.24	0.24	95.12	0.12
Stack CO ₂	+50 ppm	109.24	8.52	91.99	1.99	95.99	0.99
	- 50 ppm	92.2	-8.52	86.68	-3.32	93.34	-1.66
Stack CH ₄	+ 1 ppm	100.89	0.17	89.55	-0.45	94.53	-0.47
	- 1 ppm	100.55	-0.17	90.44	0.44	95.47	0.47
Relative Humidity	+2	100.61	-0.11	90	0	95	0
	-2	100.83	0.11	90	0	95	0
Maximum Change	+	110.65	9.93	91.78	1.78	95.7	0.7
	-	91.01	-9.71	86.82	-3.18	93.76	-1.24

5.4 Estimating Uncertainty

There are several methods for estimating the uncertainty of a number calculated from experimental data. Here we use the recommendation of Kline and McClintock [1953]. This method was also used in Bourguignon et al. [1999] to estimate the uncertainty of the combustion inefficiency at two different conditions.

We are interested in the uncertainty of the two performance measures: carbon conversion efficiency (CCE) and destruction efficiency (DE). The performance measures are calculated from our data measurements. We can write the relationship as

$$CCE = f(X_i) \quad (5-12)$$

for example. We have the uncertainty ε_i for each measured value X_i . The uncertainty of the calculated CCE is estimated by

$$\varepsilon_{CCE} = \left[\sum_i \left(\frac{\partial f}{\partial X_i} \varepsilon_i \right)^2 \right]^{1/2} \quad (5-13)$$

We now derive, through some minor simplifications, an explicit form of the uncertainty for CCE and DE described in the previous section.

We start with a single hydrocarbon species in the flare gas with no carbon dioxide. This is only for simplicity of notation. We repeat the calculation with carbon dioxide included in the flare gas in Appendix B-3. We will also neglect the flux of particulate carbon. The expression for the CCE is

$$CCE = \frac{\Delta \dot{m}_{CO_2}^c}{\Delta \dot{m}_{CO_2}^c + \Delta \dot{m}_{CO}^c + \Delta \dot{m}_{HC}^c} \quad (5-14)$$

$$DE = 1 - \frac{\Delta \dot{m}_{HC}^c}{\Delta \dot{m}_{CO_2}^c + \Delta \dot{m}_{CO}^c + \Delta \dot{m}_{HC}^c} \quad (5-15)$$

The total mass efflux from the system is the sum of the mass flows for inlet air and flare gas. The specific carbon fluxes are

$$\dot{m}_{i,in}^c = \dot{m}_a x_{i,in}^c \quad (5-16)$$

$$\dot{m}_{i,out}^c = (\dot{m}_a + \dot{m}_f)x_{i,out}^c$$

and the change is

$$\Delta \dot{m}_i^c = \dot{m}_a (x_{i,out}^c - x_{i,in}^c) + \dot{m}_f x_{i,out}^c \quad (5-17)$$

We can neglect \dot{m}_f when

$$\frac{x_{i,out}^c - x_{i,in}^c}{x_{i,out}^c} \gg \frac{\dot{m}_f}{\dot{m}_a} \quad (5-18)$$

For our situation, the mass flow of flare gas is in the range of 10 to 30 kg/h (22 to 66 lb/h), while that of air is from 35,000 to 95,000 kg/h (77,140 to 209,380 lb/h). The ratio is smaller than 0.001. The condition above shows that the mass flow of fuel can be neglected when the relative change of mass fraction is greater than 0.1%. Since our instrument accuracy is on the order of 1%, this condition is always met.

The measurements are taken in volume fraction units. These are related to the mass fractions by

$$\dot{x}_i^c = \frac{N_c y_i M_c}{\sum_j y_j M_j} \quad (5-19)$$

The denominator is the average molar mass. The specific carbon flux can be written as

$$\Delta \dot{m}_i^c = \dot{m}_a \frac{N_{ci} M_c}{\bar{M}_{in}} \left(\frac{\bar{M}_{in}}{\bar{M}_{out}} y_{i,out} - y_{i,in} \right) \quad (5-20)$$

With the very high dilution in our situation, the average molecular weight changes very little and the ratio can be taken to be unity. Substituting the expression for specific carbon flux into the expressions for *CCE* and *DE* gives

$$CCE = \eta = \frac{\Delta y_{CO_2}}{\Delta y_{CO_2} + \Delta y_{CO} + N_c \Delta y_{HC}} \quad (5-21)$$

$$DE = 1 - \frac{N_c \Delta y_{HC}}{\Delta y_{CO_2} + \Delta y_{CO} + N_c \Delta y_{HC}} \quad (5-22)$$

The very high dilution has allowed us to derive an explicit expression for the performance measures CCE and DE in terms of measured concentrations of CO_2 , CO and HC in the inlet air and stack gas. Note particularly that the air and fuel flow rates do not appear. This is in agreement with the sensitivity analysis that showed very little sensitivity of the full calculation to these variables.

With this formulation we can calculate the partial derivatives needed for the uncertainty estimate. Let

$$\sigma_c = \left(\Delta y_{CO_2} + \Delta y_{CO} + N_c \Delta y_{HC} \right)^{-1} \quad (5-23)$$

Then

$$\frac{\partial \eta}{\partial y_{CO_2, out}} = \sigma_c (1 - \eta) \quad (5-24)$$

$$\frac{\partial \eta}{\partial y_{CO_2, in}} = -\sigma_c (1 - \eta)$$

$$\frac{\partial \eta}{\partial y_{CO, out}} = -\sigma_c \eta$$

$$\frac{\partial \eta}{\partial y_{CO, in}} = \sigma_c \eta$$

$$\frac{\partial \eta}{\partial y_{HC, out}} = -N_c \sigma_c \eta$$

$$\frac{\partial \eta}{\partial y_{HC, in}} = N_c \sigma_c \eta$$

Substituting these into the formula for uncertainty gives

$$\varepsilon_\eta = \sigma_c \left[(1 - \eta)^2 (\varepsilon_{CO_2, out}^2 + \varepsilon_{CO_2, in}^2) + \eta^2 (\varepsilon_{CO, out}^2 + \varepsilon_{CO, in}^2) + N_c^2 \eta^2 (\varepsilon_{HC, out}^2 + \varepsilon_{HC, in}^2) \right]^{1/2} \quad (5-25)$$

Thus the uncertainty is expressed in terms of the uncertainties in the measurements, the conversion efficiency, and the total net carbon efflux, which is the same as the total carbon input in the flare gas. In a similar manner, the uncertainty for the destruction efficiency is

$$\varepsilon_{DE} = \sigma_c \left[(1 - DE)^2 (\varepsilon_{HC,out}^2 + \varepsilon_{HC,in}^2) + DE^2 (\varepsilon_{CO_2,out}^2 + \varepsilon_{CO_2,in}^2 + \varepsilon_{CO,out}^2 + \varepsilon_{CO,in}^2) \right]^{1/2} \quad (5-26)$$

These expressions are easily programmed into a spreadsheet along with the experimental data.

The magnitude of the uncertainty and the range is shown by considering the extremes of dilution. The best case is the lowest dilution, meaning lowest air flow and the highest fuel flow. The worst case is the highest dilution, with lowest fuel flow and high air flow. The analytical solution presented above was used to calculate the uncertainty for these extremes. The values used in the calculations are given in Table 6.

Table 6 - Uncertainty values for measurements for estimation of uncertainty of CCE and DE.

Variable		Low Dilution	High Dilution
$y_{CO_2,out}$	ppm	1940	580
$y_{CO_2,in}$	ppm	390	
σ_c	ppm ⁻¹	0.000645	0.00526
$\varepsilon_{CO_2,out}$	ppm	50	10
$\varepsilon_{CO_2,in}$	ppm	5	
ε_{CO}	ppm	0.5	
ε_{CH_4}	ppm	1	

The example is for methane. The uncertainty for the inlet CO₂ and for CO and CH₄ are 1% of full-range (500 ppm, 50 ppm and 100 ppm respectively). The uncertainty for outlet CO₂ is also 1% of full-scale, which is 5000 ppm for the low dilution case and 1000 ppm in the high dilution case.

The estimated uncertainty is plotted in Fig. 10 for *CCE* and in Fig. 11 for *DE*. The uncertainty increases with decreasing efficiency. The uncertainty is almost the same for each measure. In the worst case, the high dilution case, the uncertainty is less than 2% even at 70% efficiency. At the threshold level of 98%, the uncertainty is $\pm 0.12\%$ in the low dilution case, $\pm 0.82\%$ in the high dilution case.

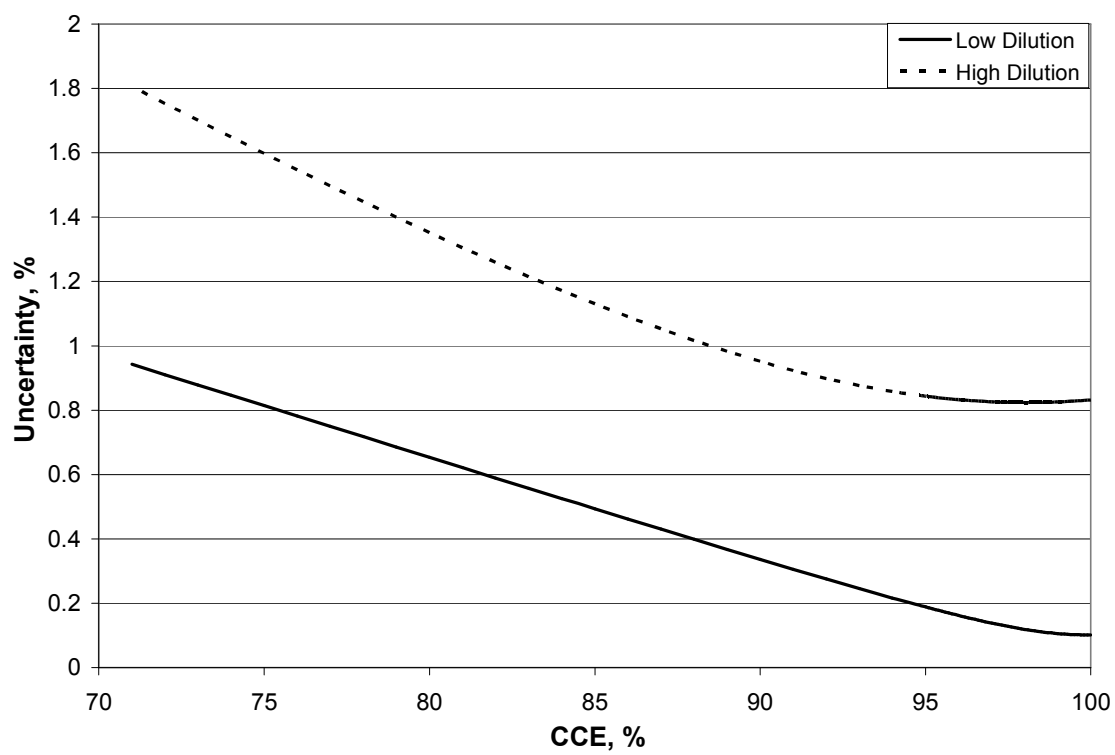


Figure 11 - Uncertainty curves for carbon conversion efficiency (CCE).

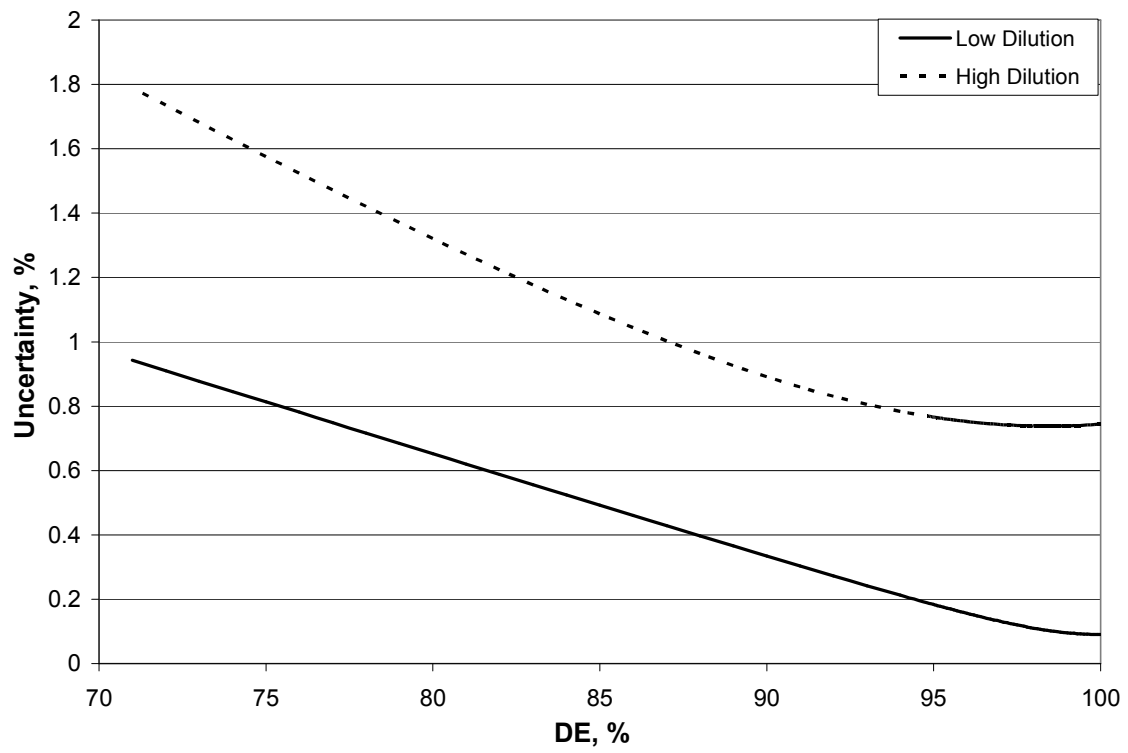


Figure 12 - Uncertainty curves for the destruction efficiency (DE).

6.0 CONCLUSION

The Flare Test Facility at CanmetENERGY has been designed and proven for the experimental program of the International Flaring Consortium. It has the following capabilities:

- It can fire a gas mixture composed of natural gas, propane, ethylene or propylene, and nitrogen or carbon dioxide, with total hydrocarbon flow from 5 kg/h to 30 kg/h (11 lb/h to 66 lb/h) and inert gas flow up to 150 kg/h (331 lb/h).
- The wind speed can be varied from 5 km/h to 35 km/h (3.1 miles/h to 22 miles/h).
- Steam-assisted flare tip has 7.5 cm (3 inch) outside diameter flare gas pipe, with a flame retention ring (open area 21.7 cm² or 3.36 in²), with 12 steam-nozzles and three pilot-burners. The steam supply system can deliver from 5 kg/h to 30 kg/h (11 lb/h to 66 lb/h).
- On-line analysis of gas samples was performed for O₂, CO₂, CO, CH₄ and non-methane hydrocarbons, NO_x, HRVOCs, and BTEX compounds.

The performance measures, carbon conversion efficiency (CCE) and destruction efficiency (DE), are calculated from the measurements. Due to the high dilution of the combustion products in the wind tunnel, these measures are most sensitive to the accuracy of the CO₂ measurement, both upstream and downstream of the flare.

The uncertainty of these measures is shown to increase with decreasing efficiency. The uncertainty also depends upon the dilution level, where there is higher uncertainty with higher dilution. At maximum dilution, the worst case, the uncertainty of the DE is $\pm 0.82\%$ at 98% DE, increasing to $\pm 2\%$ at 70% DE. At minimum dilution, the uncertainty is $\pm 0.12\%$ at 98% DE.

7.0 REFERENCES

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- Kline, S.J. and F.A. McClintock, [1953] "Describing Uncertainties in Single-Sample Experiments, *Journal of Mechanical Engineering*", pp. 3-8.

8.0 APPENDIX

A. Imperial Figures and Graphs

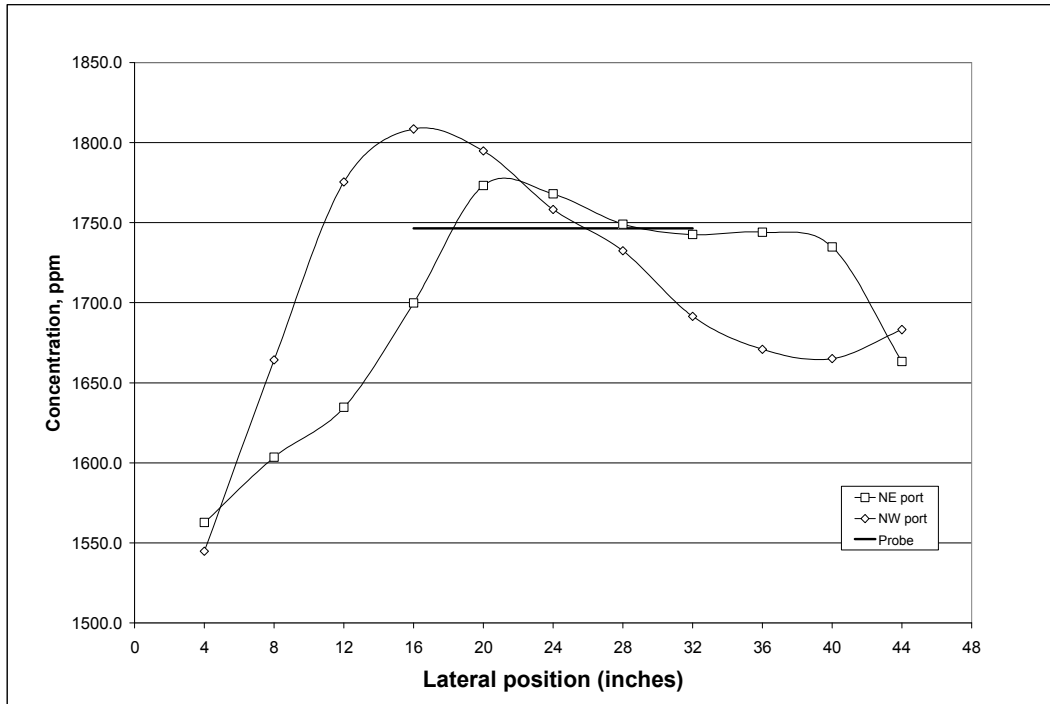


Figure 13 - Concentration profiles for CO₂ in stack, with the probe value indicated by the line.

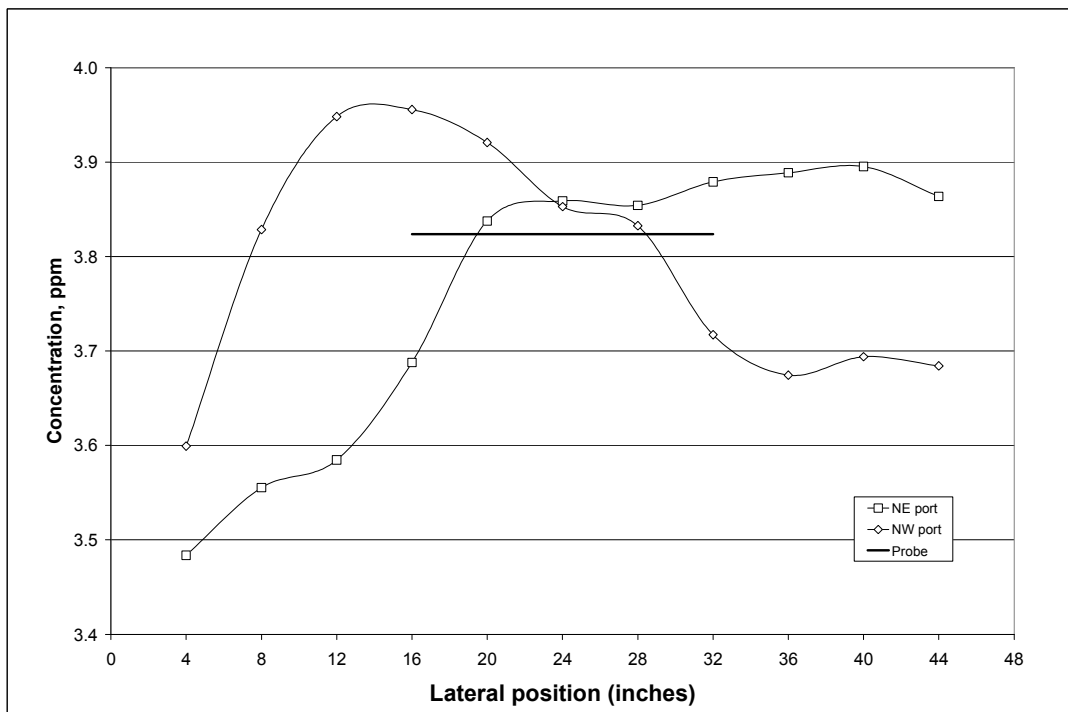


Figure 14 - Concentration profiles for CO in stack, with the probe value indicated by the line.

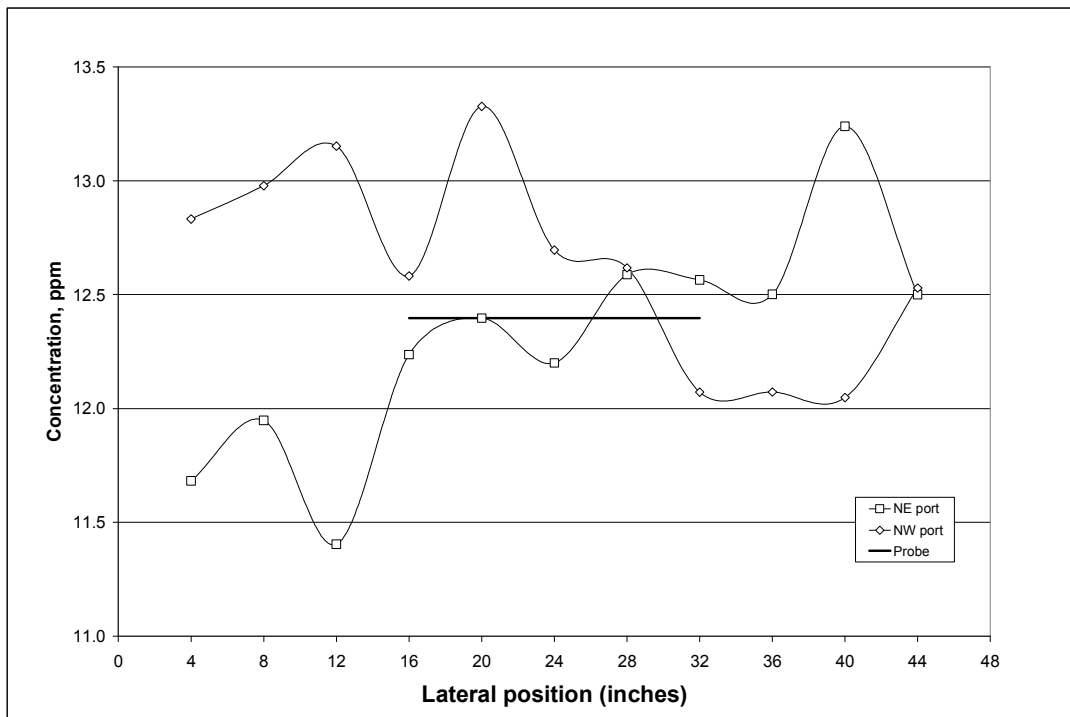


Figure 15 - Concentration profiles for CH₄ in the stack, with the probe value indicated by the line.

B. Analyzer Descriptions and Specifications

1. Composition of NG and Propane

Table A 1 – Composition of NG and propane

	Vol % for NG	Vol % for Propane
CH ₄	95.330	0
C ₂ H ₆	2.100	2.0
C ₃ H ₈	0.130	97.2
C ₄ H ₁₀	0.020	0.8
C ₅ H ₁₂	0.000	0
C ₆ H ₁₄	0.000	0
N ₂	1.800	0
CO ₂	0.620	0
Total	100.000	100.0

2. K Factors

Table A 2 – K correction factor

Gas	Correction factor
Propane	1.01716
Ethylene	1.01983
Propylene	1.066722

3. Flow Meter Specifications

Table A 3 – Flow meter specifications

Location	Manufacturer	Principle	Range	Accuracy
CO ₂ /Nitrogen line	Endress and Hauser	Thermal mass	Gas and process condition dependent	±0.6% of reading
Propane/Propylene/Ethylene line	Endress and Hauser	Thermal mass	Gas and process condition dependent	±0.6% of reading
Natural Gas line	Endress and Hauser	Thermal mass	Gas and process condition dependent	±0.6% of reading
Pilot line	Sierra Instruments	Thermal mass	Gas dependent	±1.0 % of full scale
Steam line	McCrometer	Pressure difference	Gas dependent	±0.5% of reading

4. Direct Methane, Non-methane Hydrocarbon Analyzer

Manufacturer: Thermo Environmental Instruments Inc.

Model: 55C

Description:

- A back-flush gas chromatography (GC) system designed for automated measurement of methane and non-methane hydrocarbons
- Back-flush GC method permits direct measurement of non-methane hydrocarbons resulting in precise and accurate measurement of low levels of non-methane hydrocarbons (NMHC), even in the presence of high concentration methane
- An automated batch analyzer repeatedly collects and analyzes small amounts of sample stream drawn in by the pump

- An eight port, two position, rotary valve is used to introduce the gas sample into the analyzer and to control the flow of gases through the chromatographic column

Specifications:

Measurement Ranges	0-20 ppm
(Methane and NMHC set independently)	0-200 ppm
(Other ranges optional)	0-2000 ppm
Recorder Ranges	1-2000 ppm
(User selectable)	
Limits of Detection	20 ppb methane, 50 ppb NMHC as propane
Analysis Time of 1 Sample	70 seconds (approximate)
Accuracy	±2% of measured value
Precision	±2% of measured value
Drift	
(without auto calibration)	±2% of span
Ambient Operating Temperature	15°C to 35°C
Sample Temperature	Ambient to 80°C (standard) (higher temperatures optional)
Analog Outputs	Separate outputs for Methane, NMHC, THC and chromatogram. Current outputs optional.
Digital Outputs	RS-232
Alarm Systems	Methane Concentration, NMHC Concentration, Calibration Failure, System Failure
Sample Flow Rate	0.5 L/min minimum
Power Requirements	90-110 VAC @ 50/60 Hz 105-125 VAC @ 50/60 Hz 210-250 VAC @ 50/50 Hz
Support Gases	HC free air (200-300 cc/min)
(From AL/BOC or Linde)	N ₂ carrier (35 cc/min) H ₂ fuel (25 cc/min)

Span mix (2-litre/calibration)

Physical Dimensions

42.5 cm (W) x 21.9 cm (H) x 58.4 cm (D)

Weight

27.2 kg

5. NO-NO₂-NO_x Analyzer

Manufacturer: Thermo Electron Corporation

Model: 42C

Description:

- Basis is that nitric oxide (NO) and ozone (O₃) react to produce a characteristic luminescence (chemiluminescence)
- The intensity of the luminescence is linearly proportional to the concentration of NO
- Ambient air sample enters through sample bulkhead and flows through particulate filter and capillary to solenoid valve
- In NO mode the solenoid valve sends sample directly to reaction chamber
- In NO_x mode the solenoid valve sends sample through NO₂ to NO converter and then to reaction chamber
- A flow sensor for measurement of sample flow is located directly before the reaction chamber
- Dry air enters through the dry air bulkhead and flows through a flow sensor and then a silent discharge ozonator
- Ozone reacts with NO from ambient air sample to produce electronically excited NO₂ molecules
- Photomultiplier tube in thermoelectric cooler detects NO₂ luminescence
- Outputs of NO, NO₂, and NO_x concentrations to front panel display and analog outputs

Specifications:

Preset Ranges	0-0.05, 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, and 100 ppm 0-0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100, and 150 mg/m ³
Extended Ranges	0-0.2, 0.5, 1, 2, 5, 10, 20, 50, and 100 ppm 0-0.5, 1, 2, 5, 10, 20, 50, 100, and 150 mg/m ³
Custom Ranges	0-0.05 to 100 ppm for NO, NO ₂ , and NO _x 0-0.1 to 150 mg/m ³
Zero Noise	0.20 ppb RMS (60 second averaging time)
Lower Detectable Limit	0.40 ppb (60 second averaging time)
Zero Drift (24 hour)	<0.40 ppb
Span Drift (24 hour)	±1% full scale
Response Time	40 sec (10 second averaging time)
(in automatic mode)	80 sec (60 second averaging time) 300 sec (300 second averaging time)

Precision	±0.4 ppb (500 ppb range)
Linearity	±1% full scale
Sample Flow Rate	0.6 L/min
Operating Temperature	15°C to 35°C (may be safely operated over the range of 0 to 45 °C in non-condensing environment)
Power Requirements	90-110 VAC @ 50/60 Hz 105-125 VAC @ 50/60 Hz 210-250 VAC @ 50/50 Hz 300 Watts
Physical Dimensions	42.5 cm (W) x 21.9 cm (H) x 58.4 cm (D)
Weight	24 kg
Outputs	NO, NO ₂ , and NO _x , selectable voltage, 4-20 mA, RS-232, RS-485

6. Upstream and Downstream CO₂ Analyzers

Manufacturer: HORIBA Instruments Inc

Model: VIS-510

Description:

- Basis is non-dispersive infrared (IR) analysis method
- Continuously measures components in sample gas, for IFC tests, this was CO₂
- IR rays pass through sample and are absorbed by sample gas
- This causes detection cell membrane to vibrate which generates an electric output
- The electric output corresponds to changes in the capacity between electrodes
- Detection is of IR absorption in the particular wavelength band for a component
- Changes in the IR absorption of the measured component result in changes in the concentration of the component
- Outputs measured concentration to digital panel display

Specifications:

Ranges

Table A 4 – Analyte measurement ranges

Standard		Option ^{*1}	
Constituent	Min. Range	Max. Range	Min. Range
CO	0-100 ppm	0-100 vol%	0-50 ppm
CO ₂	0-100 ppm	0-100 vol%	0-50 ppm
NO	0-200 ppm	0-100 vol%	0-100 ppm
SO ₂	0-100 ppm	0-100 vol%	0-50 ppm
CH ₄	0-100 ppm	0-100 vol%	0-50 ppm
C ₂ H ₄	0-200 ppm	0-100 vol%	0-100 ppm

Within the above concentration ranges, up to 4 ranges can be selected with the maximum range ration being 10.

Reproducibility

±0.5% full scale

(However, ±1.0% of full scale when CO, CO₂, SO₂, CH₄, C₂H₄ are less than 100 ppm or NO is less than 200 ppm.)

Zero Drift (24 hour)	±1.0% of full scale <i>Note:</i> =2.0%/d in full scale for *1
Span Drift (24 hour)	±1.0% full scale <i>Note:</i> =2.0%/d in full scale for *1
Response Speed	Within 30 s for 90% response from analyzer inlet.
Display	LED digital (4 digits effective)
Flow Rate of Sample Gas	Approx. 500 ml/min
Ambient Temperature	0 to 40 °C
Output Signal	Insulated output: DC 0-16 mA or 4-20 mA DC 0-1 V DC 0-10 V
Power Requirements	100 VAC @ 50/60 Hz 115 VAC @ 50/60 Hz 240 VAC @ 50/50 Hz
Weight	Approx. 15 kg

7. Paramagnetic Oxygen Analyzer

Manufacturer: California Analytical Instruments Inc

Model: 100P

Description:

- Basis is that analyzer measure paramagnetic susceptibility of sample gas with a magneto-dynamic type cell
- Measuring cell consists of a dumbbell made of diamagnetic material and the temperature is electronically controlled to 50 °C
- As oxygen concentration increases the dumbbell is deflected from rest position
- An increase in oxygen concentration increases the displacement of the dumbbell
- Deflection is detected by optical system connected to an amplifier
- Coil of wire surrounds dumbbell
- Current passed through the coil returns the dumbbell to the original rest position
- The current applied is linearly proportional to the %oxygen concentration in the sample gas at the set temperature
- Outputs %oxygen concentration to a digital panel display

Specifications:

Sample Contact Material	Platinum, glass, stainless steel, vitron
Ranges (Standard fixed ranges, choose A, B, or C)	A) Range 1: 0-1%, Range 2: 0-15%, Range 3: 0-25% B) Range 1: 0-5%, Range 2: 0-10%, Range 3: 0-25% C) Range 1: 0-25%, Range 2: 0-40%, Range 3: 0-100%
Response Time	90% full scale in 2 seconds
Linearity	Better than 1% full scale
Repeatability	Better than 1% full scale
Sample flow rate	1 L/min
Noise	< 1% full scale
Zero Spin Drift	< 1% full scale in 24 hours
Zero & Span Adjustment	Ten turn potentiometer
Display	3 ½ digit panel meter (eg. 100.5)
Outputs	0-10 VDC and 4-20 mA (0-20 mA)
Ambient Temperature	5 to 45 °C
Sample Temperature	0 to 50 °C
Sample Condition	Clean, dry gas

Fittings	¼" tube
Power Requirements	115/230 (±10%) VAC, 50/60 Hz, 70 watts/channel
Relative Humidity	less than 90% RH (non-condensing)
Dimensions	13.3 cm (H) x 48.3 cm (W) x 38.1 cm (D)
Weight	4.5 kg

8. Gas Chromatograph with Peltier trap, FID and PID

Manufacturer: SRI Instruments

Model: 8610C

Description:

- Gas chromatograph (GC) is equipped with a Peltier cool trap, a small vacuum pump, Peltier trap, a flame ionization and a photo ionization detector connected in series
- A Nafion dryer is connected to the inlet of the GC to eliminate water from the sample stream
- The sampling pump, Peltier trap and sampling valve are activated using the programmed events function in the Peak Simple 3.29 software
- The separation chromatography is done with a GS GasPro capillary column under the following conditions: sampling time: 0.5 min, temperature program: initial temperature: 40°C, hold for 9 minutes, final temperature: 110°C with a ramp of 10°C/min and the final temperature is held for 20 minutes
- The carrier gas is helium
- Data collection and GC temperature programming are controlled by the Peak Simple 3.29 software
- Plots can be seen in “Online Analysis of Flaring Emissions” [Caravaggio and Caverly, 2008]

Specifications:

Detectors	FID and PID
Gas Sample Inlet	1/8” tube
Fittings	
Gas Sample Outlet	1/8” tube
Fittings	
Column Dimensions	0.32 mm x 60 m
Column Flow Rate	3.58 ml/min
Column Temperature	-80 °C to 260 °C
Sampling Pump	91.5 ml/min
Flow Rate	
GC Operating Temperature	-15 °C to 250 °C (with Peltier trap and above column)
Electrical Requirements	110 VAC, 50/60 Hz, 1150 VA max
Display	LED digital (2 digit effective)
Dimensions	47.0 cm (W) x 31.8 cm (H) x 36.8 cm (D)
Weight	Approx 27 kg

9. Sample Conditioning Unit

Manufacturer: Perma Pure

Model: Mini-GASS

Description:

- Prepare gas samples for the analysis by removing particulates, mists and water vapour without removing the monitored compounds from the gas phase
- Based on a shell and tube model
- Sample passes through a 1 μ filter to remove particulates and aerosols
- Downstream of filter is a Nafion membrane dryer which selectively removes water vapour from the sample through permeation distillation
- Water is continually removed as sample passes from inlet to outlet which reduces the sample dew point as the sample travels through the dryer
- Dry purge gas enters the dryer at the sample outlet end to provide a medium for water vapour to be carried away and creates a temperature gradient along the dryer length
- Ambient purge air enters dryer at sample outlet to cool that portion of the dryer
- This counter flow produces a temperature gradient along the dryer length
- The temperature of the purge gas exhaust is monitored and controlled by an electronic temperature controller to maintain the gradient
- Purge gas passes through the dryer and is heated to the desired sample inlet temperature
- The temperature gradient permits both rapid vapour removal and decreases the final dew point
- If the purge gas temperature falls below the programmed temperature an aluminum heating block conducts energy from the system backplate to the dryer's shell tube.
- This causes purge gas traveling through the dryer's shell to acquire heat from the shell
- It is therefore possible to closely control the final temperature of the purge gas so that a consistent temperature gradient can be maintained
- The sample pump draws the sample and supplies it to the analyzer at up to 5 L/min of sample
- Head of pump is in heated section of system, motor is in control section to keep pump head temperature above dew point of sample to prevent condensation formation

Specifications:

Maximum Sample 0-10 L/min

Flow Rate

Maximum Inlet	121 °C W/SST filter	
Sample Temperature	110 °C W/KYNAR filter	
Maximum Gas Sample	30%	
Water vapour content		
Outlet Sample Dew Point	-4 °C at 10 L/min	
	-12 °C at 5 L/min	
	-25 °C at 2 L/min	
Soluble Gas Removal	NO, NO2	0% losses
Rates	SO2	0% losses
	CO, CO2	0% losses
	H2S, HCl	0% losses
Maximum Gas Sample	20 psig	
Inlet pressure		
Minimum gas sample inlet	5" H2O Vacuum	
Pressure (without purge educator option)		
Gas Sample Inlet Fittings	1/4" or 3/8" tube	
Gas sample Outlet Fittings	1/4" or 3/8" tube	
Air Requirements	Purge air -40 °C dew point maximum one CFM	
Electrical Requirements	110/220 VAC, 50/60 Hz, 5.0 A/2.5 A, 475 watts	
Fuse	5 AMP buss type AGC or equivalent	
Enclosure	NEMA 4x, fibreglass with polycarbonate cover	
Dimensions	30.5 cm (W) x 50.8 cm (H) x 17.8 cm (D)	
Operating Environment	-20 °C to 40 °C ambient temp.	
	0-95% R.H.	

C. Correlations

1. Steam Flow Correction

Bucket tests were performed to check the mass flow meter for steam. The flow meter is a Micrometer V-cone, working on the differential pressure principle.

The 45 gallon plastic barrel was filled with water and ice and placed on an electronic scale. The steam nozzles were submerged into the ice water. The steam flow was turned on. Once steady flow was obtained, the scale was zeroed and timer started. At the allotted time, the scale reading was logged. The steam flow rate is directly calculated from the weight increase and time. The testing had to end when the ice was melted. The steam flow from the flow meter was logged and the average over the sampling time was calculated. Table B1 has the results of the tests. The plot of the bucket flow against the logged average flow is shown in Fig. B1.

Table B 1 – Steam flow bucket test results

Test Number	Nominal Flow	Logged Average	StdDev	Bucket Flow
	kg/h	kg/h		kg/h
1	5	5.812962406	0.381529738	3.4
2	10	9.687420635	0.346938942	9.4
3	15	14.56892308	0.507615695	16.5
4	20	20.47219149	0.910547724	22.2
5	25	25.05207692	0.982680485	29
6	30	31.69609091	0.965781833	38

There is a clear linear relationship between the bucket flow rate and the flow meter reading. The equation is

$$\dot{m}_{bucket} = 1.3066\dot{m}_{meter} - 3.6144$$

This has a significant offset and slope different from unity. It shows that the flow meter underestimates the flow at the high flow rates and overestimates the flow at the lowest flow rates.

Subsequent investigation of the set-up of the flow meter showed that the thermocouple setting was incorrect (J-type for K-type) and the meter configured for super-heated steam whereas it has saturated steam.

The linear correction can be used to adjust the measured flow rates for earlier trials. The correction of the set-up of the flow meter is being discussed with the vendor.

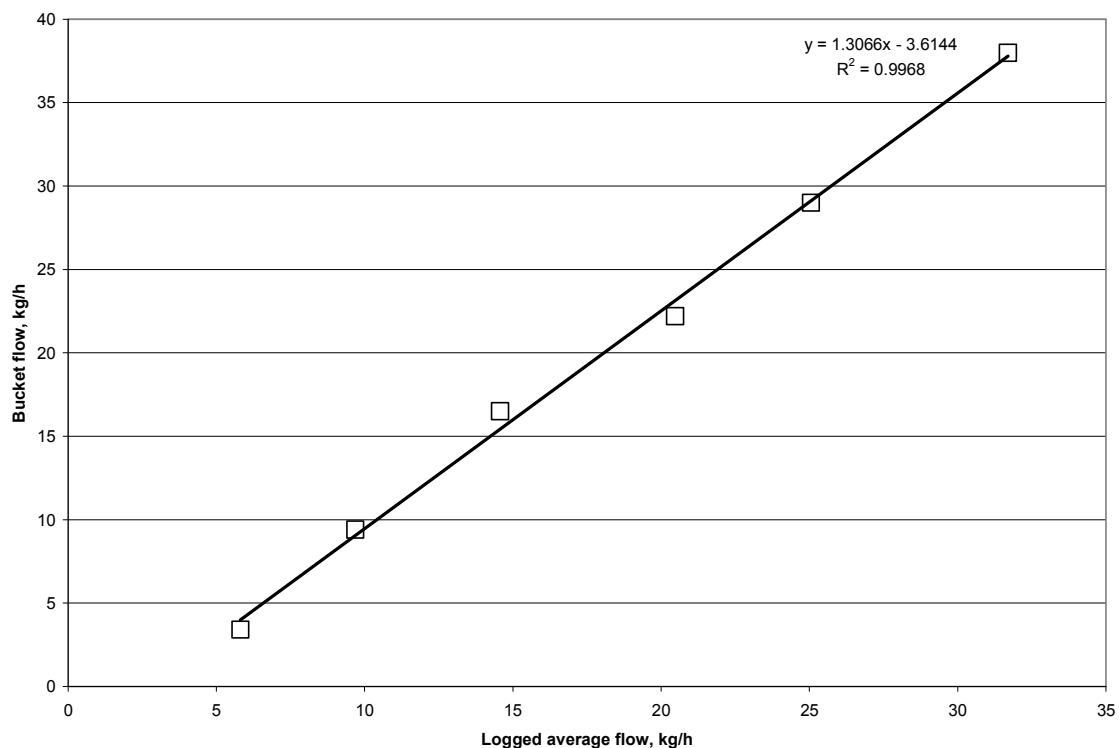


Figure B 1 – Linear relationship of steam flow measured during the bucket tests (bucket flow) and the average of the logged flow.

2. Air Flow Humidity Correction

The mass flow of air is measured from differential pressure across a rake of pitot probes with mass flow calculated using the measured static pressure and temperature at the rake. The air is assumed to have 0%-vol. water content. The actual air can have significant humidity, particularly during the summer months. A correction is needed to account for the humidity.

The vendor (Air Monitor Corp.) provided a spreadsheet giving the calculations performed by the flow meter transmitted to give the mass flow reading. These calculations were done for the range of water content from 0 %-vol to 30 %-vol. This gives the values as if the flow meter was given the water content of the air. The ratio of the moist air flow to the reading (as if dry) flow is plotted against the water content of the air in Fig. B2. The relationship is linear. The water content of air is easily calculated from the measured relative humidity and the calculated vapor pressure of water using Antoine's equation.¹

¹ Vapour Pressure $H_2O = e^{(18.3036-3816.44/(273.15+T_a-46.13))}$ mm Hg

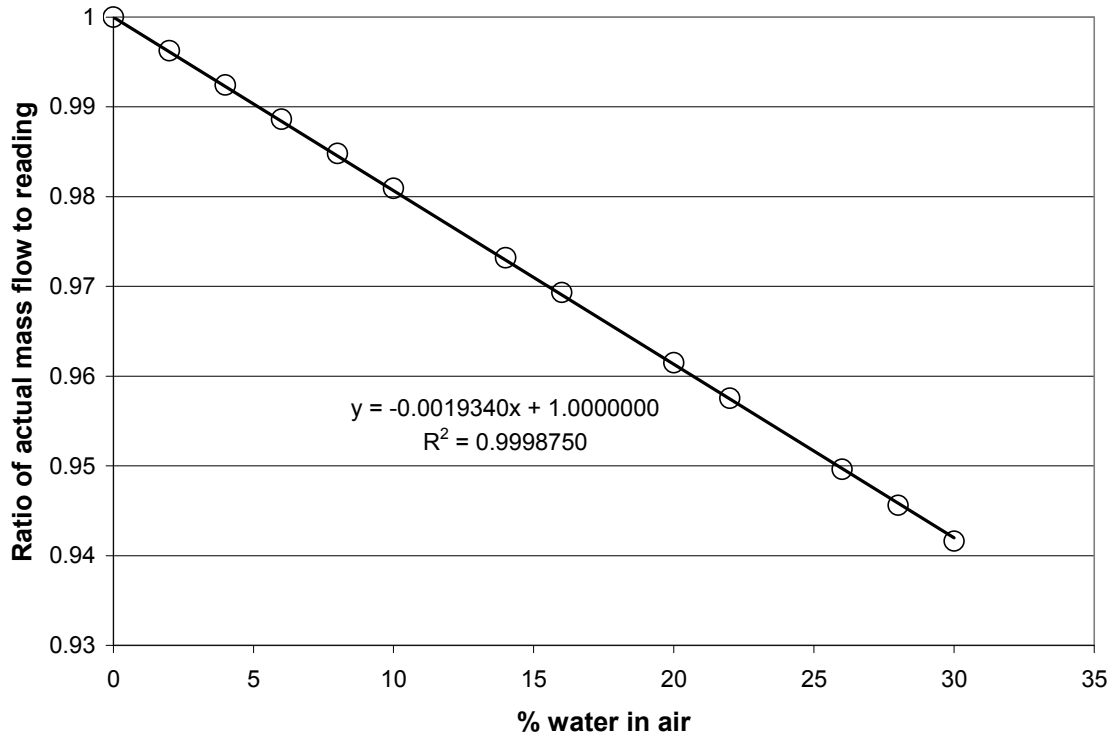


Figure B 2 – Correction of the air flow reading for humidity.

3. Uncertainty Estimation with CO₂ in the Flare Gas

The possibility of CO₂ in the flare gas (in fuel) was neglected in the analysis of uncertainty presented in the main text. In our experiments, CO₂ can appear in the flare gas either as part of the fuel gas or as a separately controlled diluent. In the former case the amount is relatively small, though there are two uncertainties introduced: the fuel flow rate and the actual fraction of CO₂ in the fuel gas. In the second case the CO₂ flow rate is of the same order or larger than the hydrocarbon flow rate. This means that the stack CO₂ is primarily from the inert diluent. Failing to account for this exaggerates the conversion efficiency to CO₂.

We start with the definition of CCE

$$CCE = \frac{\Delta \dot{m}_{CO_2}^c}{\Delta \dot{m}_{CO_2}^c + \Delta \dot{m}_{CO}^c + \Delta \dot{m}_{HC}^c}$$

The only term affected is the mass flux change of carbon as CO₂ in air. It is

$$\Delta \dot{m}_{CO_2}^c = (\dot{m}_a + \dot{m}_f) x_{CO_2,out}^c - \dot{m}_a x_{CO_2,in}^c - \dot{m}_f x_{CO_2,f}^c$$

A slight rearrangement gives two terms, the first the same as in the earlier derivation.

The second term is no longer negligible.

$$\Delta \dot{m}_{CO_2}^c = \dot{m}_a (x_{CO_2,out}^c - x_{CO_2,in}^c) + \dot{m}_f (x_{CO_2,out}^c - x_{CO_2,f}^c)$$

The concentration $x_{CO_2,out}^c$ is on the order of 10^{-3} while $x_{CO_2,f}^c$ is two orders of magnitude bigger. Therefore $x_{CO_2,out}^c$ can be neglected in the second term, giving

$$\Delta \dot{m}_{CO_2}^c = \dot{m}_a (x_{CO_2,out}^c - x_{CO_2,in}^c) - \dot{m}_f x_{CO_2,f}^c$$

Continuing as in the main text by converting to molar concentration, and writing

$\dot{m}_f x_{CO_2,f}^c = \dot{m}_{CO_2}$, gives

$$\Delta \dot{m}_{CO_2}^c = (y_{CO_2,out} - y_{CO_2,in}) - \frac{\bar{M}_{in}}{M_c} \frac{\dot{m}_f}{\dot{m}_a} = \Delta y_{CO_2} - \phi_{CO_2}$$

The second term is on the order of 10^{-3} on the same order as the change in concentration and therefore errors in each term can be increased in the subtraction. Two additional variables, \dot{m}_{air} and \dot{m}_f , are brought into the calculation, with the attendant uncertainties for the measurements. The final forms for the efficiencies are

$$CCE = \eta = \frac{\Delta y_{CO_2} - \phi_{CO_2}}{\Delta y_{CO_2} - \phi_{CO_2} + \Delta y_{CO} + N_c \Delta y_{HC}}$$

and similarly

$$DE = 1 - \frac{N_c \Delta y_{HC}}{\Delta y_{CO_2} - \phi_{CO_2} + \Delta y_{CO} + N_c \Delta y_{HC}}$$

The calculation of the partial derivatives for the uncertainty estimate is a little tedious.

There are two additional terms corresponding to \dot{m}_a and \dot{m}_f . The total carbon out is

$$\sigma_c = \Delta y_{CO_2} - \phi_{CO_2} + \Delta y_{CO} + N_c \Delta y_{HC}$$

When using η , δ , and σ_c , the terms from the main text are unchanged. The partial derivatives for the additional terms are

$$\frac{\partial \eta}{\partial \dot{m}_{CO_2}} = -\frac{\varphi_{CO_2}}{\dot{m}_{CO_2}} \sigma_c (1 - \eta)$$

$$\frac{\partial \eta}{\partial \dot{m}_{air}} = \frac{\varphi_{CO_2}}{\dot{m}_{air}} \sigma_c (1 - \eta)$$

This gives the full expression for the uncertainty

$$\varepsilon_\eta = \sigma_c \left[(1 - \eta)^2 (\varepsilon_{CO_2, out}^2 + \varepsilon_{CO_2, in}^2) + \eta^2 (\varepsilon_{CO, out}^2 + \varepsilon_{CO, in}^2) + N_c^2 \eta^2 (\varepsilon_{HC, out}^2 + \varepsilon_{HC, in}^2) + \varphi_{CO_2}^2 (1 - \eta)^2 \left(\frac{\varepsilon_{\dot{m}_{CO_2}}^2}{\dot{m}_{CO_2}^2} + \frac{\varepsilon_{\dot{m}_{air}}^2}{\dot{m}_{air}^2} \right) \right]^{1/2}$$

This formula is still easily implemented in a spreadsheet. However, it is too complex to permit simple analysis as in the main text.