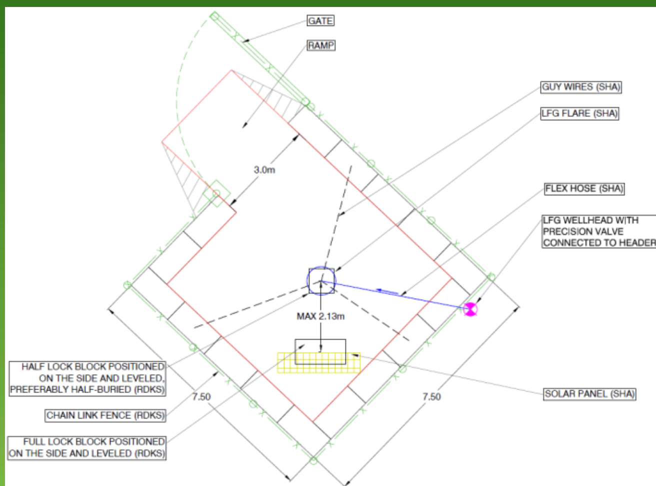
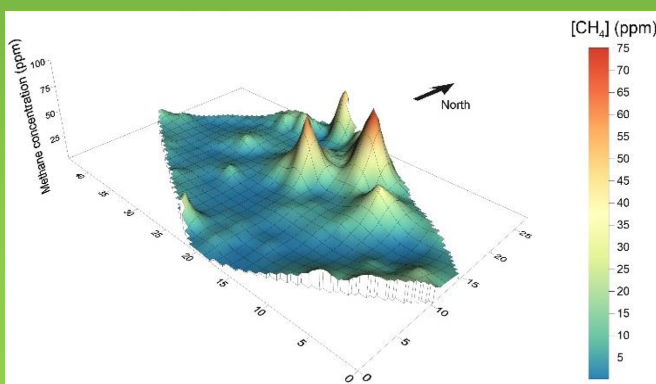
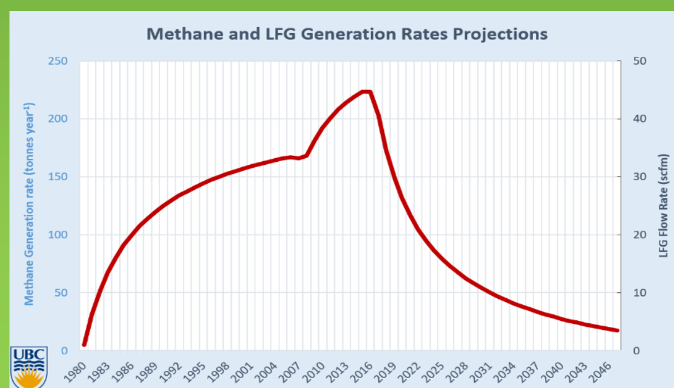
Integrated LFG Control and GHG Emissions Reduction at Thornhill Landfill

(Final Report)







PREPARED FOR: REGIONAL DISTRICT OF KITIMAT-STIKINE

PREPARED BY: SPERLING HANSEN ASSOCIATES

PRJ18059

October 2019

Sperling Hansen Associates

Regional District of Kitimat-Stikine

FCM
Fédération canadienne des municipalités
Federation of Canadian Municipalities

The preparation of this report was carried out with assistance from the Government of Canada and the Federation of Canadian Municipalities. Notwithstanding this support, the views expressed are the personal views of the authors, and the Federation of Canadian Municipalities and the Government of Canada accept no responsibility for them.

October 29, 2019 PRJ18059

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Dear Mr. Prouse,

Re: Integrated LFG Control and GHG Emissions Reduction at Thornhill Landfill

Sperling Hansen Associates (SHA) is pleased to submit the final report for the *Integrated LFG Control and GHG Emissions Reduction at Thornhill Landfill.*

This report includes detailed description and results of (i) advanced LFG generation assessment for the Thornhill Landfill, (ii) comprehensive site investigation to quantify methane emissions from passive gas system as well as surface of the landfill, (iii) installation of Solar Flare system at the Landfill, and (iv) quantification of GHG emission reduction achieve by the solar flare as well as the future biocover system that will be placed at the landfill in summer 2020.

It has been a real pleasure working with you on this project. Should you have any questions or concerns, please don't hesitate to contact us.

Yours truly,

SPERLING HANSEN ASSOCIATES

A. Ab

Dr. Ali R. Abedini
Senior Environmental Consultant
Landfill Gas Specialist

Integrated LFG Control and GHG Emissions Reduction at

THORNHILL LANDFILL

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1 INTRODUCTION

1.1 Background

The Regional District of Kitimat – Stikine (RDKS) Thornhill Landfill (Landfill) was closed in June 2017 using a low permeability clay cap system. The closure design included collection of landfill gas (LFG) from underneath the clay cap where it was eventually vented to atmosphere.

The BC Landfill Gas Management Regulation (Regulation) requires LFG management plans for facilities estimated to generate 1,000 tonnes or more of methane annually. Based on Sperling Hansen Associates (SHA) assessment, the estimated peak LFG annual generation of 223 tonnes of methane occurred in 2016 and annual generation volumes were expected to decrease each year.

Although not required to reduce the fugitive methane (CH_4) emissions from the Landfill, the RDKS with partial FCM Municipalities for Climate Innovation Program funding, conducted a study to evaluate the feasibility of Greenhouse Gas (GHG) emissions reduction through thermal or biological oxidation of the Landfill generated methane. Since methane is a GHG with a global warming potential (GWP) of 25 times higher than carbon dioxide (CO_2), oxidation of CH_4 to CO_2 would significantly reduce the GHG emissions and help the RDKS achieve its carbon neutrality goal.

Under this project, the RDKS retained Sperling Hansen Associates (SHA) to:

(i) assess and quantify LFG generation and GHG emissions from the Landfill through conducting advanced modelling and field measurements,
(ii) assess feasibility of thermal and biological methods for methane oxidation and GHG reduction at the landfill,
(iii) assist the RDKS to implement GHG reduction initiatives if deemed technically feasible, and
(iv) quantify the achieved GHG emissions reductions during the project time frame.

1.2 Scope of the Current Study

The RDKS retained SHA to complete an advanced LFG generation assessment for the Landfill. The assessment included quantifying methane emissions rate from the landfill closure cap system and LFG vents along with proposing a GHG emission reduction system for the Landfill if technically feasible.

The study included the following key tasks:

- Review previous LFG generation assessment for the Landfill;
- Review historical waste tonnages, composition studies and any other related information;

- Complete an advanced LFG generation assessment using UBCiModel©;
- Complete site investigation to quantify methane flow rate vented from the LFG vents;
- Assess and quantify fugitive methane emissions from the entire cap system;
- Recommend remediation technologies and techniques that would result in methane emission reductions from the Landfill;
- Assist the RDKS to implement the suggested techniques; and
- Quantify the actual methane emissions reductions achieved through implementation of the suggested techniques.

1.3 Landfill Information

1.3.1 Landfill

The Thornhill Landfill is located approximately 8 km southeast of downtown Terrace and is operated on a 13.3 ha land parcel leased from B.C. Lands. Landfilling at the site began on an informal basis in the early 1960's, utilizing the area fill method of landfill construction. Sand and gravel cover material was obtained from a borrow pit located on the south side of the site, upslope of the landfill footprint. The landfill footprint occupies 3.7 ha which was fully closed and capped in 2016-2017 with a 600 mm compacted clay cover system. A LFG collection and venting system was installed below the clay cap to passively exhaust landfill generated gas to the atmosphere.

1.3.2 Waste-in-place Tonnage and Composition

Tonnage: SHA has completed several projects for the Landfill since 1996, including several Lifespan Analysis and Updated Filling Plans, Environmental Monitoring Projects, Site Surveys and a Preliminary Closure Design. Based on these site surveys and volumetric analyses, SHA has calculated historical waste tonnages and estimates a total waste-in-place quantity of approximately 180,000 tonnes at the Landfill.

Waste Composition: The RDKS completed comprehensive waste composition studies in 2010 and in 2017. SHA believes the 2010 data better reflects the composition of the waste deposited at the Landfill historically and used the 2010 information to more accurately predict the LFG generation from the Landfill. Figure 1 presents the results of the 2010 Waste Composition Study for the overall received waste in percentages of weight. 'Total Non-Compostable' in Figure 1 was defined as organic materials which are not readily compostable in backyards.

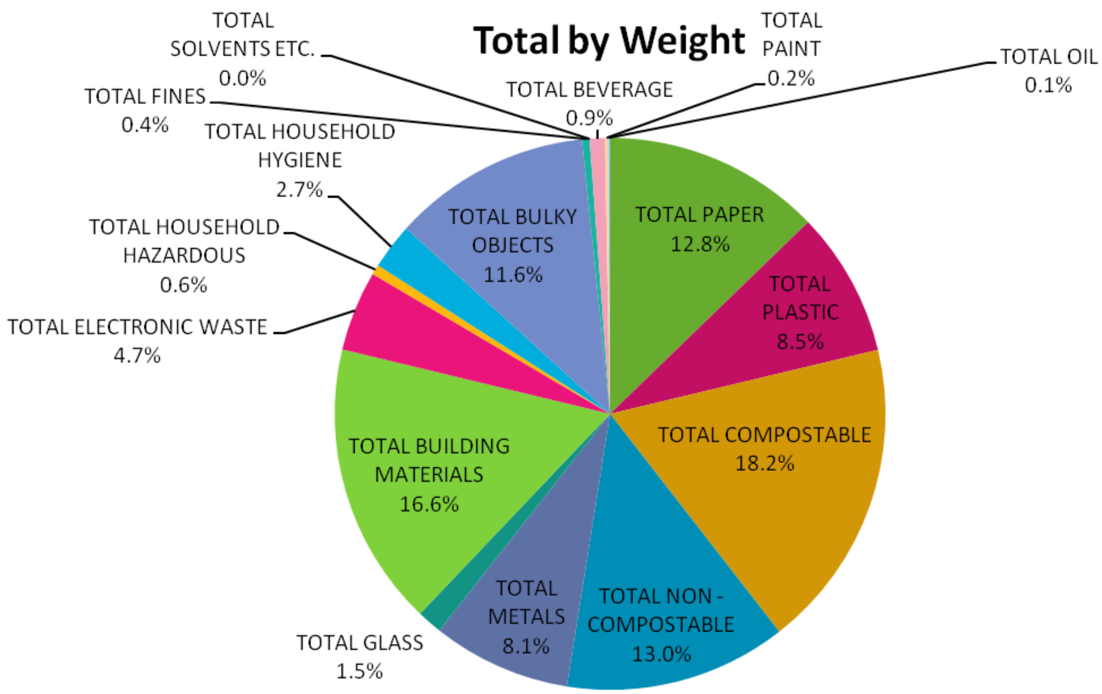

Figure 1 - RDKS 2010 Waste Composition Study Results (Overall Waste by Weight)

1.3.3 Climate Condition

The Landfill is located in a wet region of the province. The temperature and precipitation data from 1981 to 2000 were sourced from the Environment Canada website. Table 1 and Figure 2 summarize the average monthly precipitation and temperature for the Terrace Airport Weather Station. Based on the climate data, the average annual precipitation at the Thornhill Landfill is approximately 1,341 mm.

Table 1 - Climate Data for Terrace Station, 1981 to 2010

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Temperature												
Daily Average (°C)	-3	-0.9	2.4	6.3	10.6	14.2	16.5	16.3	12.1	6.4	0.7	-2.6	**6.6**
Extreme Maximum (°C)	9.4	12.7	16.9	26	34.6	36.5	**37.3**	36.2	32.2	21.4	13.4	11.3	
Date (yyyy/dd)	1962/ 30	2005/ 28	1994/ 28	2005/ 26	1983/ 29	2004/ 20	**2009/ 29**	Nov-90	Jan-74	Feb-93	May-80	1980/ 15	
Extreme Minimum (°C)	-25	-25	-19.4	-8.3	-2.2	0.6	3.3	2.8	-1.4	-13.5	-25.3	**-26.7**	
Date (yyyy/dd)	Jan-69	1956/ 15	Aug-03	Dec-66	1964/ 13	Apr-60	Jan-55	1973/ 31	1983/ 28	1984/ 31	1985/ 26	**1964/ 16**	
	Precipitation												
Rainfall (mm)	91.7	61.8	58.8	64.7	55.7	50.8	52.8	61.2	111.5	185.2	132.2	99	1025
Snowfall (cm)	88.4	51.9	34.3	8.5	0.4	0	0	0	0	4.8	56	87.1	332
Precipitation (mm)	173.5	110.6	92.3	73.7	56.4	50.8	52.8	61.2	111.5	190.3	187.1	180.9	**1341**
Extreme Daily Rainfall (mm)	**115**	79	42.7	43.4	39.6	35.4	39.4	71.8	106.6	114.8	93	111.4	
Date (yyyy/dd)	**2007/ 24**	May-61	1960/ 16	2001/ 24	Mar-85	1993/ 22	1966/ 19	Jun-78	1988/ 28	1978/ 31	Feb-56	Jul-90	
Extreme Daily Snowfall (cm)	99.1	**113.4**	44.2	49.6	6.1	0	0	0	0.3	21.3	39.4	82.8	
Date (yyyy/dd)	1974/ 17	**Nov-99**	2007/ 28	Apr-81	Mar-65	Jan-54	Jan-54	Jan-53	1972/ 27	1956/ 31	2003/ 27	Mar-90	

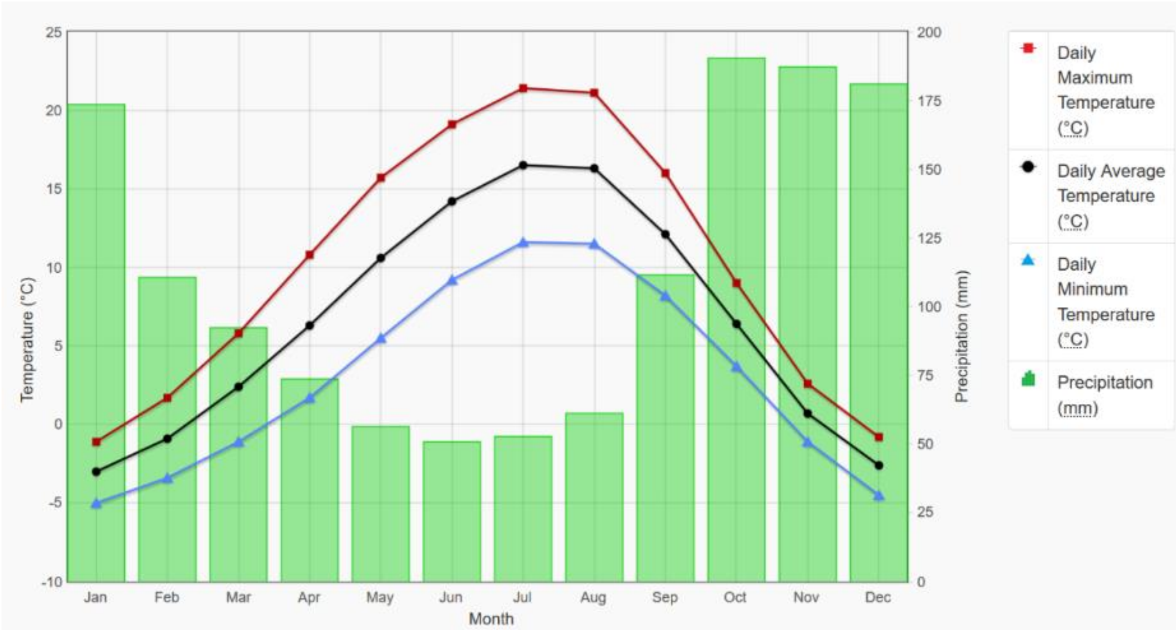

Figure 2 - Temperature and Precipitation Graph for 1981 to 2010 Canadian Climate Normals

2 ADVANCED LFG GENERATION MODELING

2.1 University of British Columbia Integrated Model (UBCiModel©)

The UBCiModel© utilizes variable methane generation potential ($L_{\circ}$) developed based on the dry decomposable organic carbon (DOC_{dry}) historically deposited at the landfill. The variable $L_{\circ}$ reflects the historical changes in waste composition, recycling, and disposal strategies. Degradability and moisture content of each waste component and several other factors defining the ultimate bioavailability of the total deposited DOC are also incorporated into development of the historical and future projection of $L_{\circ}$ for each year throughout the landfill's lifespan. In UBCiModel©, the decay rate (k) for each organic component of the waste is defined based on the biodegradation half-life of that component. Table 2 shows the values for the DOC_{dry} and Table 3 provides the decay rates used by UBCiModel©.

Table 2 - DOC_{dry} Ranges and Default Values Used by UBCiModel©

Waste Components		DOC content in % of dry waste	
		Range	Default
A.	Paper and Cardboard	40 – 50	44
B.	Textiles and Nappies	25 – 50	30
C.	Food waste	20 – 50	38
D.	Wood	46 – 54	50
E.	Garden and park waste	45 – 55	49
F.	Rubber and Leather	47	47
G.	Plastics, Metal, Glass and other inert materials	0	0

Table 3 - UBCiModel© Default Decay Rates

Waste Components	Decay Rates (k, year $^{-1}$)		
Annual Precipitation (mm)	< 500	500 to 1000	> 1000
Food Waste	0.07	0.15	0.35
Yard Waste	0.04	0.08	0.14
Paper and Textile	0.02	0.05	0.07
Wood Waste	0.02	0.03	0.04

Taking great care to analyze the results and findings from the previous projects, SHA completed an advanced LFG generation assessment based on the estimated waste tonnages, waste composition, and the site-specific modeling parameters presented in the tables above.

Model Results:

The model projections of LFG generation for the Thornhill Landfill are provided in Appendix A and an illustration of the projected lifespan LFG generation is provided below in Figure 3.

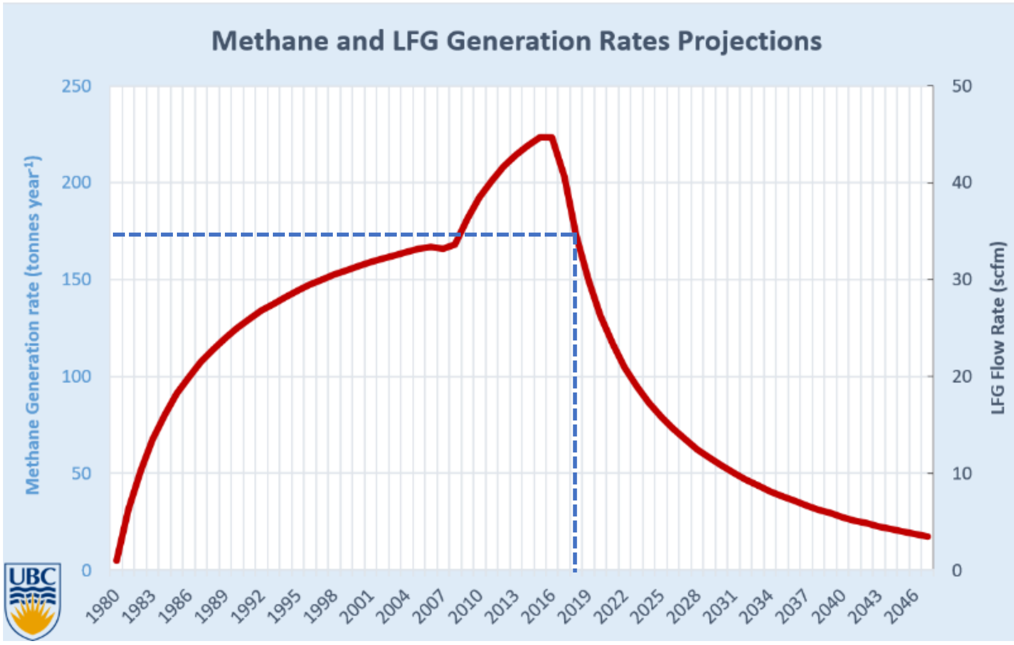

Figure 3 - Landfill Gas Generation Estimate for the Thornhill Landfill

Based on the results achieved from the UBCiModel©, the peak LFG generation from the Thornhill Landfill occurred in year 2016 when the total generated LFG was approximately 44 standard cubic feet per minute (scfm), equivalent to 223 tonnes of annual methane generation. Since then the LFG generation rate has dropped to approximately 34 scfm (i.e. 57.8 m^3/hour) of LFG flow rate equivalent to 173 tonnes of methane per year in 2018. Considering approximately 4 ha footprint of the landfill, this estimated methane generation translates to a methane emission rate of 11.9 g CH_4/m^2/day. A 10-year summary of the model output is presented in Table 4.

Table 4 - Output Summary of the Results

Year of Estimate	LFG Generation (scfm)	LFG Generation (m^3/hr)	Mass of Methane (tonnes/year)
2018	34	58	173
2019	30	51	150
2020	26	44	131
2021	23	39	117
2022	21	36	105
2023	19	32	95
2024	17	29	86
2025	16	27	79
2026	16	27	73
2027	14	24	67
2028	13	22	63

3 FIELD INVESTIGATIONS

As the next stage of the study, SHA completed a comprehensive field investigation including measurements to quantify methane emissions through the LFG collection system and through the low permeability cap system.

A breakdown of the Landfill field work and data analysis including calculation results are presented below.

3.1 Passive LFG Control System Monitoring

SHA's first task was to review the existing LFG collection system's passive venting network to determine the most appropriate sampling and monitoring location, assess the quality and quantity of venting gas, and determine if installation of a passive LFG flare system would be technically feasible for the site.

During the field work, SHA regularly monitored gas pressure and gas composition from LFG collection system sampling ports installed on Vent #2, Vent #3, and clean outs CO #6 and CO #10 as shown on Figure 4. All vents were blocked with Fernco caps to prevent the LFG system from venting and to facilitate collection of gas from monitoring ports. Monitoring station Vent #3 was used for the majority of the gas flow data collection and monitoring station Vent #2 was used during the last day of the field work while gas composition data was observed and recorded from all vents.

Photo 1 shows flow monitoring set up at Vent #3 using a low flow venturi wellhead, a thermo anemometer flow measurement device and a GEM2000+ gas analyzer. Photo 2 shows an example of monitoring gas pressure on the capped vents using a digital manometer.

During SHA's field work, the following data was collected and recorded multiple times during each working day:

- LFG velocity and flow from the central monitoring points - Vent #2 or Vent #3
- LFG quality (CH_4, CO_2, O_2, H_2S, CO and Balance Gas) at all monitoring points
- LFG pressure at all monitoring points
- Atmospheric pressure, and
- Ambient condition fluctuations

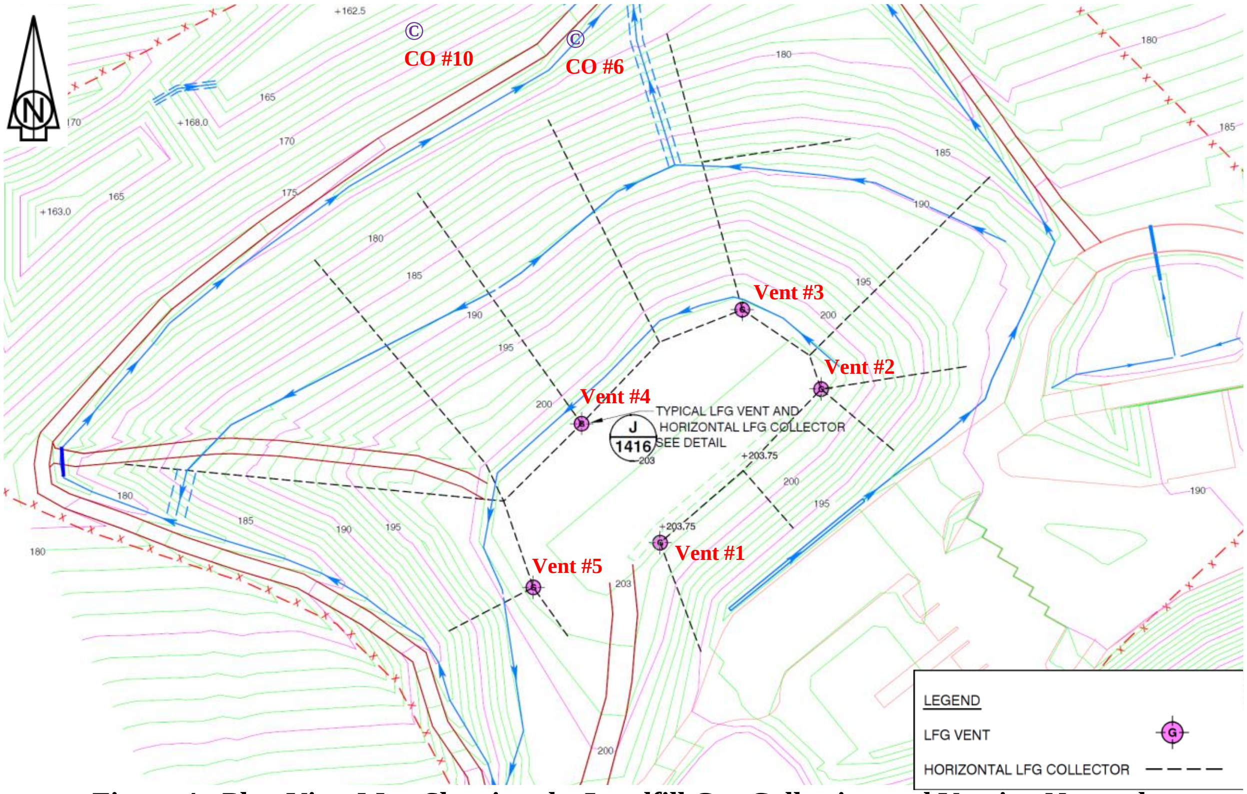

Figure 4 - Plan View Map Showing the Landfill Gas Collection and Venting Network

Photo 1 – LFG Monitoring - Vent #3

Photo 2 – Capped Vents Gas Pressure monitoring

3.2 Fugitive Methane Emission Monitoring

SHA's second main task was to quantify fugitive methane emissions from the surface of the closed Thornhill Landfill and to assess whether application of a fabricated biocover system would be beneficial to contribute to overall GHG emissions reductions at this facility.

3.2.1 GHG Emissions Measurement Technique

The technique adopted to quantify the fugitive methane emission at the Thornhill Landfill is a patented methodology developed through the PhD research of Dr. Ali Abedini at UBC (Abedini, 2014, Abedini et al., 2019). Abedini's methodology was developed based on comprehensive field investigations completed at the Vancouver Landfill and involves measurement of surface methane concentrations (SMC) from the area of interest using a flame ionization detector (FID) device.

The set of techniques and procedures used for measurement of SMC using a hand-held FID is an approved methodology used across the US, where it is required by the U.S. Environmental Protection Agency's (EPA) new source performance standard (NSPS) regulation. The NSPS requires all the regulated landfills in the US to measure and report methane concentrations at the landfill's surface on a quarterly basis. Values registered above the NSPS threshold during the FID scan imply a malfunctioning LFG control system and the owner is then required to implement control measures within a given period of time. Abedini (2014) developed a correlation between qualitative SMC data and quantitative surface methane emission rates (MER). This technique is especially useful when MER levels are very low and other measurement techniques such as flux chamber cannot be applied (e.g. in case of a biocover system surface, landfills with low methane generation rates, and/or landfills with active gas collection systems).

Photo 3 - Surface Methane Concentration Scan Using a Portable FID Instrument

In this project, the SMC scan was conducted over the entire closure surface of the Thornhill Landfill. As shown in Figure 5, the closure surface was divided into 7 different zones tagged as Slope 1 (Area S1), Slope 2 (S2), Slope 3 (S3), Slope 4 (S4), Slope 5 (S5), Slope 6 (S6), and Crest (C). A Thermo Scientific TVA 2020 FID instrument was used to measure and log methane concentrations at these measurement surfaces. The area was scanned in 10 meter to 20 meter spaced pathways while logging methane concentration every 3 seconds. The FID instrument was calibrated using calibration gas before conducting each set of measurements. The FID instrument was also tested using the same calibration gas to detect any calibration drift during the field work. Photo 3 shows Dr. Abedini conducting FID measurements at the Thornhill Landfill.

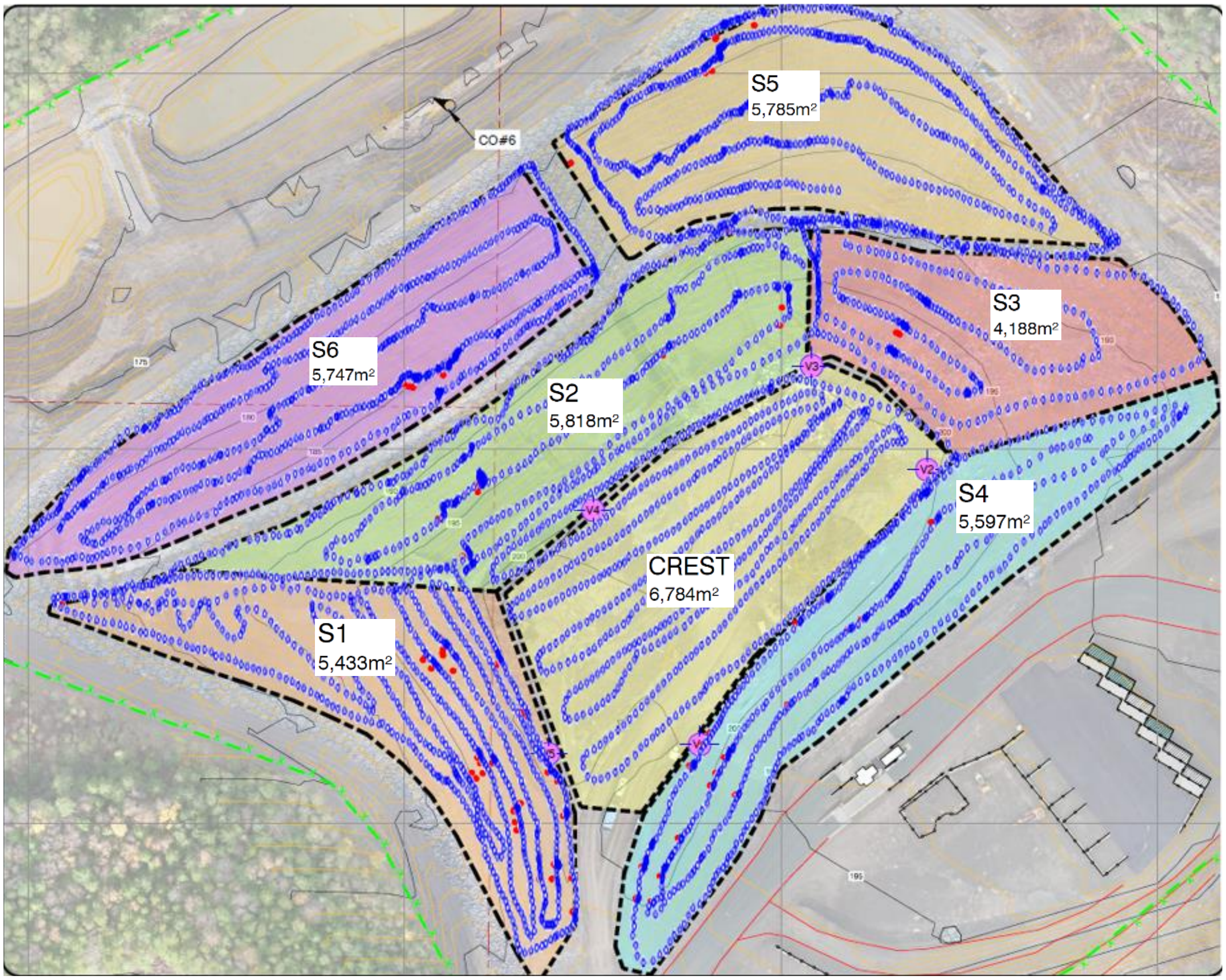

Figure 5 - Methane Emissions Surface Scan Walking Pathways

3.2.2 Barometric Pressure Fluctuations

An important aspect in monitoring methane emission from landfill surfaces and passive LFG vents is the effect of barometric pressure (BP) on the pressure build-up within the landfill. When the BP is high, the heavier atmospheric pressure is applied on the ground, restricting natural LFG venting through the landfill surface. Low BP reduces the pressure exerted on the ground, enabling LFG to move more freely from the landfill and increasing the potential for gas escape by surface emission or through the LFG vents. Typically, a slight natural decrease in BP occurs daily between morning and afternoon hours. However, in some days this trend can be the opposite, during which no reliable gas composition or flow should be recorded as reliable data. Furthermore, it should be noted that during BP increasing trends, ambient air would intrude into the landfill through the LFG vents. Therefore, a drop in the LFG quality (methane concentration) is expected during the next monitoring day or next monitoring event.

SHA's LFG specialist, Dr. Abedini, developed a mathematical correlation between rate of change in BP and surface methane emission during his PhD at UBC (Abedini et al., 2016). While there is no approved methodology to adjust gas vent's flow rates to account for barometric pressure changes during the field measurement, SHA used the rational developed by Abedini et al. (2016) to estimate the adjusted LFG flow rate as well as the surface GHG emissions for the Thornhill Landfill as shown below:

$$MERa = MER \times (1 + 1.9731 \times \Delta P/t)$$

Where:

MER = Methane Emission Rate (scfm)
MERa = Adjusted MER
$\Delta P/t$ = Rate of change in Barometric Pressure (mbar/hr)

SHA monitored the BP levels during the field work. This information was also later acquired from the Terrace Airport Weather Station for the days of field investigation. The BP data were used to make necessary adjustments when calculating the methane emission rates from the Landfill. Figure 6 below illustrates the hourly variations in atmospheric pressure and temperature in the Terrace area recorded for Day-4 of SHA's field work onsite. Full BP data is illustrated in Appendix B.

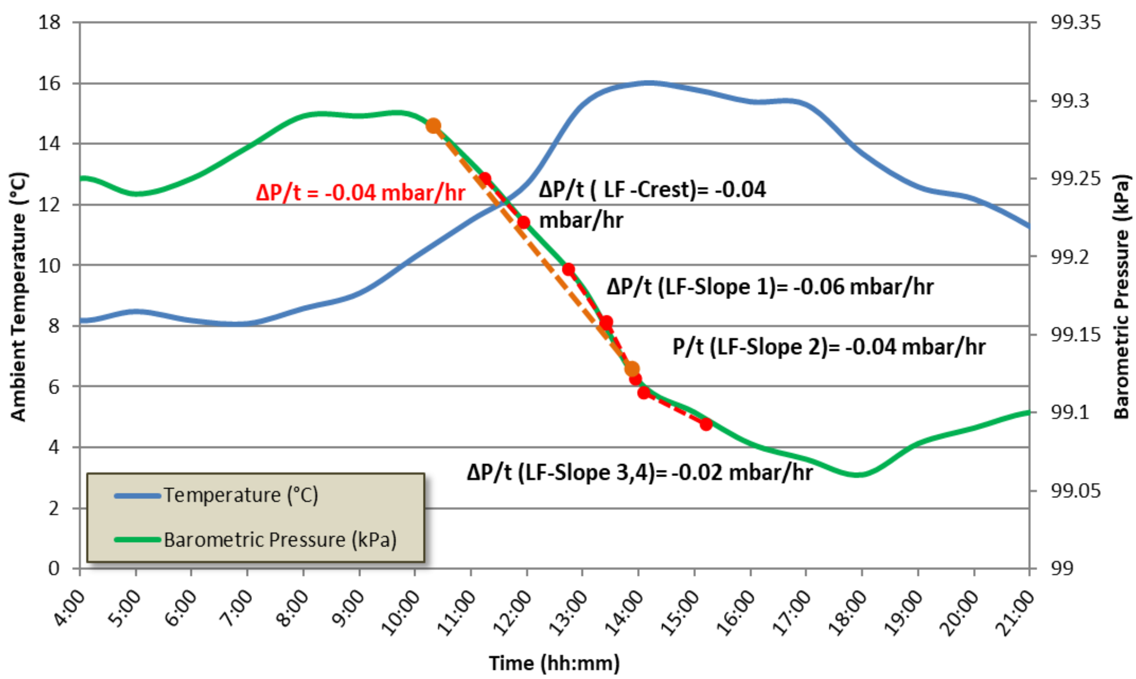

Figure 6 - Example of BP Changes During the Field Work – Day 4, Sep. 20, 2018

3.3 Field Investigations Results

3.3.1 Passive LFG Collection System Data

Gas Quantity:

Passively vented LFG flow rate was measured from Vent #3 for the first 4 days and from Vent #2 during the 5th day of the field work. SHA used three different methods to quantify the flow rate: (i) a thermo-anemometer to measure gas velocity and calculate flow rate, (ii) a 1" flow-wing wellhead and a digital manometer to measure differential pressure and calculate the flow rate, and (iii) a bag with a known volume and recorded the time that it took to fill up the bag. All these tests confirm very low gas flowing from the open vent. We concluded approximately 1 to 2 scfm of LFG flowing out of the passive vents. In the best case, we recorded 2 scfm of LFG venting from Vent #2 with 43% methane content. This is equivalent to approximately 9 tonnes of annual methane emission from the passive LFG collection system.

Gas Quality:

The full set of data collected and recorded from the 6 vents is presented in Appendix C. Figures 7 and 8 illustrate a summary of gas quality (i.e. methane volumetric percentages) at these two vents during the field tests. Gas quality graphs for capped vents are presented in the enclosed Appendix C.

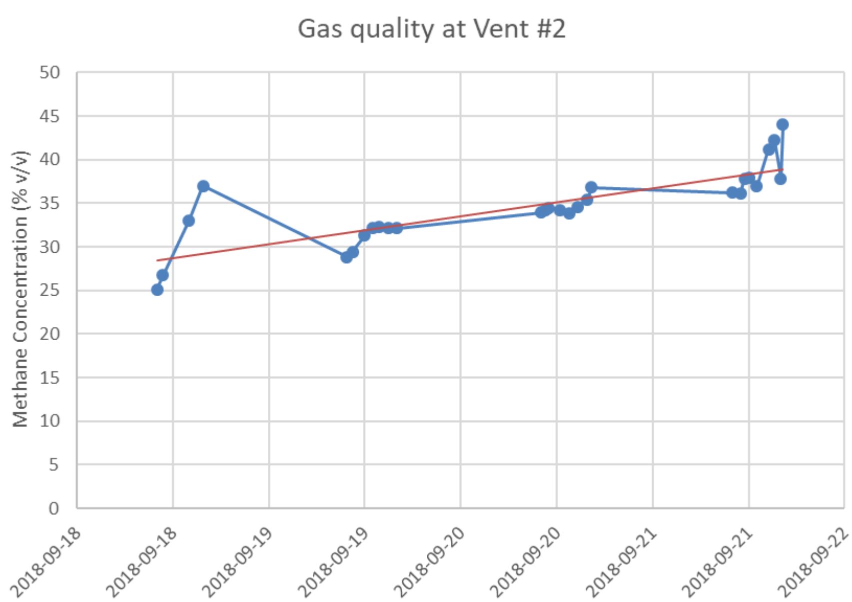

Figure 7 - LFG Quality Data for Vent #2 - Thornhill Landfill

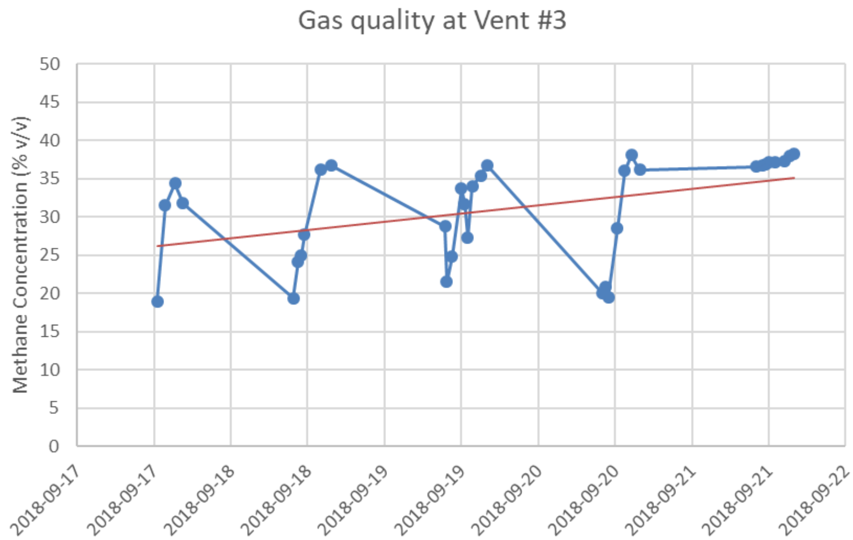

Figure 8 - LFG Quality Data for Vent #3 - Thornhill Landfill

The gas quality in Vents #2 and #3 fluctuated with a daily increase and sharp drops during the night. This is due to BP fluctuations that was previously discussed in Section 3. Nevertheless, the overall quality of the gas collected continued to improve during the 5-day field investigations. 'Best fit' lines are shown within the plotted data set in Figures 7 and 8 that show increase in methane concentrations over the five days onsite. With all the vents onsite capped, we would expect the concentrations of methane to increase over time as the blocked vents prevented ambient air from being drawn into the landfill and diluting the methane concentrations. During SHA's visit, the methane concentration percentage reached approximately 45% in Vent #2 on Day 5 of field work. SHA predicts that the methane concentrations will stabilize around 45%, which is the percent of methane being generated by the landfill without being diluted during sharp and sudden increases of barometric pressure and 'negative venting periods.'

The minimum gas quality and quantity requirement by a small passive flare system is 5 scfm flow rate of LFG gas at approximately 30% methane content. Therefore, SHA recommended installing a small solar powered fan in the design of the passive flare system to secure a sustainable flow rate of 5 to 10 scfm at the flare tip. The increased LFG flow will partly cause dilution in the collected gas and partly reduce the fugitive methane emissions currently occurring from the clay cap system. Therefore, SHA also recommended the inclusion of a "low LFG flow tube" as well as a wind shield at the flare tip.

<u>Conclusive Remarks and Recommendations for Next Steps:</u>

Installation of a low-cost, low-flow solar powered flare was recommended to the RDKS.

Field investigation results indicated the installation of a low flow solar candlestick flare at the Thornhill Landfill was feasible. Even though the flare may not operate 100% of the time as a result of low flow or diluted gas conditions, the recommended flare's continuous solar powered sparker would ignite the flare when methane concentrations exceed 30% by volume.

Additionally, SHA concluded that if a biocover system is placed in addition to installation of the flare system, the LFG quality and quantity will be improved at the central vent. This will likely result in achieving a higher annual GHG reduction at the flare facility.

3.3.2 Fugitive Methane Emissions from Landfill Cover

FID Surface Scan:

The fugitive methane emissions from surfaces of the Thornhill closure system was measured over two consecutive days. The closure surface was divided into 7 different zones as shown in the enclosed Drawing 1. Methane concentrations at the surface of the landfill were measured and emission hot spots were identified and tagged using a handheld GPS device. Photos 4 and 5 below show SHA staff recording the hotspot coordinates. Figure 9 and the enclosed Drawing 1 show the approximate locations of methane emission hotspots.

Photos 4 & 5 – Identifying Emission Hotspots during Baseline Emission Surface Scan

Figure 9 - Methane Emission Hotspots at the Thornhill Landfill

The average methane emission rates (MER) from each zone was estimated using Abedini's methodology and based on the measured surface methane concentration (SMC) data (Abedini et al., 2014). Baseline surface scan field measurements showed average SMC values between 0.46 part per million volume (ppmv) and 39.42 ppmv with an overall average of 7.9 ppmv. This SMC level translates to an annual methane emission rate of 107.6 tonnes/year from surfaces including cracks, fissures and surface ditches based on Abedini's methodology and Chanton (2014). Table 5 below presents a summary of the surface scan field data for each of the zones. A summary of the results as well as a 3D illustration of surface methane concentration data are presented in Appendix D.

Table 5 - Summary of Surface Methane FID Scan Data - Thornhill Landfill

Grid Number	Area	Surface Methane Concentration		
		MIN	MAX	AVG.
	(m^2)	(ppmv)	(ppmv)	(ppmv)
Slope 1 (S1)	5,433	0.0	64.79	2.74
Slope 2 (S2)	5,818	0.0	96.39	4.19
Slope 3 (S3)	4,188	0.0	299.58	5.02
Slope 4 (S4)	5,597	0.0	3,250.05	39.42
Slope 5 (S5)	5,785	0.0	480.22	3.99
Slope 6 (S6)	5,747	0.0	25.48	0.46
Crest (C)	6,784	0.28	21.50	0.63
TOTAL	**39,352**			**7.90**

Biological Oxidation of Methane using Biocover Systems:

Methane (CH_4) oxidation in landfill cover soil reduces GHG emissions from landfills. There are a number of published and peer reviewed scientific research papers that have reported CH_4 oxidation fractions through operational soil cover at 22-55% (Whalen, Reeburgh et al., 1990; Chanton, Powelson et al., 2009; Chanton, Abichou et al., 2011). Abedini et al. (2016) showed 28% to 34% oxidation occurring at the cover soils of the Vancouver Landfill in BC. However, considering the very porous type of soil placed over the clay cap at the Thornhill Landfill, SHA concluded a 10% baseline oxidation for this site. For engineered fabricated biocover, this rate is reported to be between 50-100%, depending on the methane loading rate provided to the biocover (Barlaz, Green et al., 2004; Stern, Chanton et al., 2007; Abichou, Mahieu et al., 2009). SHA has designed and installed several biocover and biofilter systems at a number of landfills in B.C. (e.g. Fernie Landfill, Skimikin Landfill, 7 Mile Landfill, Nanaimo Landfill, Central Subregion Landfill, Campbell Mountain Landfill). In these projects SHA used a fabricated media appropriate for growth of methanotrophic bacteria and results showed 80 – 100% oxidation of the fugitive methane.

Conclusive Remarks and Recommendations for Next Steps:

SHA has recommended the RDKS proceed with application of a biocover system at the Landfill.

The baseline surface scan completed at the Thornhill Landfill showed methane loading rate ranging between 2.3 and 16.1 $gCH_4/m^2/day$. SHA believes that this low level of methane loading rate (methane emission rate) can be effectively managed using a thin layer if fabricated biocover system achieving higher than 75% methane emission reduction. However, considering the weather data presented in Table 1 and Figure 2, SHA conclude that the biocover system will most likely be effective through April to October of each year. Based on a global warming potential (GWP) of 25, it was concluded that a GHG reduction of 1,035 tonnes CO_2-e can be achieved by application of a biocover system at Thornhill Landfill.

4 IMPLEMENTATION OF GHG REDUCTION INITIATIVES

4.1 Solar Spark Flare

According to the BC LFG Management Protocol, a candlestick flare has 96% methane destruction efficiency when the flare sustains a flame at temperature of 260°C and higher. Considering the quantity and quality of the LFG at the Landfill, SHA recommended a low-flow solar spark system to be installed at the Landfill. Based on our experience in previous similar projects implemented in BC, we found a CF-5 Solar Spark Candlestick Flare to be the most suitable option for Thornhill Landfill.

This open flare is capable of combusting LFG containing a minimum of 30% methane and at flow rates between 5 scfm to 90 scfm. The system also includes a solar-powered continuous-ignition system, a solar-powered vacuum fan, and a thermocouple with a data logger kit allowing continuous logging of the flare temperature. The fan provides a minimum continuous flow rate of approximately 10 scfm or higher through the flare. Additionally, SHA recommended a QED Environmental Systems precision wellhead, a gas flow control and metering station, to be installed on Vent #2. The precision wellhead, along with the Landtec GEM LFG analyzer, allows for controlling the LFG flow rate and monitoring the gas methane content.

4.1.1 Thornhill Landfill Flare Installation

Installation of the solar flare system at the Landfill was completed in September 2019. Prior to the flare installation, SHA assisted the RDKS to (i) procure solar flare parts, LFG wellhead, and (ii) design and build a flare pad using lock block separation walls and clean fill material. The pad was designed to provide solid ground for the flare and solar panels, as well as to accommodate the future installation of 500 to 600 mm topsoil or biocover on the landfill. As previously recommended by SHA, the pad was constructed adjacent to Vent#2 location, using this location as a central gas extraction point. Following initial installation, RDKS staff made improvements including additional solar panel bracing and a support for the gas pipe feeding flare.

Figure 10 illustrates the flare pad design for the landfill.

Photos 6 to 12 show the flare pad construction and flare installation stages.

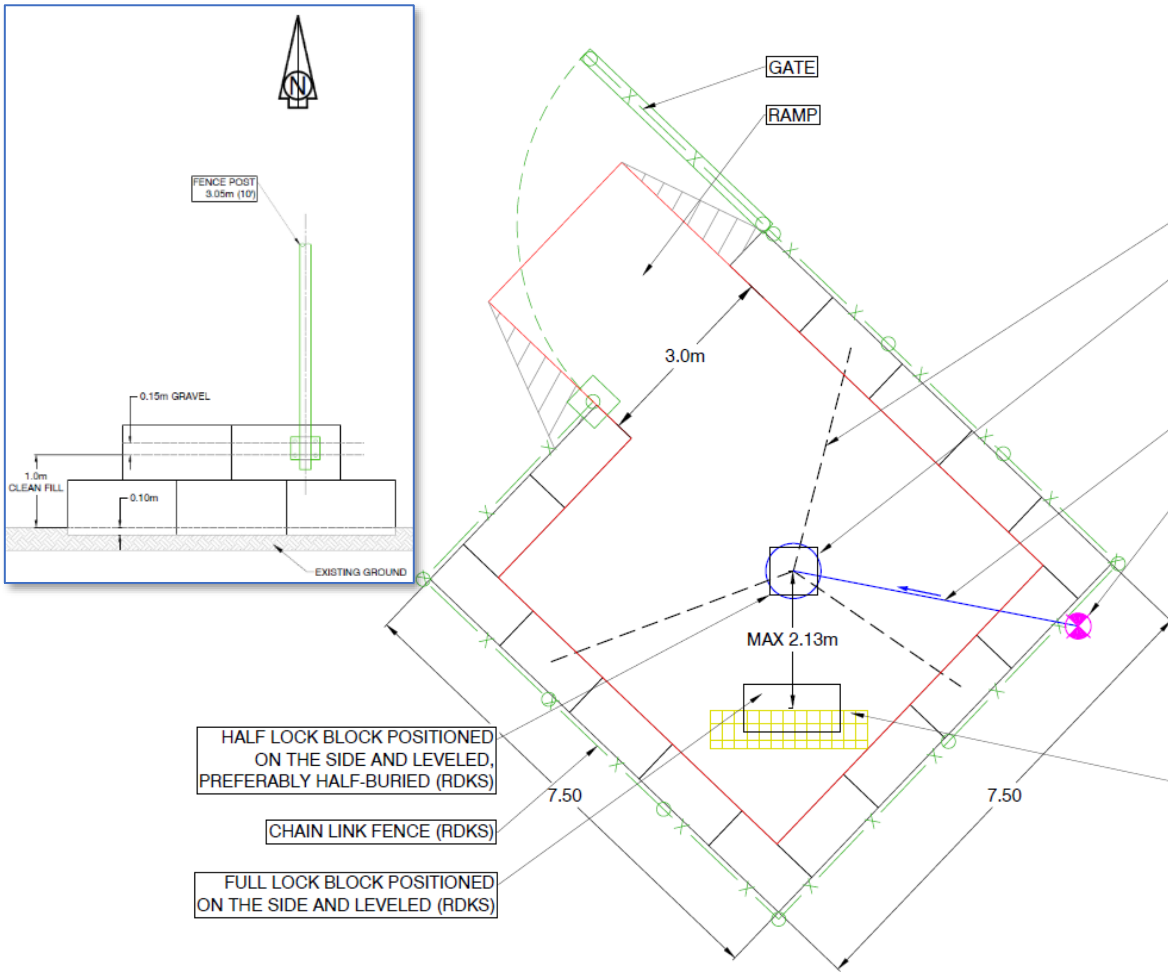

Figure 10 - Thornhill Landfill Flare Pad Design

Photo 6 – Flare Pad Construction – Lock Block walls completed

Photo 7 – Flare Pad Completed

Photos 8 & 9 - RDKS and SHA Staff installing Solar Spark Flare

The selected Vent#2 was replaced by a precision valve QED wellhead, proper size of Orifice Plate (OP) was installed, and the control value was adjusted to appropriate opening position for start-up. The Flare was commissioned immediately after main installation works that were completed on August 19, 2019. Monitoring data on August 20 showed approximately 11 to 15 standard cubic feet per minute (scfm) gas flow at 31.5% methane content.

Photos 10 & 11 – Precision Wellhead and Orifice Plate

Photo 12 – Thornhill Flare During Installation (August 19, 2019)

Upon completion of flare installation, the RDKS staff were informed on how to monitor, maintain and troubleshoot the flare system. Quantification of annual GHG reduction achieved by the flare would be possible if flare temperature, gas composition, and gas flow rate are known

4.2 Flare System Monitoring Data

In order to predict annual GHG reduction, one set of monitoring data were collected during second day of flare installation. While future data may be slightly different from these initial readings, these data provide a good understanding of potential GHG reductions in 2019 and coming years.

4.2.1 Flare Temperature

Flare temperature data were downloaded from the system data logger. Data were compiled and illustrated in Figure 11 below.

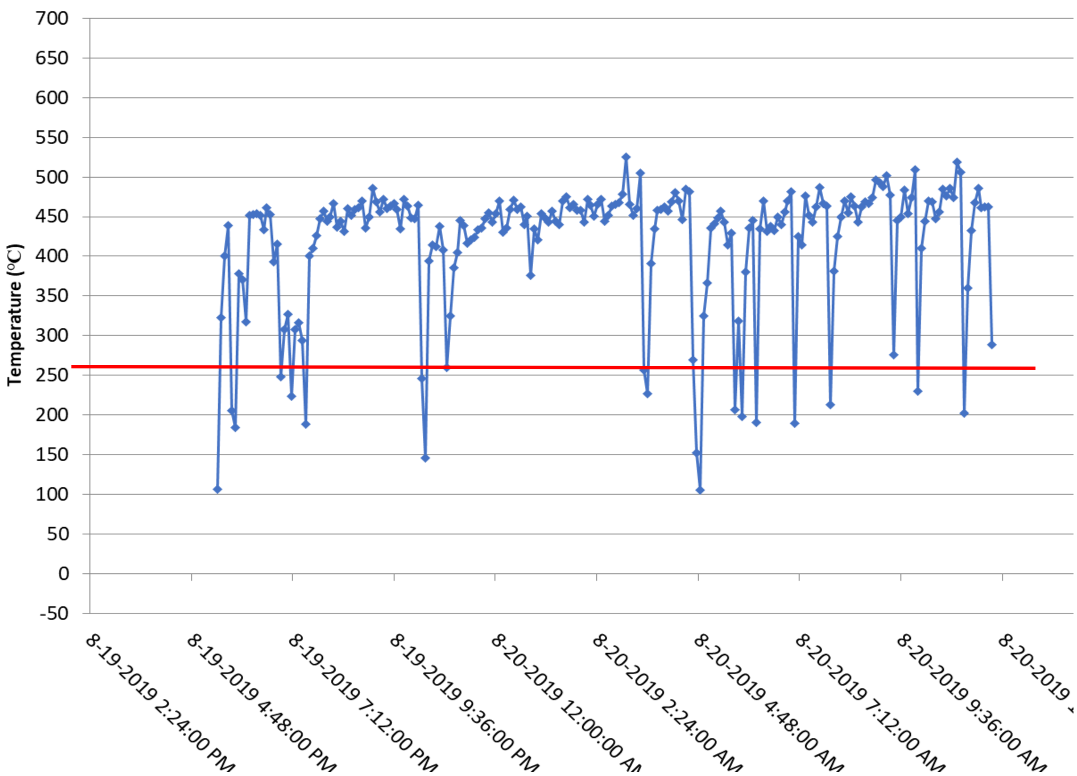

Figure 11 -Thornhill Landfill Flare Temperature Data

Based on these interim data, Thornhill Flare's temperature was recorded above 260°C for 91% of the duration that data was recorded.

4.2.2 Landfill Gas Quality and Flow Rate Data

The composition and flow rate of the LFG collected and combusted at the Landfill was measured using a Landtec GEM2000+ LFG analyzer. SHA conducted field readings on the second day of the field visit. The methane concentration in the collected LFG during the monitoring day was 31.4%. We used this information to calculate the estimated annual quantity of methane that will be captured and flared at the Landfill in a typical year. Table 6 below shows the collected LFG composition and flow rate data from the Landfill on August 20, 2019.

Table 6. LFG Flow Rate and Composition at the Thornhill Landfill

Date	CH_4 (%)	CO_2 (%)	O_2 (%)	Balance (%)	Flow Rate (scfm)
LFG Quality August 20, 2019	**31.4**	25.5	2.2	40.9	**11-15 (Avg. 13)**

4.2.3 Annual GHG Emission Reduction Quantification

The total estimated methane that would be combusted at Thornhill Landfill flare during a typical year was calculated based on the following parameters:

1. LFG flow rate (Table 6)
2. Methane content in the collected LFG (Table 6)
3. Methane density at standard temperature and pressure (15 °C and 1 atm (CRA, 2013))
4. Flare Temperature (above 260°C status) (Figure 11)
5. Flare destruction efficiency (96% (CRA, 2013))

Based on the collected data and assuming the same runtime of 91% will be achieved during a typical year, SHA estimates that a total of 36 tonnes of methane would be combusted at the Thornhill Landfill every year. Therefore, total GHG emissions reduction that can be achieved with this initiative would be approximately 900 tonnes of CO_2-e. The GHG offset calculation is based on the methane's global warming potential (GWP) of 25 (BC MOE, 2014). A summary of the aforementioned parameters and the calculated values are presented below:

Open Flare Destruction Efficiency:	96	%
Methane GWP:	25	tonne/tonne
Methane Density:	0.678	kg/m^3
Standard Pressure:	1	atm
Standard Temperature:	15	°C
LFG Flow Rate:	13	scfm
Methane Content:	31.4	% by volume
Average LFG Flow Rate:	22.1	m^3/hr
Total Methane Collected in a year:	41.2	tonnes/year
Total Methane Destructed in a year:	36.0	tonnes/year
Estimated GHG Emissions Reduction per year:	**900**	**tonnes CO_2-e/year**

4.3 Next Steps and Future Biocover Application

SHA is working with Metro Vancouver and the RDKS on transporting dried bio-solids from the Iona Island wastewater treatment plant in Richmond BC, to the Thornhill Landfill. The bio-solids will be used with sand and woodwaste (hog fuel) to produce an Engineered Biocover blend. The engineered biocover will not only assist with attenuating fugitive methane emissions from the entire landfill closure cover, but also will help the cover to support the required vegetative closure cover and reduce erosion risk from heavy rainfall events.

In addition to using bio-solids for landfill closure and to reduce GHG emissions, Metro Vancouver biosolids have been used in mines reclamation projects and local government landscaping initiatives.

Moving forward, a detailed biocover fabrication and application plan will be prepared covering the following aspects:

- Regulatory Considerations – the RDKS / SHA will work with a consulting agrologist to complete the required notifications, plans, and consultation prior to importing materials to the site.
- Biocover Mix Design - a site-specific mix design will be determined.
- Cost Identification – a cost assessment, based on the mix designs, will be completed so that all parties are aware of the capital and operational costs associated with the biocover application program.
- Vegetation control – appropriate control measures for the vegetation will be determined in consultation with a QP; this may include manual removal (cutting/brushing) and/or chemical treatment (herbicide) of the existing vegetation.
- Biocover Fabrication – fabrication and blending of the material will occur on the crest of the landfill. Ideally, the blended materials will be stockpiled or windrowed along the perimeter of the landfill so that the material can be applied with minimal double-handling. This will require access and stockpile areas be well thought-out prior to material being received at the site.
- Biocover Application – an application plan will be prepared for the site that provides efficient application while considering the site's topography (i.e. slope ditches) etc.
- Hydroseeding Plan – the RDKS will work with a QP to determine an appropriate seed-mix for the site. Hydroseed will be applied before winter 2020.

5 SUMMARY AND CONCLUSIONS

The RDKS wanted to implement GHG emissions reduction initiatives at its closed Thornhill Landfill. SHA conducted an advanced LFG generation assessment showing approximate methane generation of approximately 170 tonnes CH_4/year and dropping at an approximate rate of 10% per year. SHA also completed a comprehensive 5-day field investigation quantifying (i) methane venting from the existing passive LFG collection system, and (ii) fugitive methane emissions from the surface of the closure system.

The Thornhill Landfill LFG collection system was open and passively venting / breathing aerobically since the final closure construction in 2016/2017. As a result, our field data showed an initial low methane concentration in the vented gas. Methane concentration increased from approximately 20% to 45% over the course of the field work. SHA also completed a full-scale fugitive methane emissions measurement from surface of the closure system. These investigations showed a methane emission rate of 2.3 to 16.1 gCH_4/m^2/day being emitted through the low permeability cap system. This emission rates are equivalent to an annual methane emission of approximately 110 tonne CH_4/year emitting from soil cover, surface ditches etc.

SHA assisted the RDKS to purchase and install a low-cost solar flare system. Flare system successfully commissioned in August 19, 2019. Our initial assessment and calculations show that the flare system will combust approximately 36 tonnes of methane per year equivalent to 900 tonnes of CO_2-e GHG emissions reduction. The initial monitoring data showed that installed flare system has an overall efficiency of 87%. This is a great achievement resulted by implementation of this project.

Additionally, SHA and RDKS are actively exploring placement of a fabricated biocover that can achieve more than 75% oxidation of the fugitive methane from the cover soil. SHA estimated that this initiative will result in an approximately an additional GHG emissions reduction of 1,035 tonnes of CO_2-e/year. The Biocover system is planned to be installed in summer 2020.

6 LIMITATIONS

This report has been prepared by Sperling Hansen Associates (SHA) on behalf of the Regional District of Kitimat-Stikine (RDKS) in accordance with generally accepted engineering practices to a level of care and skill normally exercised by other members of the engineering and geo science professions currently practicing under similar conditions in British Columbia, subject to the time limits and financial and physical constraints applicable to the services. The report, which specifically includes all tables and figures, is based on engineering analysis by SHA staff on data compiled during the course of the project. Except where specifically stated to the contrary, the information on which this study is based has been obtained from external sources. This external information has not been independently verified or otherwise examined by SHA to determine its accuracy and completeness.

SHA has relied, in good faith, on this information and does not accept responsibility for any deficiencies, misstatements or inaccuracies contained in the reports as a result of omissions, misinterpretation and/or fraudulent acts of the persons interviewed or contacted, or errors or omissions in the reviewed documentation. The report is intended solely for the use of the RDKS.

Any use which a third party makes of this report, or any reliance on, or decisions to be made based on it, are the responsibilities of such third parties. SHA does not accept any responsibility for other uses of the material contained herein nor for damages, if any, suffered by any third party because of decisions made or actions based on this report. Copying of this intellectual property for other purposes is not permitted. The findings and conclusions of this report are valid only as of the date of this report. The interpretations presented in this report and the conclusions and recommendations that are drawn are based on information that was made available to SHA during the course of this project. Should additional new data become available in the future, SHA should be requested to re-evaluate the findings of this report and modify the conclusions and recommendations drawn, as required.

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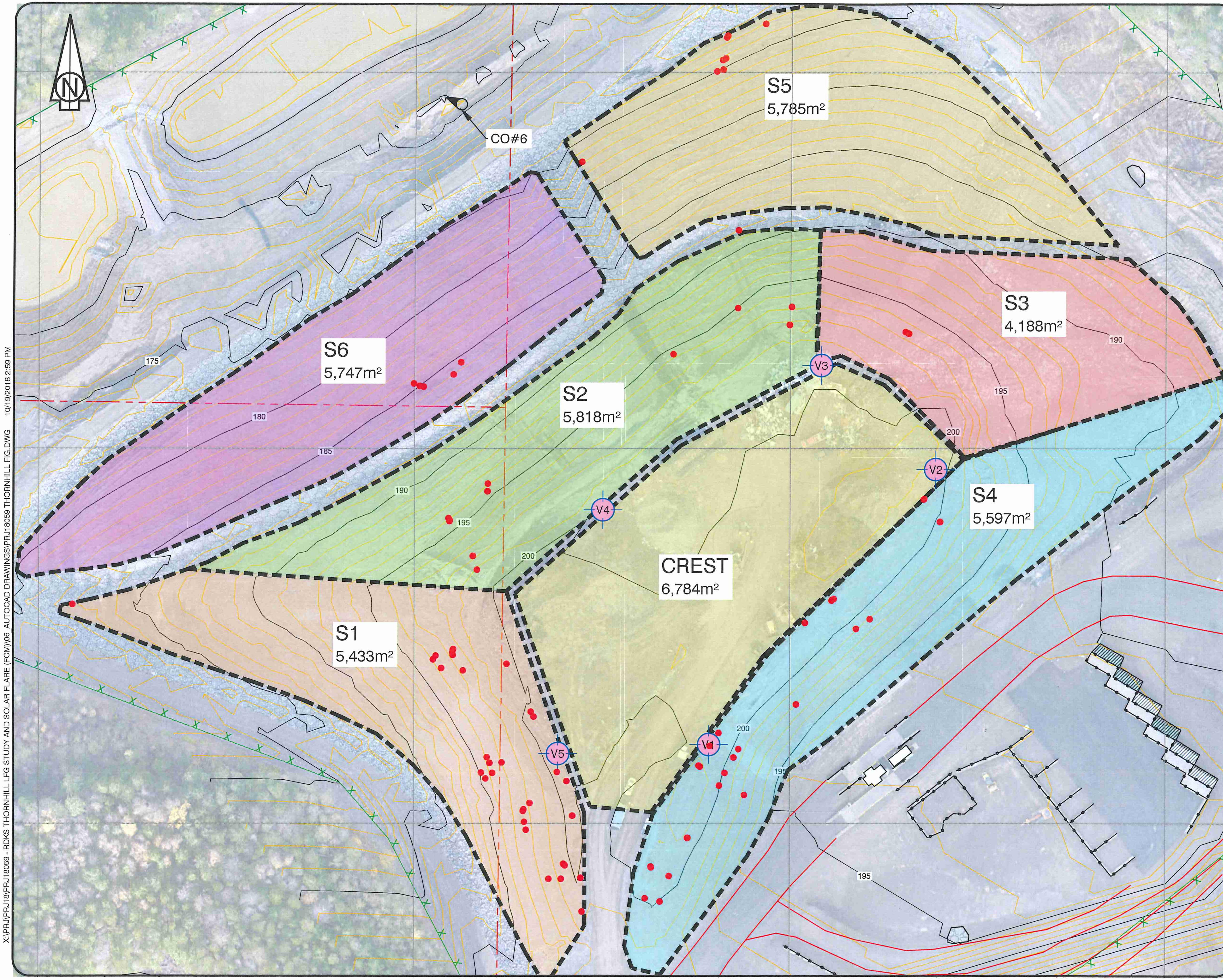

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LEGEND:

- 5m EXISTING CONTOUR
- 1m EXISTING CONTOUR
- METHANE EMISSION HOTSPOTS
- APPROXIMATE SURFACE SCAN ZONES

CLIENT:

Regional District of Kitimat-Stikine

PROJECT:

RDKS THORNHILL LFG STUDY AND SOLAR FLARE (FCM)

TITLE:

STUDY AREAS AND METHANE EMISSION HOTSPOTS (EXISTING TOPO JULY 2017)

SCALE:	DATE:	PROJECT NO:
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DESIGNED	AA	DRAWING NO:
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CHECKED	AA	

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APPENDICES

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Appendix A:
UBCiModel LFG Generation Estimates Full Results
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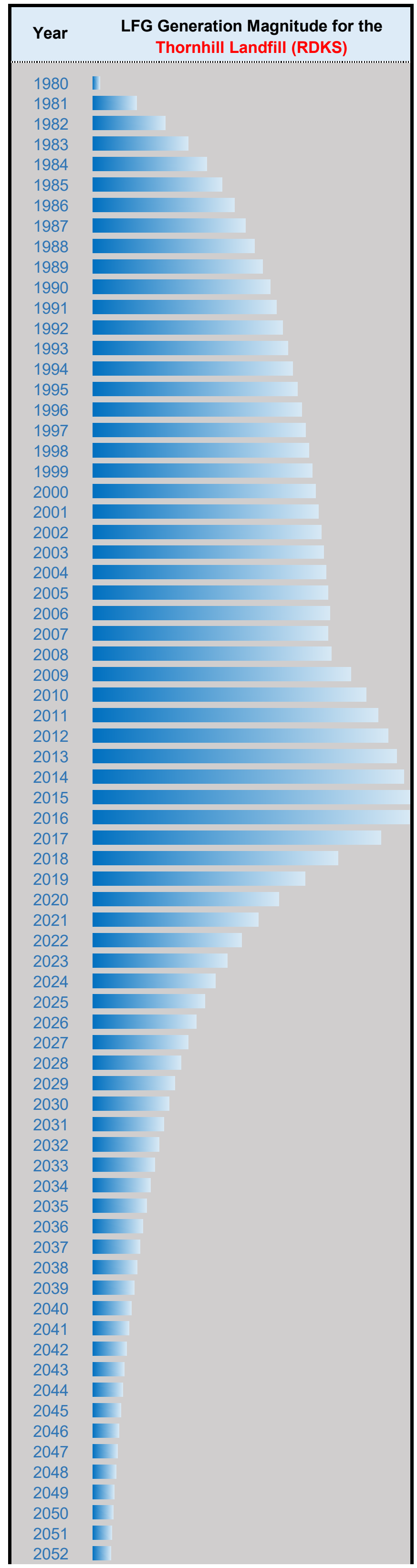
Methane Generation Estimates from the Thornhill Landfill (RDKS)

Actual CH_4 Yields

L_o (m^3/tonne)	127	158	143	72	114	103	62.1

Year	Methane generation estimates for the Thornhill Landfill (RDKS)							Methane Generation Potential	Total LFG Flow Rate Estimated
	Food (tonnes)	Garden (tonnes)	Paper (tonnes)	Wood (tonnes)	Textile (tonnes)	Nappies (tonnes)	Total (tonnes)	(L_o, m^3/tonne)	(scfm)
1980	4	0	1	0	0	0	5	62.1	1
1981	21	1	4	1	3	1	31	62.1	6
1982	33	3	8	1	5	1	51	62.1	10
1983	42	3	11	2	7	2	67	62.1	13
1984	48	4	14	3	9	2	80	62.1	16
1985	53	5	17	3	11	3	91	62.1	18
1986	56	6	20	4	13	3	100	62.1	20
1987	58	6	22	4	14	3	108	62.1	21
1988	59	7	24	5	16	4	114	62.1	23
1989	60	7	27	5	17	4	120	62.1	24
1990	61	7	28	5	18	4	125	62.1	25
1991	62	8	30	6	20	5	130	62.1	26
1992	62	8	32	6	21	5	134	62.1	27
1993	62	8	34	7	22	5	138	62.1	27
1994	62	8	35	7	23	5	141	62.1	28
1995	63	8	37	7	24	6	144	62.1	29
1996	63	9	38	8	25	6	147	62.1	29
1997	63	9	39	8	25	6	150	62.1	30
1998	63	9	40	8	26	6	152	62.1	30
1999	63	9	41	9	27	6	155	62.1	31
2000	63	9	42	9	27	6	157	62.1	31
2001	63	9	43	9	28	7	159	62.1	32
2002	63	9	44	10	29	7	161	62.1	32
2003	63	9	45	10	29	7	163	62.1	32
2004	63	9	46	10	30	7	164	62.1	33
2005	63	9	46	10	30	7	166	62.1	33
2006	63	9	47	11	30	7	167	62.1	33
2007	61	9	47	11	31	7	166	62.1	33
2008	62	9	48	11	31	7	168	62.1	33
2009	70	10	50	11	32	8	182	62.1	36
2010	76	10	52	12	34	8	192	62.1	38
2011	81	11	54	12	35	8	201	62.1	40
2012	84	11	56	13	36	8	208	62.1	41
2013	86	12	58	13	37	9	214	62.1	42
2014	87	12	59	14	38	9	219	62.1	43
2015	88	12	61	14	39	9	223	62.1	44
2016	86	12	61	14	40	9	223	62.1	44
2017	71	11	59	14	38	9	203		40
2018	50	10	55	14	36	8	173		34
2019	35	9	52	13	33	8	150		30
2020	25	7	48	13	31	7	131		26
2021	17	6	45	12	29	7	117		23
2022	12	6	42	12	27	6	105		21
2023	9	5	39	11	25	6	95		19
2024	6	4	36	11	24	6	86		17
2025	4	4	34	10	22	5	79		16
2026	3	3	32	10	20	5	73		14
2027	2	3	29	9	19	4	67		13
2028	2	2	28	9	18	4	63		12
2029	1	2	26	9	17	4	58		12
2030	1	2	24	8	15	4	54		11
2031	1	2	22	8	14	3	50		10
2032	0	1	21	8	13	3	47		9
2033	0	1	19	7	13	3	44		9
2034	0	1	18	7	12	3	41		8
2035	0	1	17	7	11	3	38		8
2036	0	1	16	7	10	2	36		7
2037	0	1	15	6	9	2	33		7
2038	0	1	14	6	9	2	31		6
2039	0	1	13	6	8	2	29		6
2040	0	0	12	6	8	2	27		5
2041	0	0	11	5	7	2	26		5
2042	0	0	10	5	7	2	24		5
2043	0	0	10	5	6	1	23		4
2044	0	0	9	5	6	1	21		4
2045	0	0	8	5	5	1	20		4
2046	0	0	8	4	5	1	19		4
2047	0	0	7	4	5	1	18		3
2048	0	0	7	4	4	1	16		3
2049	0	0	6	4	4	1	15		3
2050	0	0	6	4	4	1	14		3
2051	0	0	5	4	4	1	14		3
2052	0	0	5	3	3	1	13		3



Year	Methane generation estimates for the Thornhill Landfill (RDKS)							Methane Generation Potential	Total LFG Flow Rate Estimated
	Food	Garden	Paper	Wood	Textile	Nappies	Total		
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(L_o, m^3/tonne)	(scfm)
2053	0	0	5	3	3	1	12		2
2054	0	0	4	3	3	1	11		2
2055	0	0	4	3	3	1	11		2
2056	0	0	4	3	3	1	10		2
2057	0	0	4	3	2	1	9		2
2058	0	0	3	3	2	1	9		2
2059	0	0	3	3	2	0	8		2
2060	0	0	3	3	2	0	8		2
2061	0	0	3	2	2	0	7		1
2062	0	0	3	2	2	0	7		1
2063	0	0	2	2	2	0	7		1
2064	0	0	2	2	1	0	6		1
2065	0	0	2	2	1	0	6		1
2066	0	0	2	2	1	0	5		1
2067	0	0	2	2	1	0	5		1
2068	0	0	2	2	1	0	5		1
2069	0	0	2	2	1	0	5		1
2070	0	0	1	2	1	0	4		1
2071	0	0	1	2	1	0	4		1
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2075	0	0	1	1	1	0	3		1
2076	0	0	1	1	1	0	3		1
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2078	0	0	1	1	1	0	3		1
2079	0	0	1	1	1	0	3		1
2080	0	0	1	1	0	0	2		0
2081	0	0	1	1	0	0	2		0
2082	0	0	1	1	0	0	2		0
2083	0	0	1	1	0	0	2		0
2084	0	0	1	1	0	0	2		0
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2091	0	0	0	1	0	0	1		0
2092	0	0	0	1	0	0	1		0
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2097	0	0	0	1	0	0	1		0
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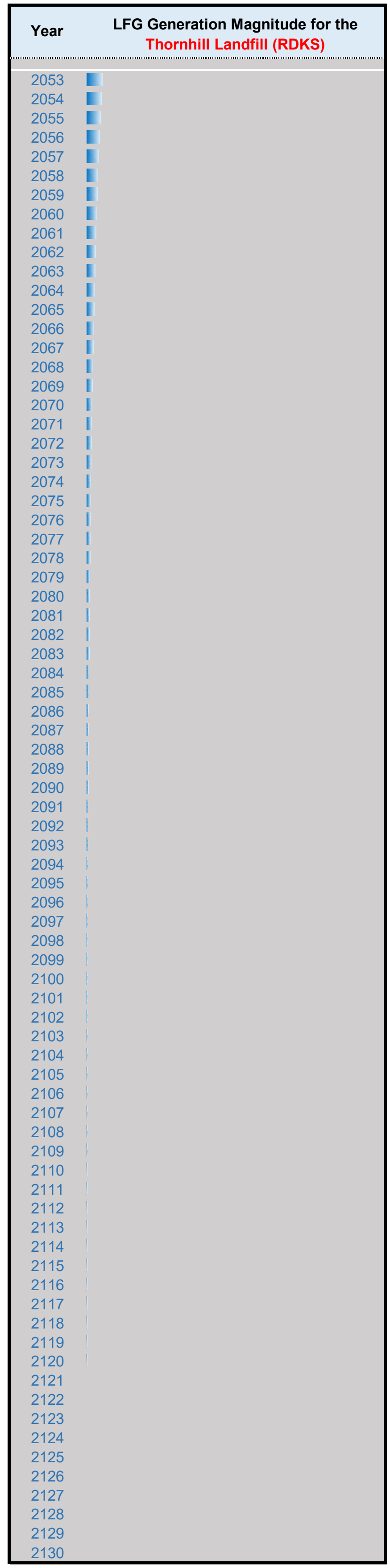
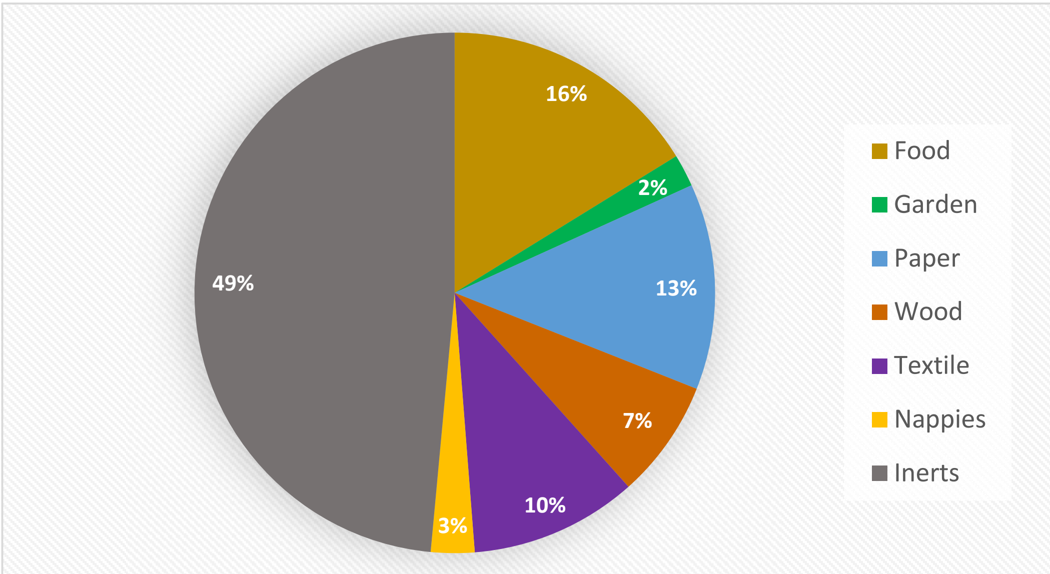
2104	0	0	0	0	0	0	1		0
2105	0	0	0	0	0	0	1		0
2106	0	0	0	0	0	0	1		0
2107	0	0	0	0	0	0	1		0
2108	0	0	0	0	0	0	1		0
2109	0	0	0	0	0	0	1		0
2110	0	0	0	0	0	0	1		0
2111	0	0	0	0	0	0	0		0
2112	0	0	0	0	0	0	0		0
2113	0	0	0	0	0	0	0		0
2114	0	0	0	0	0	0	0		0
2115	0	0	0	0	0	0	0		0
2116	0	0	0	0	0	0	0		0
2117	0	0	0	0	0	0	0		0
2118	0	0	0	0	0	0	0		0
2119	0	0	0	0	0	0	0		0
2120	0	0	0	0	0	0	0		0
2121	0	0	0	0	0	0	0		0
2122	0	0	0	0	0	0	0		0
2123	0	0	0	0	0	0	0		0
2124	0	0	0	0	0	0	0		0
2125	0	0	0	0	0	0	0		0
2126	0	0	0	0	0	0	0		0
2127	0	0	0	0	0	0	0		0
2128	0	0	0	0	0	0	0		0
2129	0	0	0	0	0	0	0		0
2130	0	0	0	0	0	0	0		0



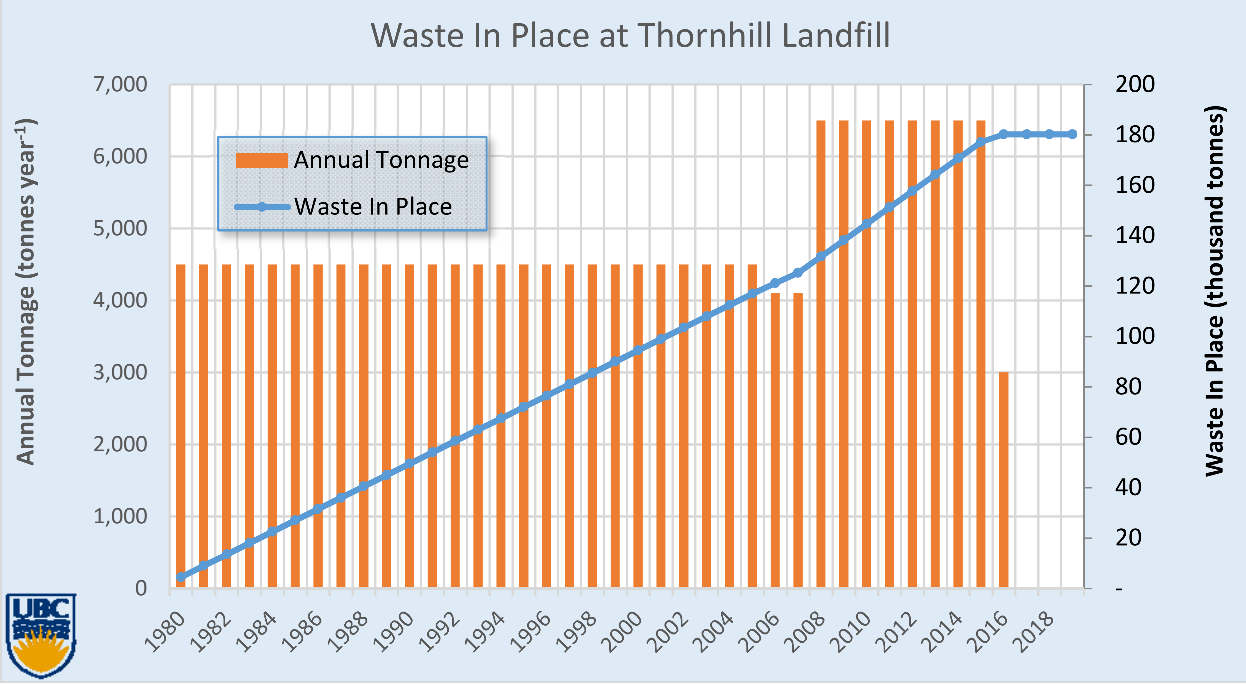
Thornhill Landfill (RDKS)

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**

Average Deposited Waste Composition

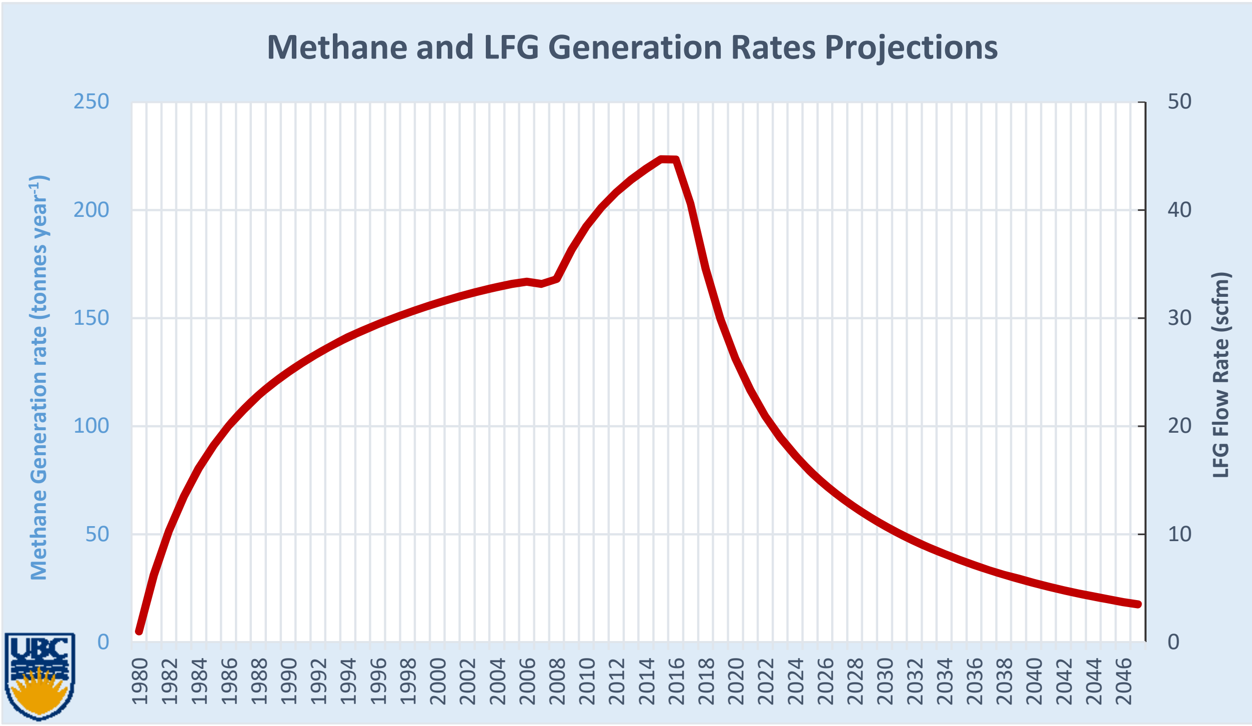


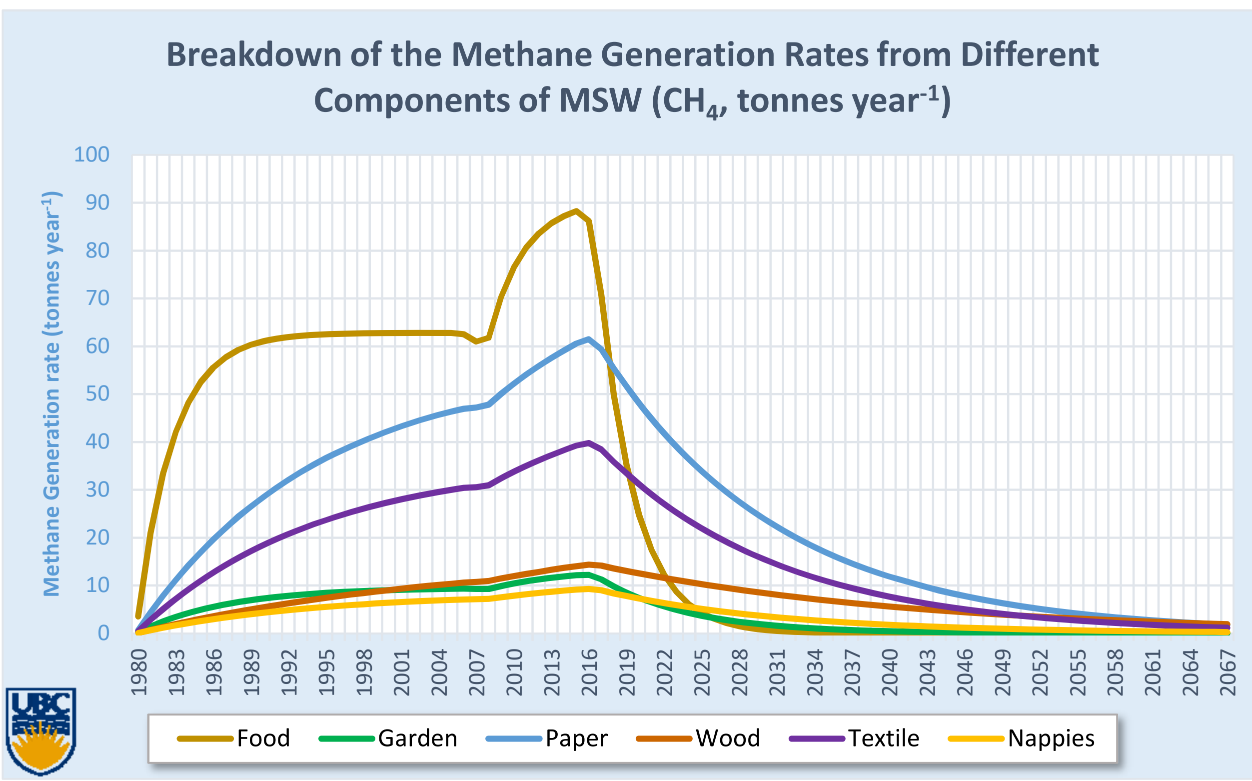
Annual MSW Deposition Rates and Total Waste In Place



Thornhill Landfill (RDKS)

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**





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Appendix B:

Field Investigations - Barometric Pressure Records (Terrace Airport)

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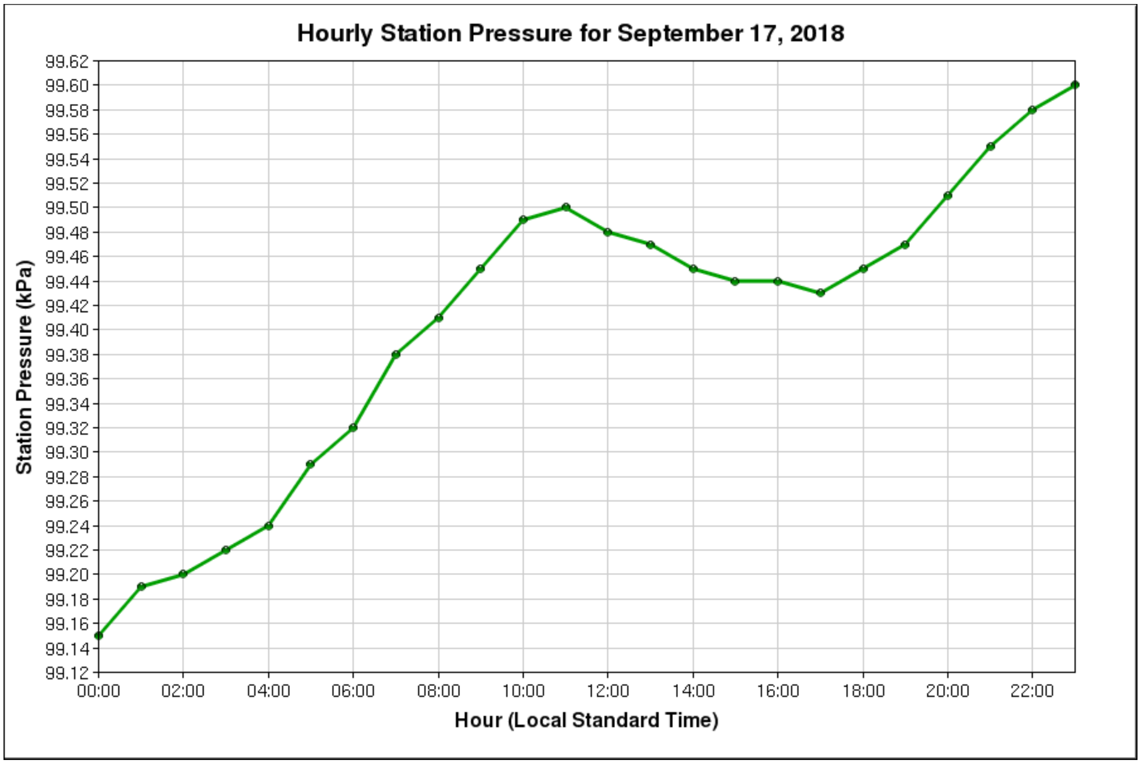
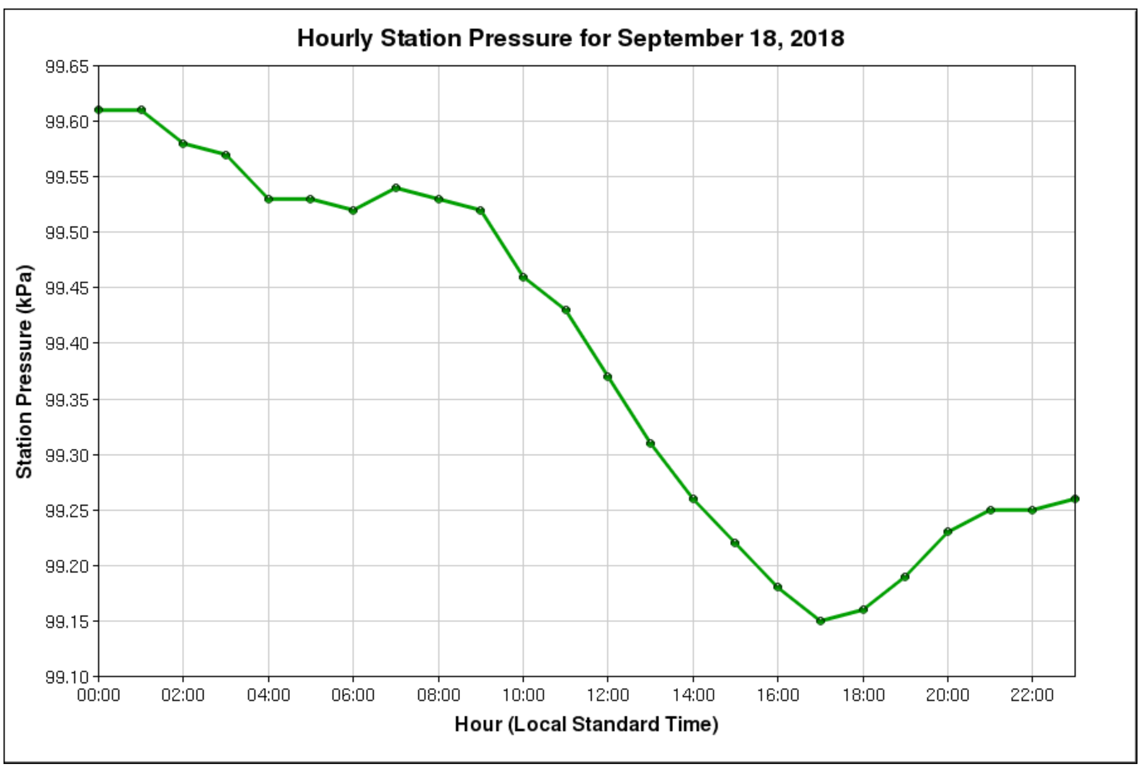
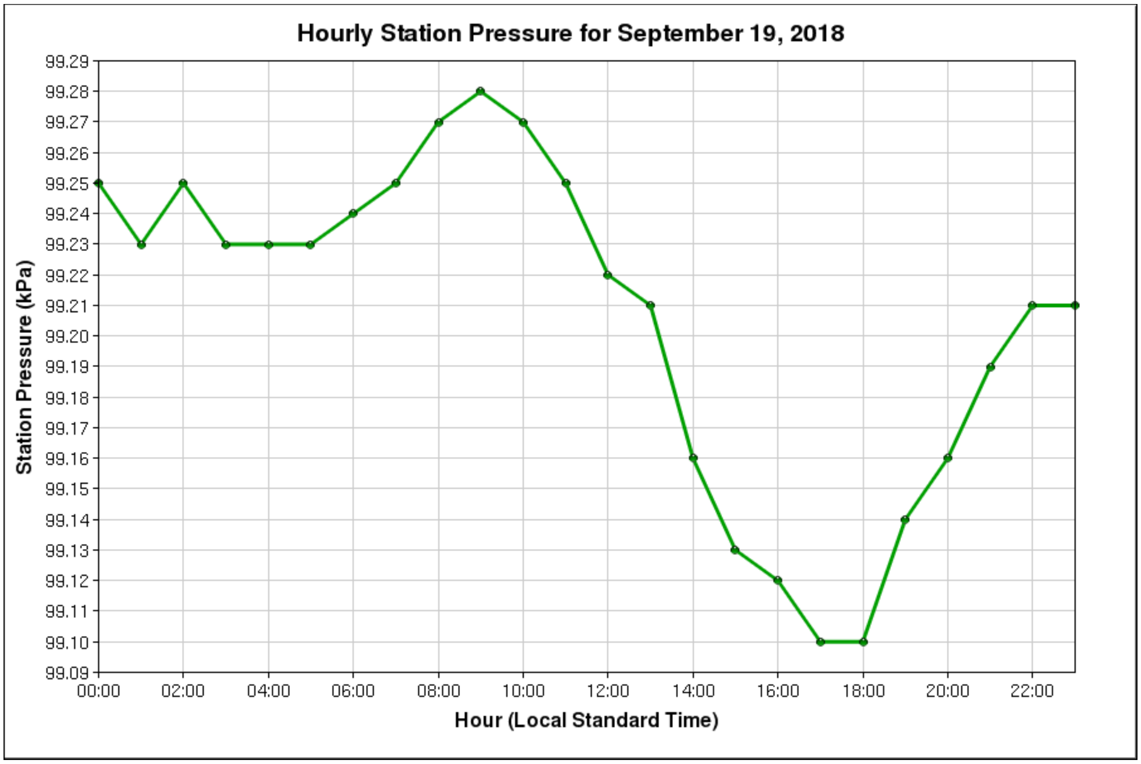


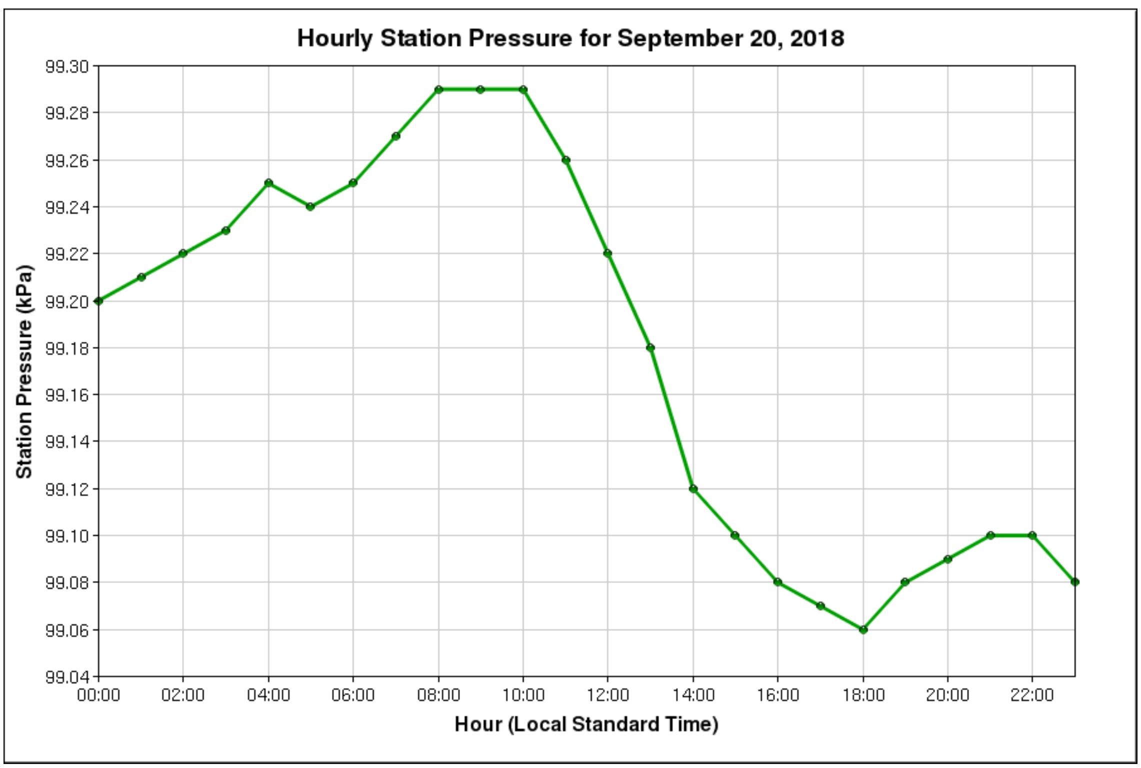
Hourly Station Pressure for September 17, 2018
Station Pressure (kPa)
Hour (Local Standard Time)



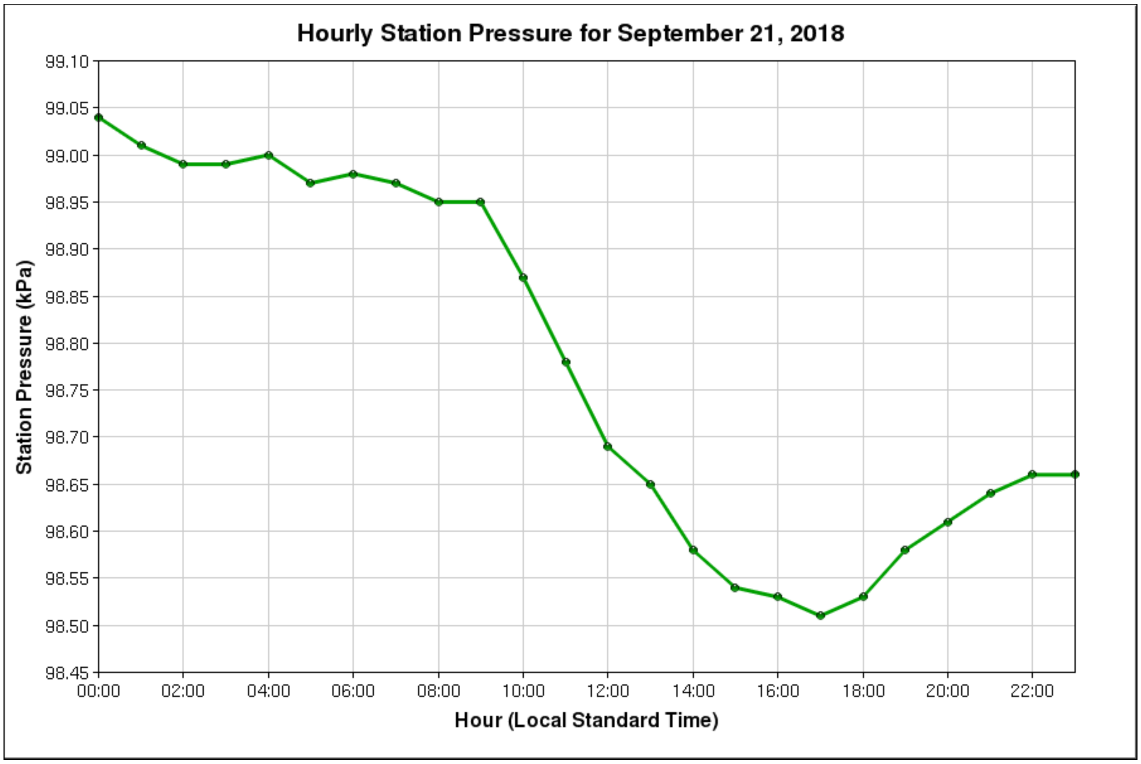
Hourly Station Pressure for September 18, 2018
Station Pressure (kPa)
Hour (Local Standard Time)



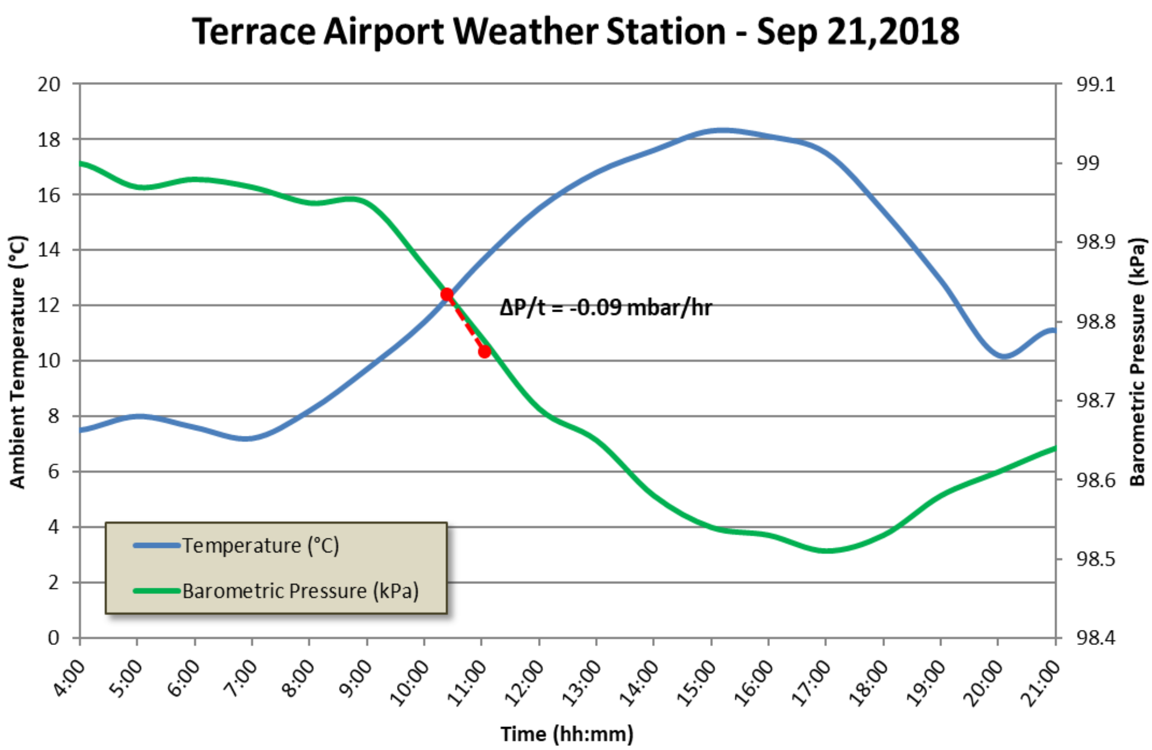
Hourly Station Pressure for September 19, 2018
Station Pressure (kPa)
99.29
99.28
99.27
99.26
99.25
99.24
99.23
99.22
99.21
99.20
99.19
99.18
99.17
99.16
99.15
99.14
99.13
99.12
99.11
99.10
99.09
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Hour (Local Standard Time)



Hourly Station Pressure for September 20, 2018
Station Pressure (kPa)
99.30
99.28
99.26
99.24
99.22
99.20
99.18
99.16
99.14
99.12
99.10
99.08
99.06
99.04
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Hour (Local Standard Time)



Hourly Station Pressure for September 21, 2018
Station Pressure (kPa)
99.10
99.05
99.00
98.95
98.90
98.85
98.80
98.75
98.70
98.65
98.60
98.55
98.50
98.45
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Hour (Local Standard Time)



Terrace Airport Weather Station - Sep 21,2018
Ambient Temperature (°C)
Barometric Pressure (kPa)
ΔP/t = -0.09 mbar/hr
Temperature (°C)
Barometric Pressure (kPa)
Time (hh:mm)
20
18
16
14
12
10
8
6
4
2
0
99.1
99
98.9
98.8
98.7
98.6
98.5
98.4
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00

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Appendix C:

Field Investigations - Recorded Gas Quality Data

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Vent #1

Date and Time	Pressure (" w.c.)	CH4 (% vol.)	CO2 (% vol.)	O2 (% vol.)	BAL (% vol.)	CH4:CO2
2018-09-18 10:00						
2018-09-18 10:45	0.03	44.5	33	0.2	22.2	1.35
2018-09-18 14:00	0.01	44.9	32.8	0.1	22.1	1.37
2018-09-18 15:45	0.01	45.7	32.9	0.2	21.2	1.39
2018-09-19 9:45	0.02	44.5	32.9	0.5	22.2	1.35
2018-09-19 10:30	0.01	44.1	33	0.3	22.6	1.34
2018-09-19 12:00	0.01	44	33	0.1	22.8	1.33
2018-09-19 13:00	0.01	44	33	0.1	22.9	1.33
2018-09-19 13:45	0.01	44.1	33	0.1	22.8	1.34
2018-09-19 15:00	0.01	43.9	32.9	0.1	23.1	1.33
2018-09-19 16:00	0.1	44.1	33	0.1	22.8	1.34
2018-09-20 10:00	0.01	44.5	32.9	0.3	22.3	1.35
2018-09-20 10:30	0.01	44.5	33	0.2	22.2	1.35
2018-09-20 11:00	0.01	44.3	32.9	0.3	22.2	1.35
2018-09-20 12:20	0.01	43.9	32.7	0.4	22.9	1.34
2018-09-20 13:30	0.01	43.9	32.7	0.2	23.3	1.34
2018-09-20 14:35	0.01	43.9	32.9	0.1	23.3	1.33
2018-09-20 15:50	0.01	44	32.9	0.1	23	1.34
2018-09-21 10:00	0.02	44.4	32.5	0.5	22.2	1.37
2018-09-21 11:00	0.01	44.4	32.9	0.2	22.7	1.35
2018-09-21 11:30	0.04	44.6	33	0.4	22.1	1.35
2018-09-21 12:00	0.03	44.7	33.1	0.3	22	1.35
2018-09-21 13:00	0.02	44.7	33	0.3	22	1.35
2018-09-21 14:30	0.02	44.6	33	0.2	22.2	1.35
2018-09-21 15:15	0.02	45.7	33	0.3	21.2	1.38
2018-09-21 16:00	0.02	45.6	33	0.3	21.2	1.38

Vent #2

Time	V (M/S)	Flow (scfm)	DP	Pressure (" w.c.)	CH4 (% vol.)	CO2 (% vol.)	O2 (% vol.)	BAL (% vol.)	CH4:CO2
2018-09-18 10:00				0.02	25.1	23.3	3.6	48	1.08
2018-09-18 10:45				0.02	26.7	25.1	2.3	45.9	1.06
2018-09-18 14:00				0.01	33	28.3	0.4	38.3	1.17
2018-09-18 15:45				0.01	37	29.3	0.3	33.4	1.26
2018-09-19 9:45				0.02	28.8	25.6	2.1	43.6	
2018-09-19 10:30				0.01	29.4	26.3	1.5	42.8	1.12
2018-09-19 12:00				0.01	31.3	27.8	0.7	40.2	1.13
2018-09-19 13:00				0.01	32.2	28.1	0.4	39.4	1.15
2018-09-19 13:45				0.01	32.3	28	0.3	39.4	1.15
2018-09-19 15:00				0.01	32.2	27.9	0.4	39.5	1.15
2018-09-19 16:00				0.01	32.1	27.9	0.2	39.8	1.15
2018-09-20 10:00				0.01	33.9	28.4	0.4	37.4	1.19
2018-09-20 10:30				0.01	34.2	28.6	0.2	36.9	1.20
2018-09-20 11:00				0.01	34.4	28.7	0.4	36.4	1.20
2018-09-20 12:20				0.01	34.2	28.5	0.2	37	1.20
2018-09-20 13:30				0.01	33.8	28.4	0.1	37.4	1.19
2018-09-20 14:35				0.01	34.6	28.8	0.2	36.5	1.20
2018-09-20 15:50				0.01	35.4	29	0.1	35.9	1.22
2018-09-20 16:20				0.01	36.8	29.6	0.1	33.6	1.24
2018-09-21 10:00	0.21	0.507	0.02	open	36.2	29.4	0.4	34.4	1.23
2018-09-21 11:00	0.38	0.918	0.02	open	36.1	29.5	0.1	34.6	1.22
2018-09-21 11:30	0.38	0.918	0.03	open	37.8	30.2	0.3	33.3	1.25
2018-09-21 12:00	0.3	0.725	0.02	open	37.9	30.2	0.1	33.1	1.25
2018-09-21 13:00	0.38	0.918	0.03	open	36.9	29.6	0.1	33.6	1.25
2018-09-21 14:30	0.6	1.449	0.05	open	41.2	30.2	0.1	33.9	1.36
2018-09-21 15:15	0.8	1.932	1	open	42.2	31	0.2	32.1	1.36
2018-09-21 16:00				open	37.8	29.5	0.3	32.4	1.28
2018-09-21 16:15				open	44	31.6	0.2	24.4	1.39

Vent #3

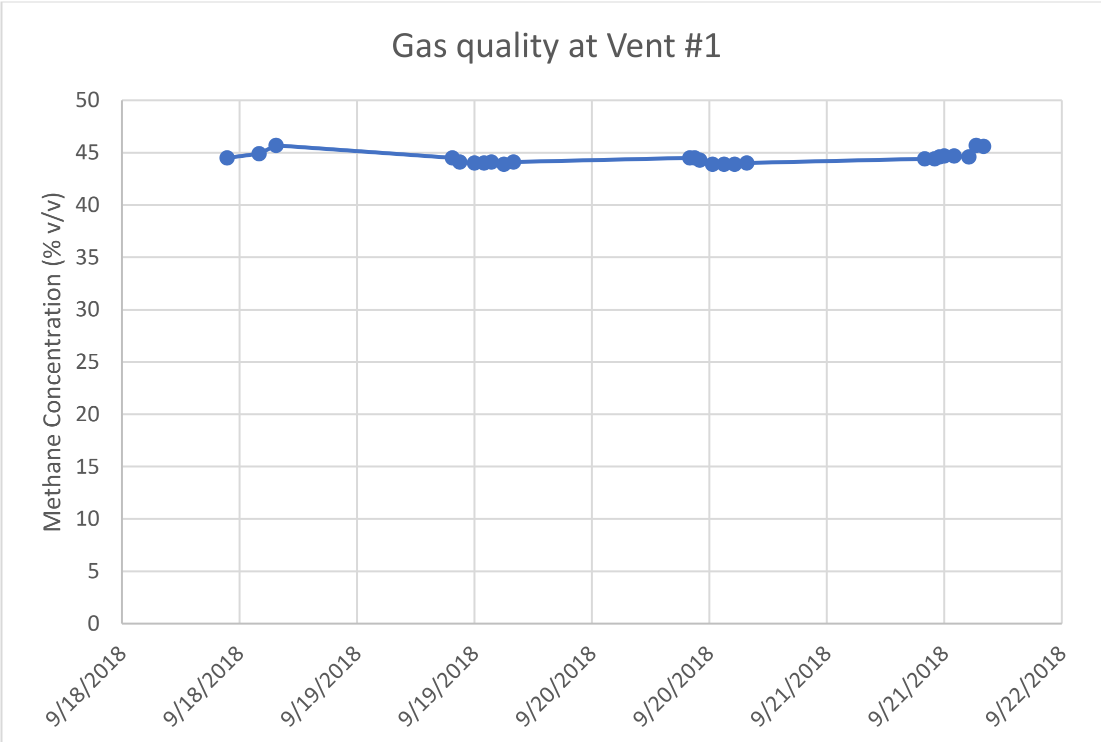
Date and Time	V (m/s)	Flow (scfm)	Pressure (" w.c.)	CH4 (% vol.)	CO2 (% vol.)	O2 (% vol.)	BAL (% vol.)	CH4:CO2
9/17/2018 12:30			Open	19	21.2	4.7	54	0.90
9/17/2018 13:45			Open	31.5	29	0.5	39.3	1.09
9/17/2018 15:20			Open	34.4	29.5	0.1	34.4	1.17
9/17/2018 16:30			Open	31.8	28.1	0.8	39.3	1.13
9/18/2018 9:45	0.34	0.821	Open	19.4	18.3	7.5	34.5	1.06
9/18/2018 10:30	0.36	0.870	Open	24.2	22.9	4.5	48.8	1.06
9/18/2018 11:00			Open	25	22.8	4.8	47.8	1.10
9/18/2018 11:30	0.26	0.628	Open	27.7	25	3	44.3	1.11
9/18/2018 14:00			Open	36.2	30.1	0.2	33.3	1.20
9/18/2018 15:45			Open	36.69	29.8	0.1	33.2	1.23
9/19/2018 9:30	0.25	0.604	Open	28.8	25.6			1.13
9/19/2018 9:45			Open	21.5	20.4	5.8	52.3	1.05
9/19/2018 10:30	0.27	0.652	Open	24.8	23.4	4	47.9	1.06
9/19/2018 12:00	0.34	0.821	Open	33.7	29.3	0.2	36.9	1.15
9/19/2018 12:30	0.2	0.483	Open	31.7	28.1	1	39.2	1.13
9/19/2018 13:00	0.16	0.386	Open	27.3	25.4	2.5	44.9	1.07
9/19/2018 13:45	0.2	0.483	Open	34	29.4	0.5	36.1	1.16
9/19/2018 14:00	0.24	0.580	Open					
9/19/2018 15:00			Open	35.4	30	0.2	34.4	1.18
9/19/2018 16:00			Open	36.8	30.5	0	32.7	1.21
9/20/2018 10:00	0.2	0.483	Open	20.1	19.8	5.9	54.2	1.02
9/20/2018 10:30			Open	20.8	20.1	5.6	53	1.03
9/20/2018 11:00	0.13	0.314	Open	19.5	19.3	6.3	54.8	1.01
9/20/2018 12:20	0.13	0.314	Open	28.5	26.1	2	43.3	1.09
9/20/2018 13:30			Open	36	30	0.2	33.7	1.20
9/20/2018 14:20	0.17	0.411	Open					
9/20/2018 14:35			Open	38.1	31	0.1	30.7	1.23
9/20/2018 15:50			Open	36.2	30	0.1	33.7	1.21
9/21/2018 10:00			0.02	36.6	29.4	0.8	32.8	1.24
9/21/2018 11:00			0.03	36.7	30	0.3	33.1	1.22
9/21/2018 11:30			0.01	36.9	30	0.5	32.7	1.23
9/21/2018 12:00			0.01	37.2	30.1	0.5	32.4	1.24
9/21/2018 13:00			0.03	37.1	30.1	0.7	32.2	1.23
9/21/2018 14:30			0.02	37.3	30.2	0.3	32.2	1.24
9/21/2018 15:15			0.01	38	30	0.3	31.5	1.27
9/21/2018 16:00			0.01	38.2	30.1	0.2	31	1.27

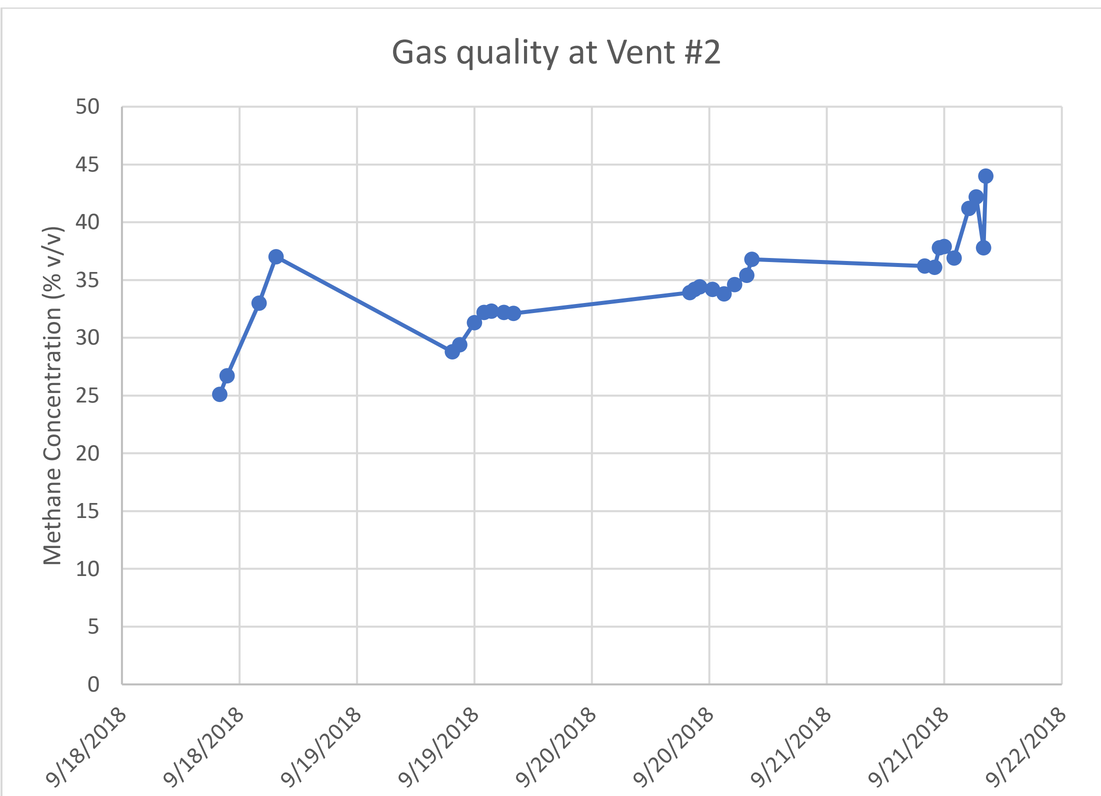
Vent #4

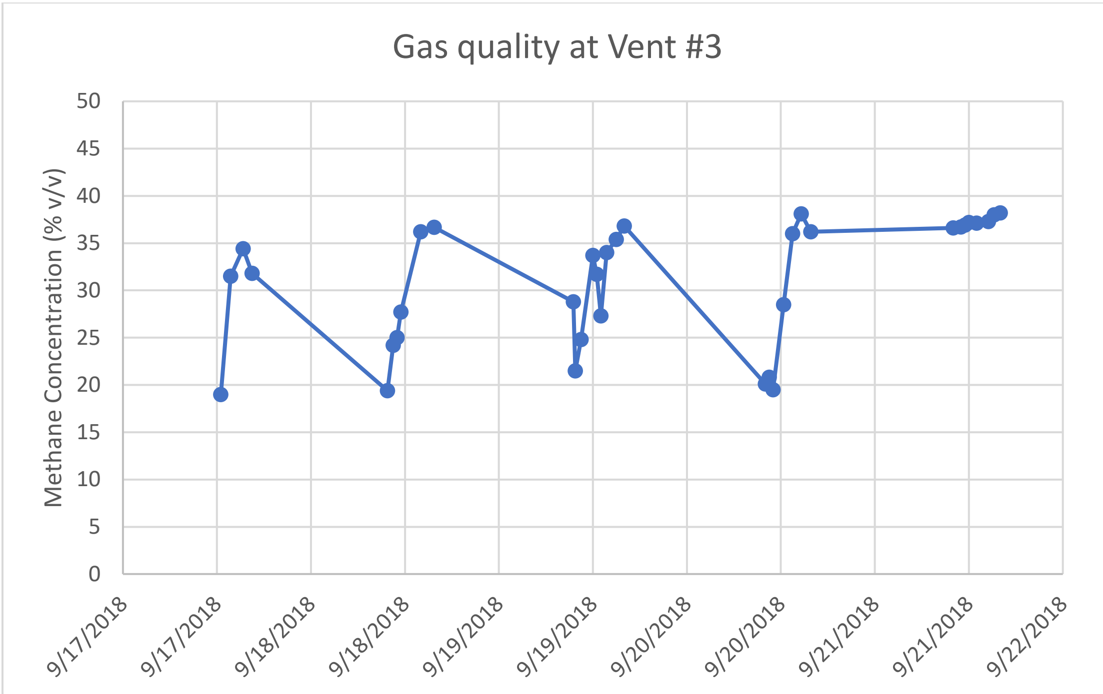
Date and Time	Pressure (" w.c.)	CH4 (% vol.)	CO2 (% vol.)	O2 (% vol.)	BAL (% vol.)	CH4:CO2
2018-09-18 10:00						
2018-09-18 10:45	0.01	0	2.3	18.9	78.8	0.00
2018-09-18 14:00	0	0	2.5	17.9	79.5	0.00
2018-09-18 15:45	0	0.2	2.8	17.3	79.5	0.07
2018-09-19 9:45	0.01	0	2.8	18.4	78.8	0.00
2018-09-19 10:30	0	0	2.8	18.3	78.9	0.00
2018-09-19 12:00	0	0	2.9	18.3	78.9	0.00
2018-09-19 13:00	0	0	2.9	18	79	0.00
2018-09-19 13:45	0	0.6	3.8	17.2	78.4	0.16
2018-09-19 15:00	0	0.1	3.1	17.5	79.3	0.03
2018-09-19 16:00	0	0.1	3.1	17.6	79.2	0.03
2018-09-20 10:00	0	0	3	17.8	79.1	0.00
2018-09-20 10:30	0	0	2.9	17.8	79.1	0.00
2018-09-20 11:00	0	0	2.9	17.9	79	0.00
2018-09-20 12:20	0	0	2.9	17.5	79.5	0.00
2018-09-20 13:30	0	0	3	17.3	79.5	0.00
2018-09-20 14:35	0	0	3	17.1	79.8	0.00
2018-09-20 15:50	0	0	3.2	17	79.8	0.00
2018-09-21 10:00	0	0	3	17.8	79.1	0.00
2018-09-21 11:00	0	0.8	3.8	16.9	78.3	0.21
2018-09-21 11:30	0	0.8	4.1	16.6	78.3	0.20
2018-09-21 12:00	0	0.3	3.8	16.6	79.1	0.08
2018-09-21 13:00	0	4.3	6.8	14.4	74.5	0.63
2018-09-21 14:30	0.01	18.9	17.1	7.5	56.7	1.11
2018-09-21 15:15	0.01	22	18.8	6.3	53.3	1.17
2018-09-21 16:00	0.01	23.5	20.1	5.3	51.2	1.17

Vent #5

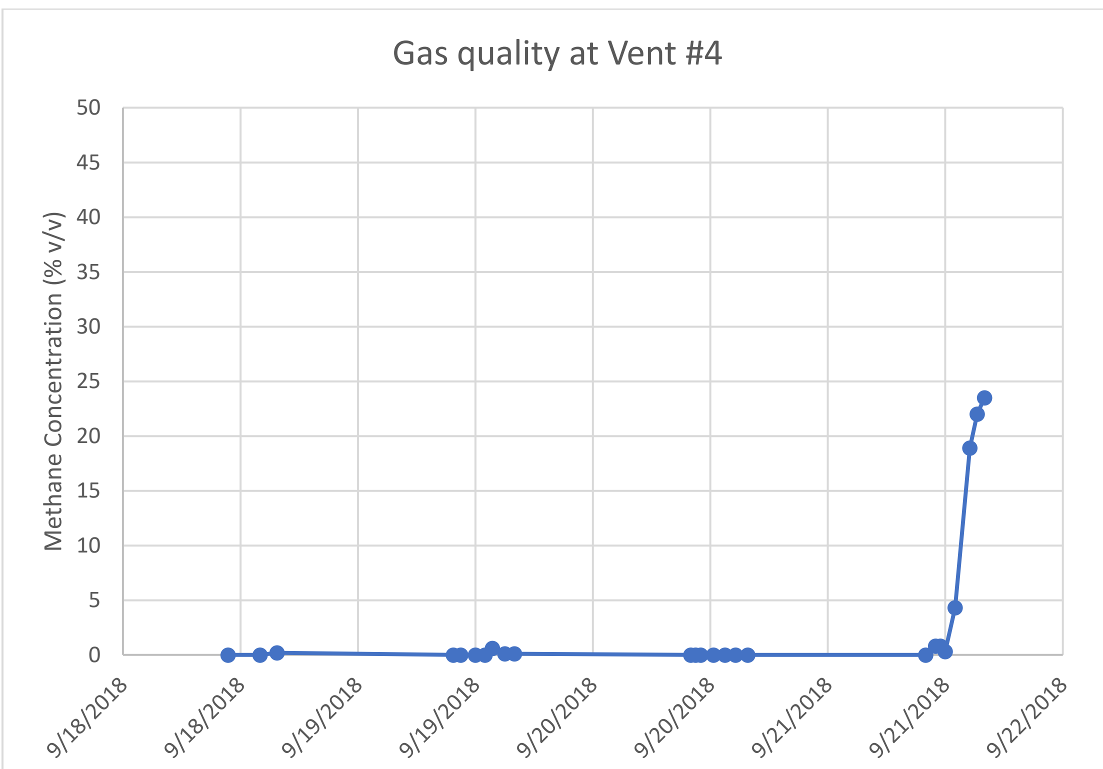
Date and Time	Pressure (" w.c.)	CH4 (% vol.)	CO2 (% vol.)	O2 (% vol.)	BAL (% vol.)	CH4:CO2
2018-09-18 10:00						
2018-09-18 10:45	0.01	1.9	5.6	15.3	77.2	0.34
2018-09-18 14:00	0.01	3.7	8.7	11.7	75.9	0.43
2018-09-18 15:45	0	8.3	13.3	7.1	7.12	0.62
2018-09-19 9:45	0.01	2.5	6.5	15	76	0.38
2018-09-19 10:30	0.01	2.4	6.6	14.9	76.1	0.36
2018-09-19 12:00	0	2.4	7.1	14.3	76.2	0.34
2018-09-19 13:00	0	2.6	7.5	13.8	76.1	0.35
2018-09-19 13:45	0	3.1	8.1	13.2	75.6	0.38
2018-09-19 15:00	0	3.4	8.6	12.4	75.6	0.40
2018-09-19 16:00	0	3.3	8.5	12.4	75.8	0.39
2018-09-20 10:00	0	2	6.4	14.6	77	0.31
2018-09-20 10:30	0	2	6.4	14.6	77	0.31
2018-09-20 11:00	0	1.9	6.3	14.5	77	0.30
2018-09-20 12:20	0	1.9	6.9	14.1	76.9	0.28
2018-09-20 13:30	0	3	8.8	11.9	76.2	0.34
2018-09-20 14:35	0	6.2	12.3	8.6	73	0.50
2018-09-20 15:50	0	13.2	19.6	2.3	65.1	0.67
2018-09-21 10:00	0	9.6	12.4	10.2	67.9	0.77
2018-09-21 11:00	0	16.3	18.8	5	60	0.87
2018-09-21 11:30	0.01	19.8	21.8	2.8	55.7	0.91
2018-09-21 12:00	0	22.3	23.8	1.2	52.7	0.94
2018-09-21 13:00	0.01	24	24.8	0.8	50.6	0.97
2018-09-21 14:30	0.01	24.9	25.2	0.5	49.6	0.99
2018-09-21 15:15	0.01	25.5	25.2	0.6	48.6	1.01
2018-09-21 16:00	0.01	25.5	25.1	0.6	48.7	1.02


Gas quality at Vent #1
Methane Concentration (% v/v)
50
45
40
35
30
25
20
15
10
5
0
9/18/2018
9/18/2018
9/19/2018
9/19/2018
9/20/2018
9/20/2018
9/21/2018
9/21/2018
9/22/2018


Gas quality at Vent #2
Methane Concentration (% v/v)
50
45
40
35
30
25
20
15
10
5
0
9/18/2018
9/18/2018
9/19/2018
9/19/2018
9/20/2018
9/20/2018
9/21/2018
9/21/2018
9/22/2018



Gas quality at Vent #3
Methane Concentration (% v/v)
50
45
40
35
30
25
20
15
10
5
0
9/17/2018
9/17/2018
9/18/2018
9/18/2018
9/19/2018
9/19/2018
9/20/2018
9/20/2018
9/21/2018
9/21/2018
9/22/2018



Gas quality at Vent #4
Methane Concentration (% v/v)
50
45
40
35
30
25
20
15
10
5
0
9/18/2018
9/18/2018
9/19/2018
9/19/2018
9/20/2018
9/20/2018
9/21/2018
9/21/2018
9/22/2018

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Appendix D:
Fugitive Methane Emissions Measurement – 3D Illustrations
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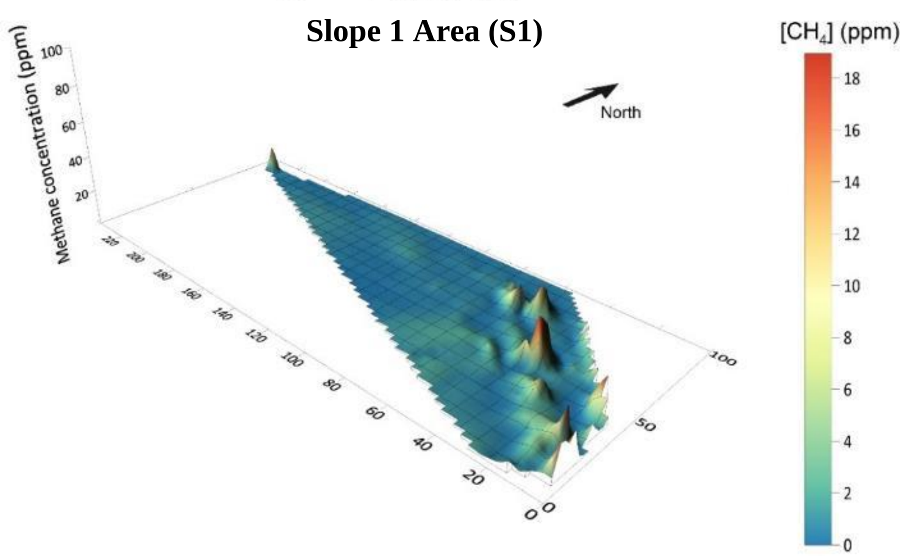


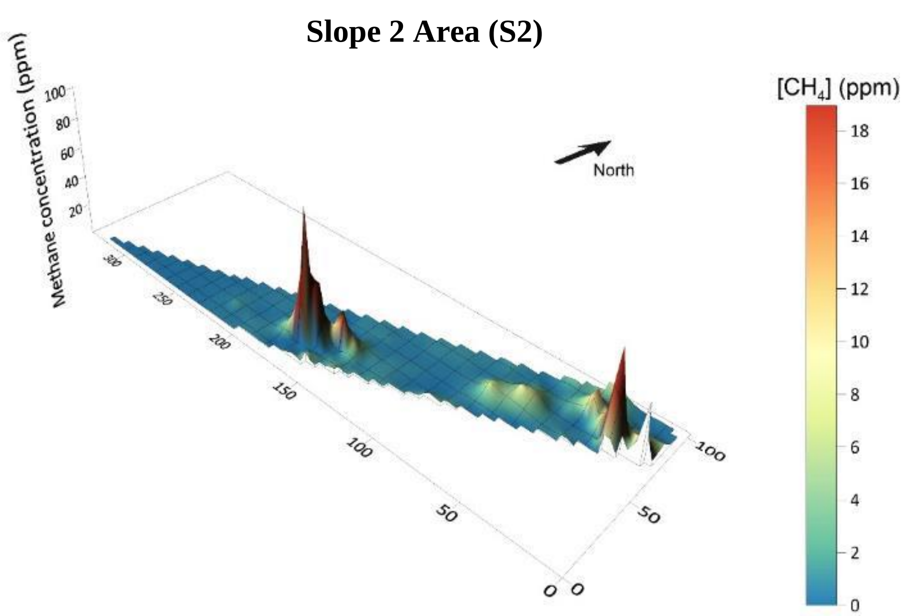
Thornhill LF – Slope 1

Baseline Sampling
Date: Sep. 20, 2018

Minimum SMC [CH_4]: 0 ppmv
Maximum SMC [CH_4]: 64.8 ppmv
Average SMC [CH_4]: 2.74 ppmv

Average MER: 3.1 gCH_4/m^2/day

Figure D1 - 3D Illustration of surface methane scan in S1 Area



Thornhill LF – Slope 2

Baseline Sampling
Date: Sep. 20, 2018

Minimum SMC [CH_4]: 0 ppmv
Maximum SMC [CH_4]: 96.39 ppmv
Average SMC [CH_4]: 4.19 ppmv

Average MER: 3.6 gCH_4/m^2/day

Figure D2 - 3D Illustration of surface methane scan in S2 Area

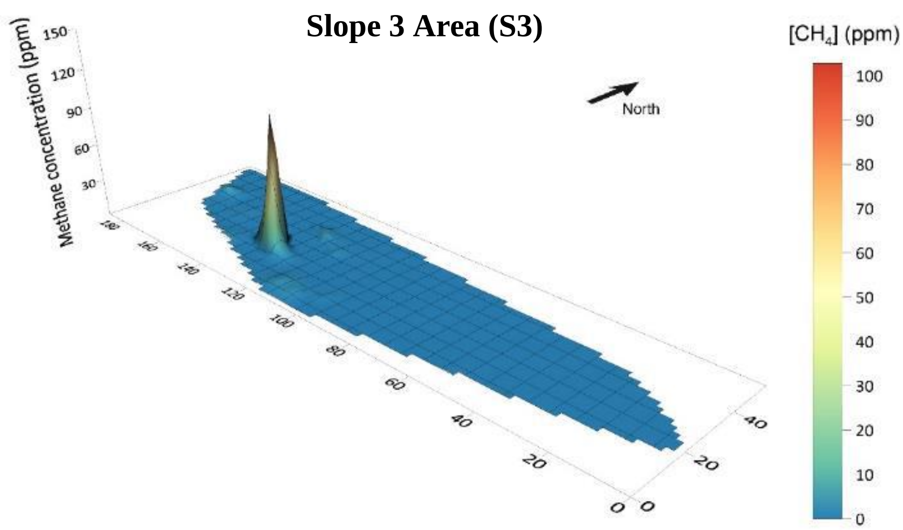


Figure D3 - 3D Illustration of surface methane scan in S3 Area

Thornhill LF – Slope 3

<u>Baseline Sampling</u>
Date: Sep. 20, 2018

Minimum SMC [CH_4]: 0 ppmv
Maximum SMC [CH_4]: 299.6 ppmv
Average SMC [CH_4]: 5.02 ppmv

Average MER: 3.9 $gCH_4/m^2/day$

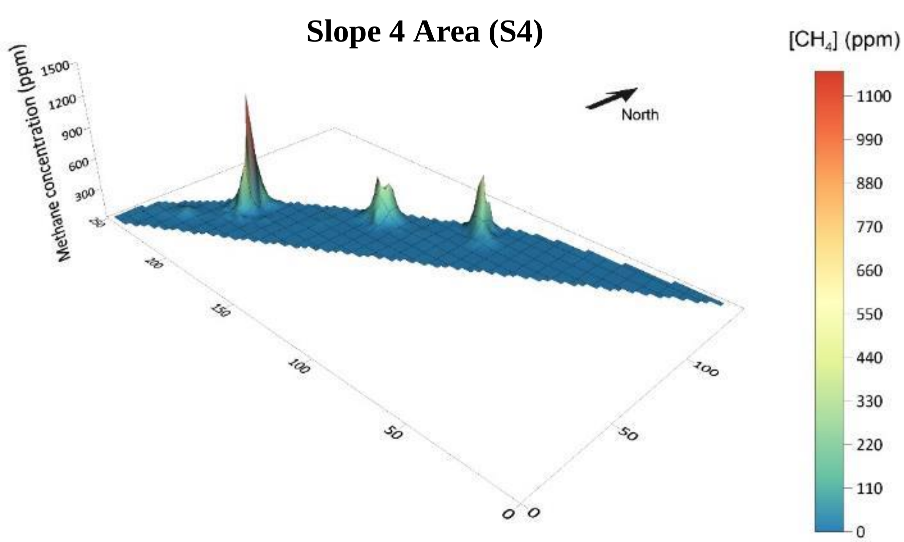


Figure D4 - 3D Illustration of surface methane scan in S4 Area

Thornhill LF – Slope 4

<u>Baseline Sampling</u>
Date: Sep. 20, 2018

Minimum SMC [CH_4]: 0 ppmv
Maximum SMC [CH_4]: 3250 ppmv
Average SMC [CH_4]: 39.42 ppmv

Average MER: 16.1 $gCH_4/m^2/day$

Slope 5 Area (S5)

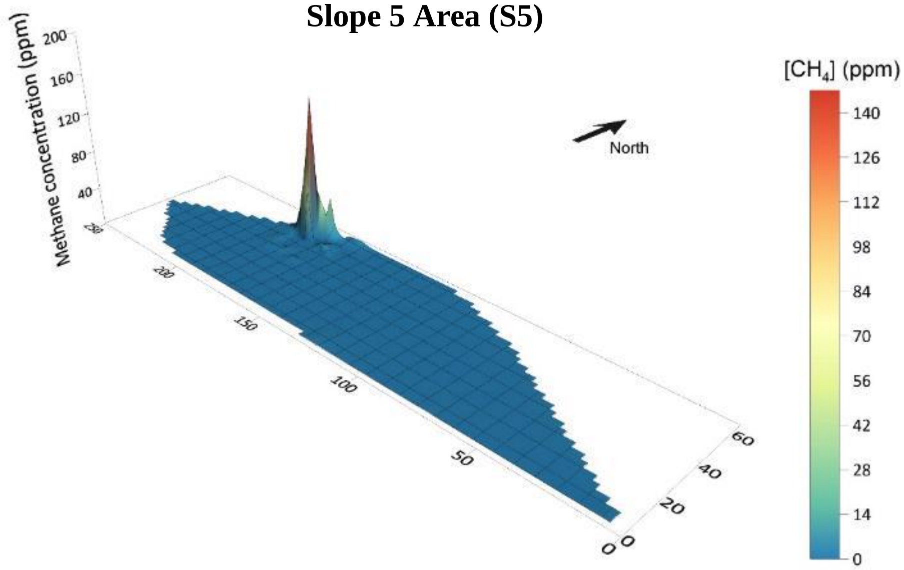


Figure D5 - 3D Illustration of surface methane scan in S5 Area

Thornhill LF – Slope 5

Baseline Sampling
Date: Sep. 21, 2018

Minimum SMC [CH_4]: 0 ppmv
Maximum SMC [CH_4]: 480.2 ppmv
Average SMC [CH_4]: 3.99 ppmv

Average MER: 3.6 gCH_4/m^2/day

Slope 6 Area (S6)

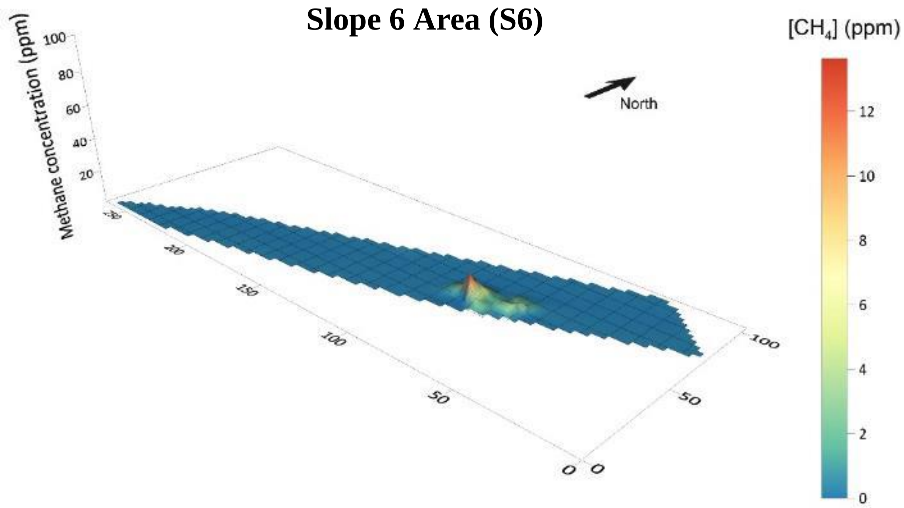


Figure D6 - 3D Illustration of surface methane scan in S6 Area

Thornhill LF – Slope 6

Baseline Sampling
Date: Sep. 21, 2018

Minimum SMC [CH_4]: 0 ppmv
Maximum SMC [CH_4]: 25.48 ppmv
Average SMC [CH_4]: 0.46 ppmv

Average MER: 2.3 gCH_4/m^2/day

Crest Area (C)

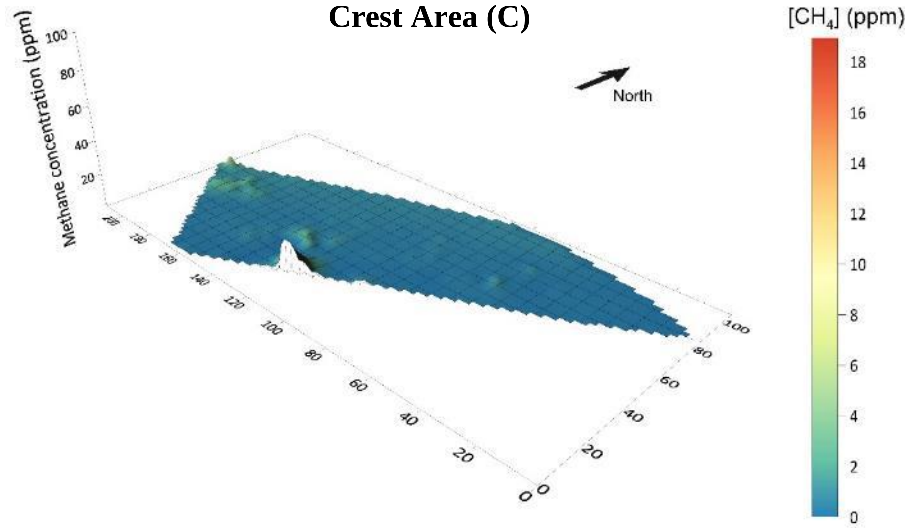


Figure D7 - 3D Illustration of surface methane scan in C Area

Thornhill LF – Crest

Baseline Sampling
Date: Sep. 20, 2018

Minimum SMC [CH_4]: 0.28 ppmv
Maximum SMC [CH_4]: 21.5 ppmv
Average SMC [CH_4]: 0.63 ppmv

Average MER: 2.4 $gCH_4/m^2/day$